Introduction: Letter from the Director

Annual Report: 2003–2004
Letter from the NAI Director
Bruce Runnegar

We live in exciting times. From an astrobiological perspective, the enduring triumph of the Mars Exploration Rovers, *Spirit* and *Opportunity* , the promise of Cassini–Huygens, and the accumulating catalog of extrasolar planets and planetary systems, are obvious highlights. We also live in interesting times. The transformation of NASA from an agency focused on the origin, future, and occurrence of life in the Universe (NASA 2003 Strategic Plan) to one with a novel Vision for Space Exploration is still underway.
The broad astrobiological goals, articulated in the Strategic Plan and the Astrobiology Roadmap, remain the priorities of any enlightened civilization. But the Vision adds the important component of human exploration to create an integrated whole, which melds adventure with discovery, as only NASA can.

The NASA Astrobiology Institute (NAI) was founded by NASA in order to help develop astrobiology as a new field of knowledge, to undertake scientific research in astrobiology, and to educate and train the next generation of astrobiologists. After seven years, how are we doing?

Astrobiology is prospering. We see it in the literature (books, journals, and articles devoted solely to astrobiology), in media reports and websites, but most importantly, in people. In this report, we count nearly 800 persons who are members of the NAI. These “card–carrying astrobiologists” are only a fraction of the astrobiology community, just as NAI is only a little over a third (in dollars) of the NASA Astrobiology Program. There are are also many astrobiologists and astrobiological organizations in other nations, and the NAI, through the international Federation of Astrobiology Organizations (FAO), is in touch with most of them. Currently, the FAO is working with three other bodies that have significant astrobiological interests to develop and implement the concept of a World Congress in Astrobiology by 2010.

Within the NAI, there is ample evidence that both the field of astrobiology and the Institute are mature. Research in astrobiology, carried out by 20 current and retired NAI teams, is reported in this searchable annual compilation. Major sections comprise reports from Teams, Focus Groups, NAI Fellows,

International Partners, and lists of publications. I encourage you to browse, search, and read. There are far too many achievements to summarize here, but a few highlights may give some flavor of the variety of astrobiological science currently being undertaken by NAI teams. These are the kinds of items that are now reported each month through the NAI website and the NAI Newsletter (both at nai.nasa.gov).

- Members of former and current NAI teams (Arizona State, Harvard–MIT, Ames Research Center, SETI Institute) are hard–working members of the Athena Science Team that is operating the Mars Exploration Rovers. The NAI contributed substantially to the planning and selection of the MER landing sites through its community–wide activities and through research that was partially funded by its cooperative agreements.
- Numerical simulations carried out by NAI team members (Carnegie, University of Washington , and UCLA teams) have validated disk coalescence as a viable alternative to the long–accepted “standard model” for the formation of planetary systems and has revealed regions of orbital stability that may permit habitable worlds in the highly eccentric extrasolar planetary systems discovered recently.
- Novel approaches to measurements of the stable isotopes of carbon, sulfur and molybdenum made by members of several NAI teams (Carnegie, Harvard–MIT, UCLA, University of Colorado) are being used to probe atmospheric chemistry on the young and middle–aged Earth.

Education and Public Outreach (EPO) and training are important components of the activities of the NAI and its partner organizations. One measure of the growth of the field—and the influence of NASA's cooperative agreements with U.S. research universities upon it—is the number and quality of faculty appointments in astrobiology that have resulted from membership in the NAI. I am thinking of faculty appointees like Chris House of the Penn State team, who runs an extremophile microbiology lab in the Geosciences department, or my Australian colleagues, Roger Buick at the University of Washington, and Roger Summons at MIT. Adding up all such appointments over the last seven years reveals that several tens of junior and senior scientists have been recruited to teach and do research in astrobiology across the United States, in addition to those who transformed themselves into astrobiologists, as I did. This demonstrates enthusiasm and commitment on the part of American universities on a multi–generational timescale.

But what of the past twelve months? And what might we expect this coming year? As Deputy Director Rosalind Grymes pointed out a year ago, the NAI had effectively just turned over with the completion of new cooperative agreements for 12 of the 16 teams. At the same time, I was coming on board as the Institute's third Director.

The first step was a strategic planning retreat, held at Jackson Hole, Wyoming for Principal Investigators (PIs) and delegates from all teams, NAI Central staff, and some invited guests (October 24–26, 2003). The primary goal was to identify Institute–wide strengths within the research and EPO activities

proposed by the teams under their separate cooperative agreements. These goals could then be developed and extended as collaborative endeavors that will allow the Institute to do more than the sum of its parts. Getting to know one another and to find out about the kinds of work being done by different teams were equally important objectives. Learning to collaborate following the fierce competition required to gain membership of the NAI was, and is, an additional challenge.

Three broad cross−disciplinary themes emerged from the three−day retreat:

1. Stellar disk evolution. A meld of astronomy and cosmochemistry using new telescopic observations, small special scale chemistry of early solar system materials (meteorites, comets, asteroids, dust particles), plus theory and numerical modeling, to investigate the fate of astrobiologically important components of the dusty disks up to the stage of planet formation. The plan is to organize three workshops, each leading to a multi−authored review article in a peer−reviewed journal, that will define the principal scientific problems that need further investigation. This initiative is being led by Ed Young, PI of the UCLA team. The three proposed workshops will deal with disk timescales, ices/icy bodies, and disk chemistry; the first is scheduled for this Fall.
2. Subsurface life. Expanded to encompass life in extreme environments in subsequent discussions, this topic brings together NAI expertise in the geosciences, oceanography, microbiology, and molecular biology. The goals of this group, as expressed in Jackson Hole , are both deep (irony intended) and forward−looking. One is to investigate microbial communities that might be metabolically divorced from the light of the sun. There have been many reports of communities that rely solely on geothermal energy sources but closer examination usually indicates that some metabolite is ultimately derived from organisms or processes that depend upon oxygenic photosynthesis. A second focus is on cold (cryospheric) environments and the microbes that inhabit them. Plans are underway, led by the Indiana−Princeton−Tennessee team (IPTAI), to explore the microbes in Canadian permafrost as an analogy for possible subsurface life on Mars. A third, ambitious goal is to work with industrial partners to develop a down−hole microbiology lab. Bruce Jakosky, PI of the University of Colorado at Boulder NAI team, led the Jackson Hole discussions and a follow−up one−day workshop held in conjunction with the Astrobiology Science Conference (AbSciCon 2004) in March. Leadership of the initiative was passed over to Tullis (T.C.) Onstott of the IPTAI team at that that time.
3. Planet in transition. A developing concept, which probably needs to be re−named, is aimed at using NAI geosciences expertise to inform planners of missions that will eventually be able to observe planets orbiting nearby stars. Discoveries in geochemistry made over the past few years are reinforcing the idea that the Earth has passed through a series of fundamentally different steady states during its 4.6 billion year history. From an astronomical point of view, these steady states are most obviously reflected in the chemical composition and oxidation state of the atmosphere and oceans. Each state is spectroscopically unique. Transitions between states are short compared with the

billion−year lifetimes of the separate states. For this endeavor, the plan is to form working groups for successive Earth states (Hadean, Archean, Proterozoic) under the aegis of the NAI's Early Earth Focus Group. The overall project leader is Peter Ward, PI of the University of Washington team.

These are not the only Institute−wide initiatives that were being nurtured and fertilized with Institute funds during the reporting period. Perhaps the most important activities, both in terms of dollars spent and potential knowledge gained, were the founding projects of the Astrobiology Drilling Program (ADP). Other activities, reviewed briefly below, include the first ever Astrobiology Graduate Conference (AbGradCon) at the University of Arizona in January; NAI's participation in AbSciCon 2004 in March; the second NAI Field Workshop to the oldest sedimentary rocks on Earth in southwest Greenland June; the now−annual Summer School in Astrobiology, taught jointly by the NAI and the Spanish Centro de Astrobiología in Spain, in July; two NAI−organized geochemistry symposia at the National Meeting of the American Chemical Society in Philadelphia in August; and an NAI−led workshop on Mars Astrobiology Science and Technology in Washington in September.

But to return to the ADP. An international consortium funded by Kagoshima University, The University of Western Australia, the Geological Survey of Western Australia, and the Pennsylvania State University NAI team led by Hiroshi Ohmoto, completed six diamond drill holes in Archean (3.5 to 2.7 billion−year−old) sedimentary and volcanic strata of Western Australia during the summer of 2003. This Archean Biosphere Drilling Project (ABDP) is the founding project of the Astrobiology Drilling Program. Its goals were to obtain unweathered, uncontaminated, and unoxidized samples of astrobiological importance from an ancient terrain that has been subjected to tropical conditions for millions of years. The cores are now being analyzed for traces of Earth's early life and to understand the environments in which it lived.

A second set of holes was drilled during the summer of 2004. Once again, the ABDP was involved, but this time in partnership with a second drilling project that came into being as a result of discussions and collaborations developed within the NAI's Mission to Early Earth Focus Group. This second project, the Deep Time Drilling Project (DTDP), is managed by Roger Buick of the University of Washington NAI team. However, funding for the analysis of the longest interval drilled this year—a one−kilometer succession in the Hamersley Basin of Western Australia—has been provided by a separate grant from the National Science Foundation. The organic geochemical analyses will be carried out in Roger Summons' state−of−the−art biomarker lab at MIT and stable isotopic surveys will take place in Ariel Anbar's new lab at Arizona State University . Both Summons and Anbar are members of NAI teams (Ames Research Center and University of Washington , respectively). The first results of the ABDP and DTDP projects will be reported in a session on astrobiology drilling projects organized by Ohmoto, Anbar, and myself at the Fall Meeting of the American Geophysical Union (San Francisco , December 2004). Additional information on the ADP and its projects is available at: nai.nasa.gov/ADP

AbGradCon (January, 2004) was the brain−child of Maggie Turnbull, then a graduate student in Astronomy at the University of Arizona, and now an NAI Postdoctoral Fellow with Sara Seager of the Carnegie Institution of Washington team. Maggie and her helpers organized everything: Speakers, talks, tours, and accommodations and food. It was remarkable. Only graduate students were allowed to present; only about a third of those who came were from NAI teams; and the talks and posters were confident, novel, exciting, multidisciplinary, and, above all, broad. This was a glimpse of the new generation of astrobiologists which the NAI is helping to train. Conference abstracts were subsequently published in *Astrobiology* , marking the first foray into the scientific literature for many of the AbGradCon participants.

AbSciCon (March, 2004) is the NASA−supported international meeting on astrobiology that alternates on a yearly basis with the NAI's own “all hands” meeting. NAI has the odd years; AbSciCon the even ones. So “NAI 2005” is scheduled for April 10−14, 2005 and will be hosted by the University of Colorado team in Boulder . However, NAI also supports and participates substantially in AbSciCon, and did so this year with additional meeting at each end. During the weekend before, the NAI held an enlarged two−day meeting of its Executive Council, which was enlivened by a visit from the NASA Administrator, Mr. Sean O'Keefe. He used the opportunity to explain the new Exploration Vision to the Council and its guests. They included representatives from our international partner organizations in Australia , Italy , Mexico , the Netherlands , Russia , Spain , Sweden , and the United Kingdom as well as countries that are in the process of developing organizations or affiliations (Canada , Japan , Russia , South Africa). Also present were Education and Public Outreach personnel from the NAI teams and partner organizations such as museums (see EPO section of this report for details). The remainder of the meeting was largely given over to scientific/organizational updates from the international guests and presentations by the team EPO leaders and their community−wide colleagues. And, of course, NAI as a whole helped fund, organize, and present AbSciCon.

Akilia, Godthaabsfjord, and Isua (June, 2004). Transcendental names to those in the know, these were the field sites for the second NAI Field Workshop, organized by UCLA team member Craig Manning and Minik Rosing, a Greenlander from the Geological Museum, Denmark. The event was timed to follow the 2004 Goldschmidt Geochemistry conference in Copenhagen and began with heated discussions in three symposia on the Early Earth and Astrobiology, organized by NAI members and colleagues in the Nordic countries (www.goldschmidt2004.dk). Participants in the Field Workshop then decamped to the Greenland Nature Institute where inclement weather (for helicopters) forced a schedule of field days interspersed with presentations and discussions in the fabulous facilities in Nuuk. As many of the major players involved in understanding the astrobiological significance of Earth's earliest sedimentary rocks (now severely metamorphosed) were on hand, many contentious issues were aired, discussed, and re−discussed at length. In particular, the 1999 report by University of Colorado team member Stephen Mojzsis, then a graduate student at the University of California , San Diego , of biogenic graphite within apatite grains on the island of Akilia was re−examined frankly and openly in all possible ways. It is now clear that the observation

needs to be verified by repetition and Alan Nutman, who provided the original sample, offered to supply additional subsamples for future analysis. On the other hand, Manning and Mojzsis presented fine field evidence and powerful geochemical arguments that the Akilia host rock was, indeed, once a sediment. Others have seriously doubted this claim. Thus, the Field Workshop achieved its principal goals: To provide field access to the finest outcrops and to enable group sampling so that different labs can analyze exactly comparable materials. However, the Greenland climate did thwart one major objective of the Field Workshop: Rosing's sedimentary graphite particles from Isua, currently the best evidence for the existence of life on Earth 3.8 billion years ago, remained under snow. The NAI will need to return!

Planet Mars (July, 2004). For the last three summers, the NAI has co−taught a graduate−level course in Astrobiology with the Spanish Centro de Astrobiología. Juan Pérez Mercader and I have been co−Directors of each course and there is a continuing agreement that they will be presented as one of the famous summer schools of the Universidad Internacional Menéndez Pelayo (UIMP) at its seasonal campus, the Palacio de Magdalena, on the Cantabrian coast of Spain . This year, the topic was “Planet Mars”, aimed at presenting all aspects of the planet, from core to atmosphere, to budding and no−so−budding astrobiologists. It was an absolute treat for the 40 participants. David Paige, from the UCLA team, first reviewed the planet and its atmosphere and hydrosphere. Then Laurie Leshin, Arizona State University and a member of the President's Commission on Space Exploration, presented the planetary geochemistry as revealed by Martian meteorites and spacecraft. Three talks on the Mars Exploration Rovers from Steven Squyres, Cornell University , who had just returned from Endurance Crater and was decompressing after months of intense activity, were a highlight of the week. But there was equally exciting news from Mars Express, reviewed by European Space Agency (ESA) Head of Research, Álvaro Giménez, and from Cassini−Huygens, given in a well−attended evening public lecture by the PI of the Titan Surface Science Package (a.k.a. “lander”), John Zarnecki, from the Open University. The school closed with an afternoon field trip to a nearby Cretaceous−Tertiary (K−T) boundary interval, where we imagined dinosaurs and ammonites going extinct. Images of the school diplomates and field trip participants are available at nai.nasa.gov/PlanetMars.

ACS, Philadelphia (August, 2004). Astrobiologists from the NAI organized and participated in two cross−disciplinary symposia at the 228th National Meeting of the American Chemical Society, held in Philadelphia , August 22−26. Aravind Asthagiri from the Carnegie team and his in−town colleague at George Washington University , H. Henry Teng, convened two very full days on “Astrobiology and the Origin of Life”; many of the 39 talks in the symposium were presented and/or co−authored by members of the NAI. Highlights included: Tice and Lowe (Stanford) on the hydrothermal control of early Earth ocean chemistry; Wang, Huang and Pizzarello's work (Brown and Arizona State universities) on the extraordinary (interstellar?) deuterium enrichment of some amino acids and other compounds from the Murchison meteorite; and Robert Hazen's (Carnegie team) presentation of Simon Platts' concept of a “PAH world” which he developed to help explain steps leading to the origin of life during his time as a Ph.D. student at RPI.

Boswell (Boz) Wing from the University of Maryland (and associate of the Carnegie team) and his NAI colleague James Lyons from the UCLA team convened a one−day symposium on “Mass−independent Isotope Fractionation” in conjunction with a week−long review of “Chemical Physics in Atmospheric Science” organized by the ACS Division of Physical Chemistry. For the first time at a major meeting, geoscientists studying the rock and ice−core records of atmospheric gas−phase reactions were able to hear and discuss the novel oxygen and sulfur chemistry that may be responsible for the anomalous isotopic effects. Applications ranged from understanding processes in the early Solar nebula (Thiemens, UC San Diego) to the use of anomalous oxygen isotope ratios to discriminate between fertilizer−derived and natural perchlorate levels in environmental assessments (Bao and Gu, LSU and Oak Ridge NL). Most of the presentations from NAI members focused on the use of anomalous sulfur isotope effects to track Earth's atmospheric history from an early anoxic stage through the “Great Oxidation Event”, just over two billion years ago.

Workshop on Mars Astrobiology Science and Technology (September, 2004).

This workshop was organized by the leaders of the new NAI Focus Group on Astrobiology Science and Technology with financial and other support from NASA HQ, the NAI, the NASA/JPL Mars Program Office, and the Carnegie Institution of Washington. The mix of engineering and science made cross−field communication a challenge but a great deal was achieved behind the scenes and in local restaurants. The Carnegie auditorium is spectacular but overpowering and tended to dampen debate. It was an important first step and a learning experience for all concerned. Look forward to hearing more from this crucial NAI Focus Group in twelve months time.

In closing, let me say that one of the pleasures of taking up this job as NAI Director has been the opportunity to work with the talented and dedicated staff of NAI Central at the Ames Research Center . Allow me to remind you that the Institute functions as a distributed organization largely through their hard work and enlightened stewardship. Please let them know, from time to time, how much you appreciate their efforts.

Bruce Runnegar

September 29, 2004

Team Reports: Introduction

Team Reports: Introduction

The NAI is a partnership between NASA and its NAI Teams located at academic institutions, research laboratories, and NASA centers. These teams work to define and conduct integrated multidisciplinary research and education in astrobiology. There are over 800 scientists and educators involved in these NAI endeavors.

Team Reports are composed of the following sections:

- Executive Summary– written by the Team's Principal Investigator
- Project Reports– describing specific research projects in the Team's group
- NAI–NRC Postdoctoral Fellows– as associated with an NAI Team
- Education & Public Outreach (EPO) activities– list with descriptions
- Publications– displayed as a full alphabetic list, and as associated with each research project
- Team Members– list with each member's name, email, and institution

Teams are supported by NASA through 5–year Cooperative Agreements with NASA Ames Research Center . This Annual Report reflects the work of Teams selected under three competitive review cycles, and are presented below under the years of their agreements.

July 1998 – October 2003

- Arizona State University
- Harvard University
- Jet Propulsion Laboratory
- Johnson Space Center
- Scripps Research Institute

July 2001 – June 2006

- Michigan State University
- University of Rhode Island
- University of Washington
- Virtual Planetary Laboratory

November 2003 – October 2008

** = Teams continuing from 1998–2003 period.*

- Ames Research Center *
- Carnegie Institution of Washington *
- University of Colorado, Boulder *
- NASA Goddard Space Flight Center
- Indiana University
- Marine Biological Laboratory *
- Pennsylvania State University *
- SETI Institute
- University of Arizona
- University of California, Berkeley
- University of California, Los Angeles *
- University of Hawaii, Manoa

Team Reports: Ames Research Center

Ames Research Center
Executive Summary
Principal Investigator: David Des Marais

LINKING OUR ORIGINS TO OUR FUTURE

The Ames Research Center team maintains complementary lines of investigation designed to understand the context for habitable environments and life, the origins of life and its impact on the planetary environment, and the future of life in changing environments. The research addresses all seven goals of the new Astrobiology Roadmap and is formulated to address specific near–term objectives of the Roadmap in ways that link these objectives to flight missions and that also help to unify astrobiology. The Ames team conveys the content of its research program into its education and public outreach program through partnerships with the California Academy of Sciences (CAS), Yellowstone National Park (YNP), New York Hall of Science, and several K–14 educational organizations. Strong conceptual and functional links to multiple NASA missions provide context, motivation, and resource–sharing opportunities for both the research and the education and public outreach efforts.

We investigate the processes that control planetary formation in order to understand both the characteristics and the cosmic distribution of habitable environments

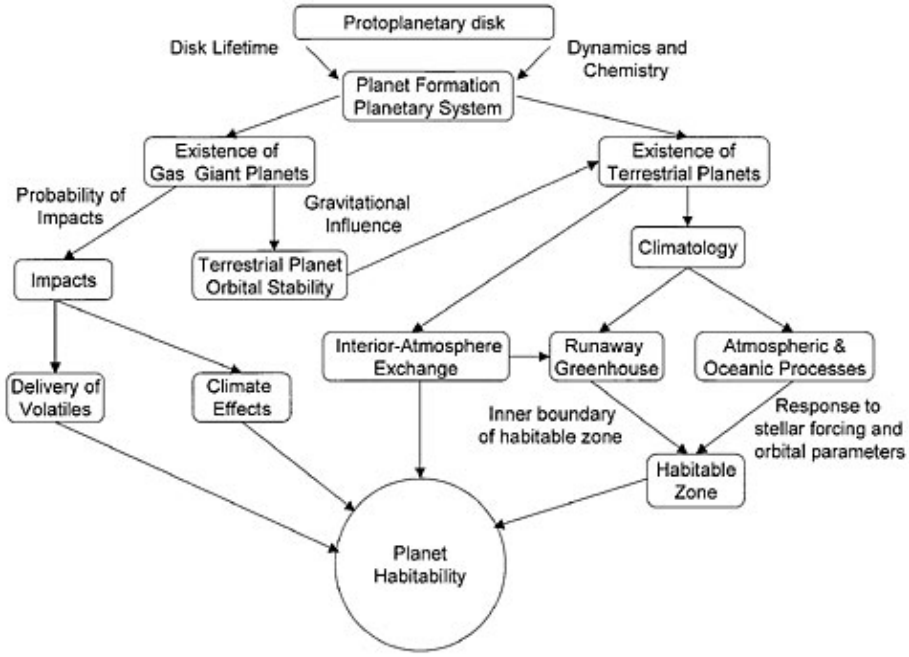


FIGURE 1 – Illustration of how processes act to determine planet habitability. These processes are of course a subset of all processes that have to be ultimately considered, but they are critical ones.

We modeled the evaporation of disks around low mass (solar–type) stars that is caused by external ultraviolet radiation from a nearby massive star. Photoevaporation can often affect the region where the giant planets form, at least in our solar system. Even terrestrial planets can be strongly affected. We are also investigating the dynamical viability of possible terrestrial planets orbiting in the habitable zones of known planet–bearing stars. Because a large amount of computing is required for models of these planets, and because public interest in both extrasolar planets and habitable worlds is intense, we are developing a distributed computing program along the lines of the seti@home model. We contributed a paper on the possible sources of turbulence that will enhance mixing and inter radial transfer in the protoplanetary nebula. We computed the migration of a condensation front; such a front might contribute to the rapid growth of gas giants such as Jupiter. A recently submitted manuscript documented that, for a sea surface temperature near 300 K, the clear sky upward longwave flux observed over the tropical Pacific Ocean exhibited the classic signature of the runaway greenhouse. We developed an analytical solution to the equations governing a runaway greenhouse, and found a region in flux and temperature space where two stable solutions exist. The “warm” solution can only be reached if a significant temperature perturbation occurs, such as a large impact. We are currently assessing the size of the impact required to produce a runaway greenhouse for a planet such as Mars.

We are tracing, spectroscopically and chemically, the cosmic evolution of organic molecules from the interstellar medium to protoplanetary disks, planetesimals, and finally onto habitable bodies. We also examine the abiotic mechanisms of primitive membrane formation under the primordial conditions

of a habitable planet. This work is complemented by astronomical observations and, ultimately, by analyses of cometary dust to be returned by the Stardust mission. We have completed studies of the infrared properties of neutral and ionized polycyclic aromatic hydrocarbons (PAHs) frozen in realistic interstellar water ice analogs. We have found a remarkable result. When frozen in water, PAHs are readily ionized and stabilized as ions as long as the ice is kept below about 50K. The spectra obtained during these studies will be used to interpret data taken with NASA's new Spitzer IR telescope. Also, we believe that we have detected evidence for deuterated PAHs in the interstellar medium, thus establishing an additional link between our ongoing lab studies of PAHs, including their photoproducts, and important biogenic species in meteorites. Finally we have studied the interstellar photostability of amino acids, nitriles, and precursor molecules in these ice analogs and compared photochemistry with proton bombardment processes.

We explore the origin of metabolism in the earliest ancestors of cells by testing the hypothesis that proteins might have arisen and initially evolved in the absence of a genome. Ultimately we will examine the evolutionary potential of an ensemble of proteins through theoretical and computational modeling. In prior years, we created, isolated, and identified a family of non−biological adenosine triphosphate (ATP)−binding proteins from an unconstrained random−sequence library. This past year, we perfomed multiple rounds of mRNA−display selection under increasingly denaturing conditions, in order to improve the folding stability of one of these proteins. We demonstrated that subsequent evolutionary optimization can readily yield sequence variants having improved folding and improved ligand binding. Using X−ray crystallography, we obtained the three−dimensional structure of an earlier protein variant that exhibited high affinity for ATP. The structure of our ATP binding protein reveals a new protein fold that has not been seen previously in biological proteins. This result supports the hypothesis that biological systems utilize only a subset of all possible protein folds. We developed and studied computationally a simple model of reaction (metabolic) networks catalyzed by functional proteins existing among random sequences. Networks can be classified into families (species) that persist even though individual networks disintegrate or transform with time. Relative populations of different families can change as environmental conditions change. Many phenomena, such as speciation, that operated in the context of genomic evolution might actually have evolved earlier in the absence of a genome. Ultimately, evolutionary progress of the systems was limited by the absence of a memory storage mechanism provided by the genome. Our findings thus support the hypothesis that initial protobiological evolution could have progressed without a genome but could not have reached the complexity approaching cellular systems as we know them today.

We are characterizing the major factors that govern the formation of potentially diagnostic biosignatures in microbial ecosystems. We documented further that marine hypersaline mats can be maintained in a relatively unchanged state in an Ames greenhouse facility under quasi *in situ* conditions. We have constructed a theoretical model predicting flows of substrate, and harvesting of energy, by various microbial guilds within the mat community. These models predict substantial production of volatile fatty acids and hydrogen, which we

have now also demonstrated experimentally. We have documented the diversity of Archaea within subtidal mats, with a particular emphasis on production of methane (as a volatile product of metabolism in photosynthetic systems). Detailed work has identified a novel methanogen in this system, and has documented the depth–dependence of methane production. We have identified an isoprenoid lipid that may serve as a biomarker characteristic of hypersaline environments. In collaboration with University of Colorado investigators, we documented the diversity of bacterial, archeal, and eukaryal domains within the subtidal mat system. This work expands the known division–level diversity of bacteria by about 40%, and has identified a novel eukaryote that branches at the kingdom level. We identified and characterized a series of spring systems hosted in northern California ophiolites. At one site, we demonstrated that serpentinization, a rock alteration reaction that yields the potenial biological substrate H_2 , is active at the relatively low temperatures encountered by this ophiolite during its 100–Myr history, but that the process of alteration of these rocks is still not yet complete.

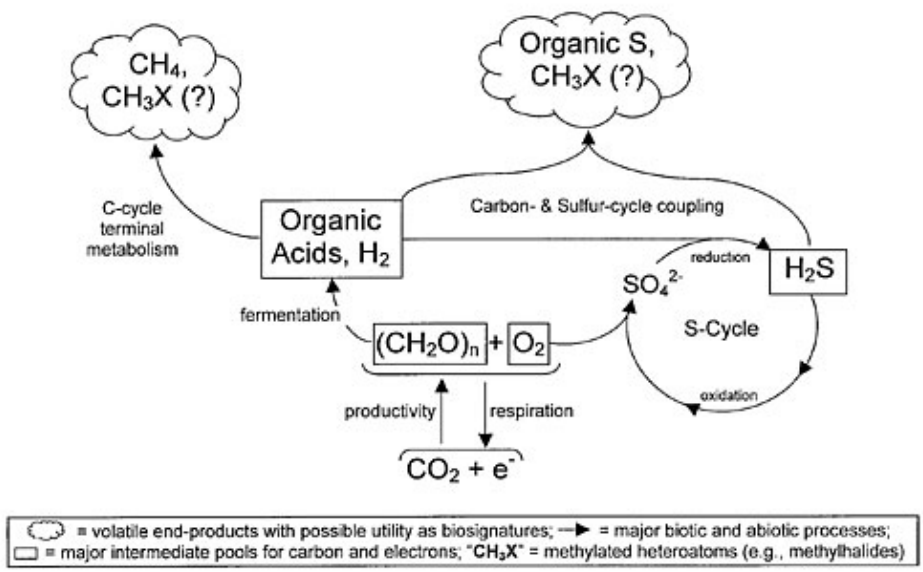


FIGURE 2 – Major steps in the anaerobic transformation of photosynthetic productivity. This approach quantifies the flow of carbon and electrons fixed by primary productivity through each of the major processes and reservoirs identified in this diagram. Molecular biology and organic biomarker approaches are used to characterize the organisms that mediate the transformation process. At major "junction points", where carbon or electrons may have alternate fates (e.g., H_2 /Organic Acid or H_2S pools), we characterize the micro– and macro–environmental factors that regulate their ultimate partitioning into the spectrum of biomarker end–products.

We extend the ecosystem–level studies of photosynthetic microbial mats to a planetary scale by refining and evaluating quantitative models that simulate energy relationships, biogeochemical cycling, trace gas exchange, and biodiversity in these systems. We refined and submitted for publication our model of hypersaline mats to Microbial BioGeoChemistry. We ran sensitivity tests to answer outstanding questions about the relative diel changes in the rates of sulfate respiration and dissimilatory sulfate reduction. We found that

cyanobacterial fermentation is critical in supplying H_2 for dissimilatory sulfate reduction, and that nighttime sulfur oxidation in colorless sulfur bacteria is critical in supplying S^o for cyanobacterial fermentation. These findings have consequences for further development of the carbon cycle component of our model, which will include organic carbon and methanogenesis. The model will address the precursors of methylamines, which can be utlized for methane production. The current challenge is to find or model pool sizes of these precursors, which include critical osmoregulants in these hypersaline ecosystems.

We have examined the effects of climate variability on a vegetation−rich biosphere over intermediate time scales, using South American ecosystems as a model. We continue to develop a predictive Paleo−Net Primary Productivity model for South America , using the output of the NASA−CASA model for 41 sites in South America . Comprehensive modern solar irradiance data have recently become available, and such data play an important role as drivers in our model. We are currently exploring potential proxies of solar irradiance in the fossil record. We are also using modern temperature and precipitation data in the model, proxies for which are found in fossil pollen and tree−rings. With Dr. Jorge Marcos, we are establishing the observation bases for intensive studies in Ecuador . We are investigating additional field sites in South America for testing our model.

We are assessing the potential for life to move beyond its planet of origin, as a potentially important component in the evolution of life in our own solar system. We have begun work on an extremely halophilic alga, *Dunaliella salina* , to test for radiation resistance. We are investigating meteorites with exceptionally large cracks as model vehicles for the interplanetary transport of microbes. We are collaborating with investigators at the DLR (German space agency) who have designed and built a chamber to simulate the conditions that microbial samples will encounter in Earth orbit. The DLR has designed and built a sample holding rack that is a duplicate of the flight rack. We demonstrated that the rack materials will not harm our microbial samples and that samples will not suffer cross contamination. We determined the maximum and minimum temperatures that samples could withstand during pre−launch, launch, during the test, and still be returned without being harmed. Results indicated that 50°C is the upper temperature limit. No deleterious effects could be detected within samples that were held at –25°C for 3 months.

We have further developed our partnerships with the California Academy of Sciences, Yellowstone National Park, and the New York Hall of Science to develop new astrobiology workshops, activities, exhibits, and other products. CAS has chosen to utilize astrobiology to link its natural history museum, planetarium, and aquarium under the theme, "Earth and its Place in the Universe." Ames personnel contributed substantial content and images to astrobiology exhibits that the CAS now displays at their newly occupied temporary campus on Howard Street in San Francisco . Ames and CAS are continuing to develop materials for future exhibits at the Howard Street site, as well as concepts for displays at the permanent site at Golden Gate Park .

FIGURE 3 – Ames team members tour California Academy of Sciences to see the new astrobiology exhibits currently on display at their newly opened temporary campus on Howard Street in San Francisco. The Ames team made significant contributions to these exhibits by submitting numerous images, captions, and content relating to astrobiology and the current research in work throughout the team.

The Ames partnership with Yellowstone National Park utilizes the important role that the Park's thermal features have regarding studies of both the early evolution of life on Earth and the search for evidence of habitable environments and life on Mars. This past year Ames contributed a book chapter on microbiology and ecology to the 2004 edition of the Yellowstone Resources and Issues Guide. The Ames team contributed considerable astrobiology content for new trailside interpretive signs. This astrobiology sign project is currently in final review at Yellowstone, with sign development and production scheduled to begin during the summer of 2004. Ultimately, astrobiology will be integrated into permanent exhibits for the major visitor centers. Working with Lockheed–Martin Space Projects Corporation and with NAI Central, the Ames team has facilitated the donation of substantial funds to the Yellowstone Foundation, as a key part of the program to develop interpretive products that disseminate astrobiology and Yellowstone to the general public.

FIGURE 4 – Volcanic activity has interacted with water on Mars, as well as on Earth. Thermal springs like the Grand Prismatic Spring at Midway Geyser Basin, in Yellowstone National Park, are natural oases for diverse life forms, and hot spring mineral deposits can preserve fossils. Yellowstone's natural wonders thus guide our search for evidence of ancient martian thermal springs, and potentially, for traces of martian life. The public's fascination with Yellowstone creates an opportunity to transfer the excitement of Mars exploration to its visitors.

The Ames team continues to work with TERC, Cambridge, MA , to apply its new astrobiology curriculum to a broad array of education and outreach projects.

The Ames team has established a substantial presence on current NASA missions. The Ames team Principal Investigator serves as one of the leads for strategic planning on the Science Operations Working Group of the Mars Exploration Rover mission. Another team member serves as a co–investigator with the Kepler mission of NASA's Discovery program. Several team members are involved with missions that are scheduled and planned missions for the next several years.

Project Report: Biosignatures in chemosynthetic and photosynthetic systems

Project Investigators:	***Daniel Albert , David Blake , Richard Castenholz , David Des Marais , Tori Hoehler , Linda Jahnke , Victoria Orphan , Mitchell Schulte , Allan Treiman , Pieter Visscher***

Project Progress

Our investigation focuses on two areas:

1. Production of volatile and stable organic biosignatures in photosynthetic ecosystems.

We conducted a field expedition to Guerrero Negro, Mexico , to collect intertidal and subtidal hypersaline microbial mats, as analogs for Earth's early microbial communities. The mats are being maintained in a greenhouse facility under quasi in situ conditions. We have constructed a theoretical model predicting flows of substrate, and harvesting of energy, by various microbial guilds within the mat community. These models predict substantial production of volatile fatty acids and hydrogen, which have now been demonstrated experimentally. We have documented the diversity of Archaea within subtidal mats, with a particular emphasis on production of methane (as a volatile product of metabolism in photosynthetic systems). Detailed work has identified a novel methanogen in this system, and has documented the depth–dependence of methane production. We have identified an isoprenoid lipid that may serve as a biomarker characteristic of hypersaline environments. This isoprenoid is hypothesized to be a diagenetic precursor of a widespread biomarker found in ancient oils. In collaboration with University of Colorado investigators, we documented the diversity of bacterial, archeal, and eukaryal domains within the subtidal mat system. This work expands the known division–level diversity of bacteria by about 40%, and has identified a novel eukaryote that branches at the kingdom level.

2. Viability of microbial communities in ophiolite–hosted alkaline springs (as possible analogs for early terrestrial or Martian habitats).

We identified and characterized a series of spring systems hosted in northern California ophiolites. Samples from Complexion Spring were prepared in thin

section and mineralogy was characterized via electron microscopy and ion microprobe analysis. These samples were found to consist of approximately one–half primary olivine mineralogy and one–half secondary alteration (i.e., serpentine) minerals, suggesting that serpentinization (to yield the potenial biological substrate, H_2), is active at the relatively low temperatures encountered by this ophiolite during its history, but that the process is not complete even after more than 100 Myr.

Highlights

- We identified a novel isoprenoid lipid that may serve as a biomarker specific to hypersaline systems. This lipid is believed to be a diagenetic precursor of a widely utilized biomarker in ancient oils.
- Our University of Colorado collaborators documented the immense microbial diversity within the subtidal hypersaline microbial mats we study. These results expand the known division–level diversity of bacteria by 40%, and have identified a novel eukaryote branching at the kingdom level.
- We documented serpentinization, a process capable of delivering H_2 to early terrestrial or Martian microbial ecosystems, in relatively low–temperature northern California ophiolite sequences.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	MER 2003	Science Team Member
1	MRO 2005 CRISM Spectrometer	Science Team Member
2	Venus/SAGE	Instrument/Payload Development
2	MSL 2009	Instrument/Payload Development
2	Copernicus	

		Instrument/Payload Development
2	Comet Odyssey	Instrument/Payload Development
3	Astrobiology and Solar System Exploration	Other

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This investigation is designed to provide science background and interpretive capacity for Mars in situ and sample return missions, as well as for telescopic life detection (e.g., TPF). By focusing on the production of mineral biosignatures in environments analogous to possible early Martian systems, and on the production of volatile biosignatures in photosynthetic ecosystems, these studies will provide an enhanced scientific context for the eventual return of data from Mars and TPF missions.

Field Expeditions

Field Trip Name: AMASE 2003	
Start Date: 8–12–2003	***End Date:*** 8–23–2004
Continent: Europe	***Country:*** Norway
State/Province: Spitzbergen	***Nearest City/Town:*** Longyearben
Latitude: 79N	***Longitude:*** 11E
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Geological and biological sampling at a variety of warm springs and volcanic outcroppings in the Norwegian high arctic	
Members Involved:	

Field Trip Name: Yellowstone 2003	
Start Date: 9–3–2003	***End Date:*** 9–10–2003
Continent: North America	***Country:*** USA
State/Province: Wyoming	***Nearest City/Town:*** West Yellowstone, MT
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Chemical and biological sampling from a variety of hot springs.	
Members Involved:	

Field Trip Name: Baja Spring 2004	
Start Date: 4–22–2004	***End Date:*** 4–27–2004
Continent: North America	***Country:*** Mexico
State/Province: Baja California Sur	***Nearest City/Town:*** Guerrero Negro
Latitude: N 27 Degrees 40 minutes	***Longitude:*** W 113 degrees 55 minutes
Name of site(cave, mine, e.g.):	***Keywords:*** microbial mats
Description of Work: Sampling microbial mats for maintenance in rooftop greenhouse facilities.	
Members Involved:	

Field Trip Name: Ophiolite Project	
Start Date: 5–10–2004	***End Date:*** 5–14–2004
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Castella
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): cold spring	***Keywords:***
Description of Work: Scouting and measurement of springs issuing from ophiolite terranes.	
Members Involved:	

Field Trip Name: Ophiolite Project	
Start Date: 8–2003	***End Date:*** 8–2003
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Clear Lake
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): cold spring	***Keywords:***
Description of Work: Scouting and measurement of springs issuing from ophiolite terranes.	
Members Involved:	

Field Trip Name: Ophiolite Project	
Start Date: 12–2003	***End Date:*** 12–2003
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Stonyford
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): cold spring	***Keywords:***
Description of Work: Scouting and measurement of springs issuing from ophiolite terranes.	
Members Involved:	

Field Trip Name: Ophiolite Project	
Start Date: 2–2004	***End Date:*** 2–2004
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Stonyford
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): cold spring	***Keywords:***
Description of Work: Scouting and measurement of springs issuing from ophiolite terranes.	
Members Involved:	

Project Report: Early Metabolic Pathways

Project Investigators:	***Andrew Pohorille , Jack Szostak***

Project Progress

The evolutionary optimization of the de novo evolved non−biological ATP−binding protein has been completed. Previously, a family of non−biological ATP−binding proteins was isolated from an unconstrained random−sequence library. One of these proteins was further optimized for high−affinity binding to ATP, but its biophysical characterization proved impossible due to poor solubility, possibly due to non−unique folding. To improve folding stability, multiple rounds of mRNA−display selection under increasingly denaturing conditions were performed. One protein so obtained was chosen for further characterization. Using several biophysical methods it was demonstrated that this protein has a unique folded structure. This work shows that even if the initially obtained proteins have poor folding and weak binding, subsequent evolutionary optimization readily yields sequence variants with improved folding and improved ligand binding.

While this work was in progress, the three−dimensional structure of earlier high affinity variants was obtained by X−ray crystallography (LoSurdo et al., Nature Struct. Biol., 2004). It appears that the presence of a charged N−terminal sequence improved solubility greatly providing a different pathway to protein optimization. The availability of this structure has allowed for a structural interpretation of the mutations observed during our evolutionary optimization of this protein. The structure of our ATP binding protein reveals a new protein fold, not previously seen in biological proteins. This result provides preliminary support for the idea that only a subset of all possible protein folds is used in biological systems; the determination of additional non−biological protein structures will be required to determine whether biological protein folds represent a small or large fraction of all possible folds.

Studies aimed at solving the solution structure of the optimized protein by nuclear magnetic resonance (NMR) spectroscopy have been initiated in collaboration with James Chou at Harvard Medical School . It is expected that this work will be completed this coming year. The results will enable the comparison between the structure of the folding−optimized protein and that of the high−affinity variant protein that has been solved by X−ray crystallography. These two proteins differ in about 25% of their residues, so it will be of interest

to see how much their structures have diverged.

A simple model of reaction (metabolic) networks catalyzed by functional proteins existing among random sequences has been developed and studied computationally. Biochemically plausible rules for identifying populations of functional proteins have been formulated in previous years of this project. By investigating large populations of networks it was demonstrated that their subset can self–organize and evolve towards increasing complexity even in the absence of a genome. Networks can be classified into families (species) that persist even though individual networks disintegrate or transform with time. As the environmental conditions change, so do relative populations of different families. These results indicate that many concepts, such as speciation, developed in the context of genomic evolution also hold for conditions in the absence of a genome.

Evolutionary progress of the systems was, however, limited by the absence of a memory storage mechanism provided by the genome. To support the increasing complexity of the system, the presence of proteins with increasing efficiency and specificity was needed. These proteins, however, are quite rare among random sequences and are not encountered on a consistent basis. The results support the hypothesis that initial protobiological evolution could have progressed without a genome but could not have reached the complexity approaching real cellular systems.

Highlights

- A novel method for evolutionary optimization of functional proteins obtained from populations of random sequences has been developed. It yields sequence variants with improved folding and ligand binding.
- The first protein evolved from random sequences was shown to have a structure not previously seen in biological proteins. This supports the idea that only a subset of possible protein folds is used in biological systems.
- Using simple, self–generating network models, both the potential and evolutionary limitations of systems not regulated by a genome has been demonstrated. Such systems can self–organize, evolve, undergo “speciation,” and exhibit robust behavior in response to environmental changes but experience evolutionary limits due to their inability to store information about efficient, specialized, and therefore rare, solutions.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems

Mission Involvement

The research outlined in the proposal has been selected by the European Space Agency (ESA) based on my proposal in response to the ESA Announcement of Opportunity for Externally Mounted Payloads during the

Early Space Utilization Period. (SP−1201). The hypotheses will be tested using ESA s external platform space exposure facility (EXPOSE). The cost of all flight related activities, the design and fabrication of flight hardware, as well as equipment and supplies to conduct ground simulation studies conducted in Europe are paid by ESA, work conducted in the US, travel, and time (salary) spent on the project in the US and Europe are to be paid by NASA. That is the funds are for ground based research in support of the ESA funded flight experiments.

EXPOSE is a multi−user external facility for exobiological experiments in the environment of space. It has been selected by ESA for the Early Utilization Period of the ISS and will stay for 1.5 years in space.

Project Report: Ecosystem to Biosphere Modeling

Project Investigators:	***Kelly Decker , Steven Klooster , Christopher Potter***

Project Progress

We refined the model of hypersaline mats Microbial BioGeoChemistry (MBGC). Working towards publication of the first version of the model (submitted May), we adopted many improvements into the model, or researched them as future adaptations. One assumption that was questioned was that oxygen supersaturation inhibits oxygenic photosynthesis. Whereas this simplifying assumption was effective in earlier models, the midday reduction in photosynthesis that occurs in the mats is more likely due to photorespiration. This has consequences for the carbon cycle and we have researched the inclusion of photorespiration into the model.

We ran sensitivity tests to answer outstanding questions about the relative diel changes in the rates of sulfate respiration and dissimilatory sulfate reduction (dsr); (Table 1; Figure 1). The relative frequency of these processes has consequences to differential interference contrast (DIC) emissions (Figure 1). We found that cyanobacterial fermentation is critical in supplying H_2 for dsr and that nighttime sulfur oxidation in colorless sulfur bacteria is critical in supplying S^o for cyanobacterial fermentation.

Table 1

DIC Sinks:		
[1,2]oxygenic photosynthesis (CYA)	1:1 CO_2 fixed: O_2 released	$CO_2+H_2O \rightarrow (CH_2O)+O_2$
[2]anoxygenic photosynthesis (CYA)	1:1 CO_2 fixed:H_2S oxidized	$2CO_2+2H_2S+2H_2O \rightarrow 2(CH_2O)+H_2S_2O_3$
[2]anoxygenic photosynthesis (PSB)	2:1 CO_2 fixed:H_2S oxidized	$2CO_2+H_2S+2H_2O \rightarrow 2(CH_2O)+H_2SO4$
[2]chemosynthesis (PSB)	1:2 CO_2 fixed:H_2S oxidized	$2CO_2+4H_2S+6O_2+2H_2O \rightarrow 2(CH_2O)+4H_2SO_4$
[2]chemosynthesis (CSB)	1:2 CO_2 fixed:H_2S oxidized	$2CO_2+4H_2S+6O_2+2H_2O \rightarrow 2(CH_2O)+4H_2SO_4$
DIC Sources::		
Diffusion from water		
Aerobic respiration (CYA)	1:1 CO_2 :O_2 used	
[2]Sulfate Reduction (SRB)		
fermentation + dissimilatory SR	*1.15:1 CO_2:H_2S released	$4C_6H_{12}O_6+4H_2O+4S^{2+}+3H_2SO_4 \rightarrow 8CH_3COOH+8CO_2+7H_2S$
sulfate respiration	2:1 CO_2 :H_2S released	$2(CH_2O)_6+H_2SO_4 \rightarrow 2CH_3COOH+2CO_2+H_2S+2H_2O$ $2(CH_2O)_6+3H_2SO_4 \rightarrow 6CO_2+3H_2S+6H_2O$

[1] from Canfield and Des Marais 1993; [2] from van Gemerden 1993 - see text; * these two ratios are combined in the model - see text

Table 1. Stoichiometric ratios that affect the DIC budget in MBGC and their associated equations. The bacteria associated with these processes are: Cyanobateria (CYA), purple sulfur bacteria (PSB), colorless sulfur bacteria (CSB), and sulfate–reducing bacteria (SRB).

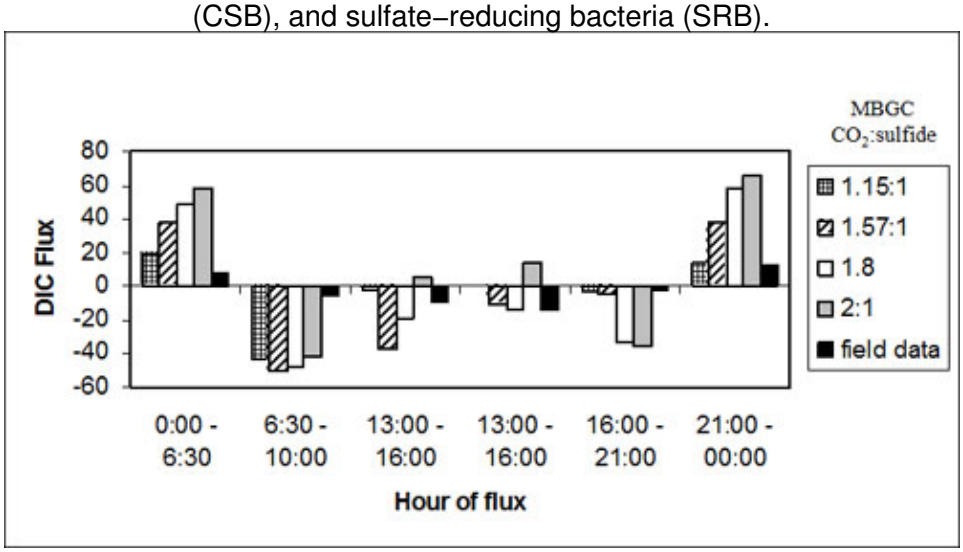


Figure 1. DIC flux across the mat boundary in mM m–2 hr –1. The figure compares field data averaged each time period) with MBGC results with various levels of sulfide created per CO2 released.

These findings have consequences for further development of the carbon cycle that will include organic carbon and methanogenesis. We have begun the development of these new carbon components by gathering literature on photorespiration, cyanobacterial fermentation, and methanogenesis in microbial mats. We focused on several sources of carbon, specifically exudation during oxygen supersaturation leading to photorespiration, fermentation, and decomposition. This can be described as a ‘top–down' approach because it examines sources of organic C. We are concurrently taking a ‘bottom–up' approach looking at one critical sink of organic C:

methanogens. In hypersaline, sulfate−rich environments, these microbes use methylamines because they are noncompetitive substrates. The precursors of methylamines are osmoregulants released during the decomposition of hypersaline bacteria, such as glycine betaine. The current challenge is to find or model pool sizes of these critical osmoregulants.

Highlights

- We submitted a paper describing the first version of Microbial BioGeoChemistry.
- We gave two presentations at national meetings.
- We conducted sensitivity tests that identified critical areas of model innovation to the carbon cycle.
- We researched critical portions of the carbon cycle including organic carbon release from cyanobacteria and decomposition, and also including methanogen activity.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

This investigation is designed to provide science background and interpretive capacity for Mars in situ and sample return missions, as well as for telescopic life detection (e.g., TPF). By focusing on the production of mineral biosignatures in environments analogous to possible early Martian systems, and on the production of volatile biosignatures in photosynthetic ecosystems, these studies will provide an enhanced scientific context for the eventual return of data from Mars and TPF missions.

Project Report: Habitable Planets

Project Investigators:	***David Hollenbach , Jeffery Hollingsworth , Gregory Laughlin , Jack Lissauer , Norman Sleep , Owen Toon , Richard Young , Kevin Zahnle***

Project Progress

Co−Is Hollenbach and Laughlin, working with outside collaborators F. Adams and U. Gorti, have been modeling the photoevaporation of protoplanetary disks around young stars. During the past year, they have finished a calculation of the evaporation of disks around low mass (solar−type) stars caused by the external ultraviolet radiation from a nearby massive star in the birth cluster (Adams et al. 2004). It is shown that photoevaporation can often affect the region where, at least in our solar system, the giant planets form. The rapid photoevaporation of gas in as close as 10 to 20 AU also then means that gas disappears quite rapidly in the inner regions as well. Hollenbach and Adams (2004 a, b) applied the results of the Adams et al. paper to study whether photoevaporation could explain a sharp cutoff in the Kuiper Belt, the sharp drop of hydrogen content in the giant planets Neptune and Uranus compared to Saturn and Jupiter, and the deficit of planets seen in large clusters. For conditions similar to the large cluster observed in the Trapezium of Orion, the conditions are so harsh—especially in the inner parts of the cluster—that all giant planet formation may be quenched, and even terrestrial planets may be strongly affected.

Co−I Greg Laughlin and collaborators at University of California , Santa Cruz have been investigating the dynamical viability of possible terrestrial planets orbiting in the habitable zones of known planet−bearing stars. Of particular interest are potentially habitable orbits in systems with several known planets (e.g. GJ 876, or 55 Cancri). Because of the large amount of computing required, and because of intense public interest in both extrasolar planets and habitable worlds, they are building a distributed computing solution for this problem along the lines of the seti@home model. Specifically, we are designing a public user interface that leverages the existing www.transitsearch.org candidates site (see http://www.ucolick.org/~laugh/) and which uses the Berkeley Open Infrastructure for Network Computing Package (http://boinc.berkeley.edu/) to handle the back−end aspects of the distributed application.

Collaborators Segura and McKay, and Co−I Toon, investigated analytical solutions to the equations governing a runaway greenhouse to show that there is a region in flux and temperature space where there are actually two stable solutions. Both are stable and correct. The warm solution can only be reached if there is a significant temperature perturbation to the system, such as a large impact. They are investigating different regions of phase space and assess how large an impact would be required to produce a runaway greenhouse for a given planet such as Mars.

Co−I Hollingsworth has conducted both mechanistic modeling and fully coupled climate modeling studies using a variety of modeling tools to model the climate of the Earth and Earth−like planets under extreme but plausible environmental conditions. Adapting a mechanistic climate modeling approach helps identify important positive and negative feedbacks between various components of the climate system. During this investigation, the focus has been on two main areas of research: (a) mechanistic fully−coupled climate simulations using the KNMI/ECBILT modeling system; and (b) realistic and extreme coupled climate simulations using the NCAR/CCM.

Co−I Davis and Collaborator Richard continue to investigate possible sources of turbulence in the protoplanetary nebula that will enhance mixing and inter radial transfer. They published a short contribution (Richard and Davis) on this subject in Astronomy and Astrophysics. They used this and related information to compute the migration of a condensation front (thought to be a factor in the rapid growth of gas giants such as Jupiter). A paper is submitted on this subject and a presentation was made at a recent conference on chemistry in the protoplanetary nebula.

Collaborators Rabbette, Pilewskie, and McKay, together with Co−I Young, submitted a paper for publication showing that the clear sky upward longwave flux as a function of sea surface temperature (SST) near SST = 300K, observed over the tropical Pacific Ocean, exhibits the classic signature of the runaway greenhouse. The key role water vapor plays in the tropical clear sky greenhouse effect was investigated. The study highlights the fact that the water vapor greenhouse effect depends not only on the total column integrated amount, but more importantly on the vertical distribution of the tropospheric water vapor.

Highlights

- It is shown that photoevaporation of a protoplanetary disk can often affect the region where, at least in our solar system, the giant planets form. The rapid photoevaporation of gas in as close as 10 to 20 AU also then means that gas disappears quite rapidly in the inner regions as well. Therefore disk photoevaporization may be a limiting factor for the formation and evolution of habitable planets.
- Large impacts appear capable of throwing an otherwise stable planetary atmosphere into a runaway greenhouse state. There is evidence this may have happened on Mars.
- The vertical distribution of water vapor in a planetary atmosphere should be an important factor in the evolution of a runaway greenhouse

state. The importance of the vertical water vapor distribution has been shown for the local super−greenhouse occurring over the terrestrial tropical Pacific Ocean.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Kepler	Co−Investigator
1	Mars Odyssey	Background Research
2	Mars Lander 200	Background Research
2	Terrestrial Planet Finder	Background Research
1	Spitzer Space Telescope	Co−Investigator,Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

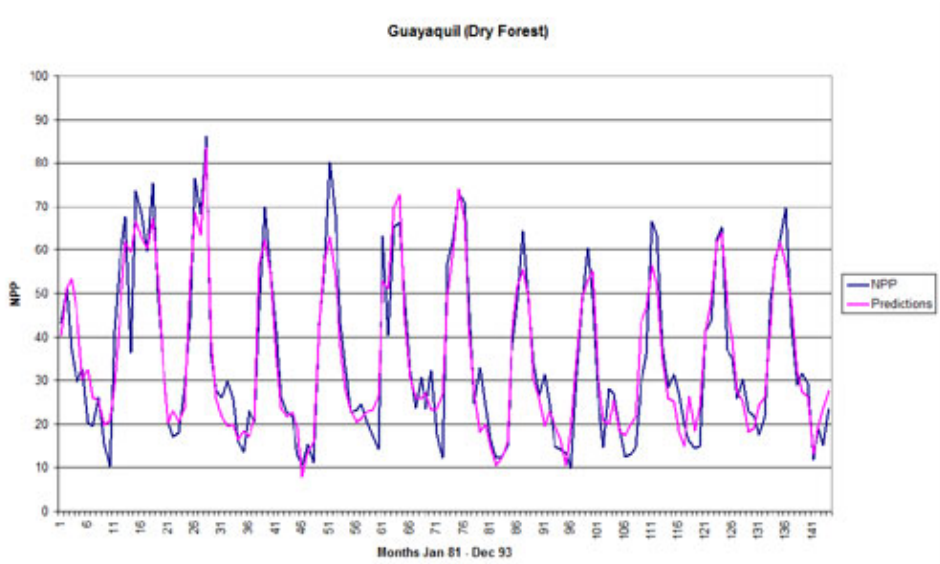
Annual Reports :: Year 6 :: Ames Research Center

Project Report: Hindcasting Ecosystems

Project Investigators:	***Lidia Burry , Hector D' Antoni , Andres Laguens , Carlos Lasta , Jorge Marcos , Jose Perez Gollan , Jay Skiles , Matilde Trivi***

Project Progress

Using results from the previously NAI–funded study, we are developing a predictive Paleo–Net Primary Productivity model for South America (D'Antoni & Skiles 2004). The model is based on the remote sensing/ecology tradition lastly enumerated by Nemani et al. (2003) and the logic used by Monteith (1981) and Running (1990). For calibration and reference purposes we use the output of the NASA–CASA model (Potter et al. 2003) for 41 sites in South America . The sites have distinctive ecological settings and there are fossil pollen or tree–ring data are available for these sites. We use modern data of variables likely to have proxies in the fossil record. Our model includes Normalized Difference Vegetation Index (NDVI) data from the advanced very–high–resolution radiometer (AVHRR) sensor at 8 km resolution. We have shown that “paleo” NDVI estimates can be extracted from fossil pollen data (D'Antoni & Schäbitz 1995). The model also includes tropical Atlantic and Pacific Sea Surface Temperature (SST). We have reconstructed 750 years of past SST from tree ring widths (D'Antoni & Mlinarevic 2002). Modern solar irradiance data have recently become available (Fröhlich & Lean 2002; Foukal 2003). These data play an important role as a driver in our model. We are currently exploring potential proxies of solar irradiance in the fossil record. We are also using modern temperature and precipitation data in the model, proxies for which are found in fossil pollen and tree–rings. With Dr. Jorge Marcos (2004), we are establishing the observation bases for intensive studies in Ecuador . Additional sites in South America are being considered for testing the model.



Guayaquil (Ecuador) – NPP Simulations by our model (purple line) as compared to those by the NASA–CASA model (blue line).

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Highlights

- We use databases recently made available (such as that of solar irradiance) that gives us a direct input from the solar energy source.

Roadmap Objectives

- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	MARTE	Research or Analysis Techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Spectroscopy analysis of samples with new, NASA−sponsored technology

Field Expeditions

Field Trip Name: Ecuadorian Dry Forest

Start Date: TBD	***End Date:*** TBD
Continent: South America	***Country:*** Ecuador
State/Province: Guayaquil	***Nearest City/Town:*** Guayaquil
Latitude: 1 S	***Longitude:*** 80 W
Name of site(cave, mine, e.g.): Dry Forest	***Keywords:*** field measurements
Description of Work: Chlorophyll concentration measurements	
Members Involved:	

Cross Team Collaborations

Due to the nature of this project we have set a network of foreign collaborators in different regions of South America

Project Report: Interplanetary Pioneers

Project Investigators:	***Rocco Mancinelli , Lynn Rothschild***

Project Progress

At Ames, Rothschild and co–workers have begun work on an extremely halophilic alga, *Dunaliella salina* , to test for radiation resistance. Kranner is investigating seeds for possible flight potential, with a current emphasis on orchids. Consolmagno is investigating meteorites with exceptionally large cracks as models for vehicles.

In conjunction with the German Space Agency (DLR) in Cologne, Germany we have conducted two ground–based studies for science and technology compatibility.

1. The DLR has designed and built a simulation chamber to mimic the conditions as close as possible as the samples will encounter during the mission.
2. The DLR has designed and built a sample holding rack that is a duplicate of flight rack.
3. Two studies have been completed using the system
    1. The first was to define sample compatibility with the rack materials as well as the potential for sample cross contamination. The results showed that the samples are not harmed by the rack materials and that samples will not cross contaminate.
    2. The second was a temperature test to define the maximum and minimum temperatures that samples could withstand during pre–launch, launch, flight, and return without being harmed. Results indicated that the upper temperature limit is 50°C. When samples were held at –25°C for 3 months no deleterious effects could be detected. If flight operations requirements require testing at lower temperatures we will do so.

Roadmap Objectives

- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	BioPan (ESA)	Co−Investigator
2	EXPOSE (ESA ISS mission)	Co−Investigator

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The research outlined in the proposal has been selected by the European Space Agency (ESA) based on my proposal in response to the ESA Announcement of Opportunity for Externally Mounted Payloads during the Early Space Utilization Period. (SP−1201). The hypotheses will be tested using ESA s external platform space exposure facility (EXPOSE). The cost of all flight related activities, the design and fabrication of flight hardware, as well as equipment and supplies to conduct ground simulation studies conducted in Europe are paid by ESA, work conducted in the US, travel, and time (salary) spent on the project in the US and Europe are to be paid by NASA. That is the funds are for ground based research in support of the ESA funded flight experiments.

EXPOSE is a multi−user external facility for exobiological experiments in the environment of space. It has been selected by ESA for the Early Utilization Period of the ISS and will stay for 1.5 years in space.

Project Report: Prebiotic Organics from Space

Project Investigators:	***Louis Allamandola , Max Bernstein , Scott Sandford***

Project Progress

We have made progress in all three focus areas pertinent to our task: interstellar prebiotic chemistry, observational astrobiology, and prebiotic membrane studies. In the prebiotic interstellar chemistry arena we have completed studies of the infrared (IR) properties of neutral and ionized polycyclic aromatic hydrocarbons (PAHs) frozen in realistic interstellar water ice analogs and are now preparing these results for publication. Water is a common interstellar and Solar System ice. These spectra will be used to interpret data taken with NASA's new Spitzer IR telescope. We have found a remarkable result. When frozen in water, PAHs are readily ionized and stabilized as ions as long as the ice is kept below about 50K. This realization will have far–reaching impact on our understanding of extraterrestrial ice physics and spectroscopy.

We have studied the interstellar photostability of amino acids, nitriles, and precursor molecules in these ice analogs and compared photochemistry with proton bombardment processes.

In the observational arena we believe we have detected evidence for deuterated interstellar PAHs, making an additional link between our ongoing lab studies of PAHs and their photoproducts with important biogenic species in meteorites. This also bears on biomarker reliability. Scott Sandford, a member of this team, has spearheaded the concept development and proposal submission for the first mission dedicated to Astrobiology, ABE the Astrobiology Explorer. Lastly, we have also submitted several proposals to Spitzer to track organic species in the Milky Way and other galaxies.

Lastly, concerning primitive membranes, Dr. Charles Apel has become a member of our team. In the short time he has been with us he has assembled the equipment necessary and already started investigating primitive membrane systems.

Highlights

- We have found the remarkable result that when PAHs are frozen in Solar System and interstellar water ice analogs they are readily ionized and stabilized as ions as long as the ice is kept below about 50K. Because this can account for unusual ice coloring, enhanced vaporization, and unexpected spectroscopic signatures, this realization will have far–reaching impact on our understanding of extraterrestrial ices.
- We have shown the mass spectral envelope of material formed by ultraviolet (UV) photolysis of realistic interstellar ice analogs bears a very close resemblance to the low mass envelope of interplanetary dust particle (IDP) organics, suggesting the interstellar ice formation mechanism may have played some role in the formation of the molecules in IDPs.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	SOFIA	Planning Support,Data Analysis,Background Research,Instrument/Payload Development,Research or Analysis Techniques
1	SIRTF/SPITZER	Planning Support,Data Analysis,Background Research,Instrument/Payload Development,Research or Analysis Techniques
1	Stardust	Co–Investigator,Science Team Member,Planning Support,Data Analysis,Background Research,Instrument/Payload Development,Research or Analysis Techniques
2	ABE	

		Project Investigator,Co−Investigator,Science Team Member,Planning Support,Data Analysis,Background Research,Instrument/Payload Development,Research or Analysis Techniques
2	CSSR – Comet Surface Sample Return	Co−Investigator,Science Team Member,Planning Support,Data Analysis,Background Research,Instrument/Payload Development,Research or Analysis Techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

These are all NASA missions.

Cross Team Collaborations

We collaborate with Dr. Jason Dworkin , a member of the NASA Goddard Astrobiology Team. As this is the first year of their program, we are at the planning experiment stage.

Fellowships: Ames Research Center

The NAI–NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Tracy Norris
Project Title: The Evolution of Desiccation Tolerance in Cyanobacteria
Advisor: Richard Castenholz, Project Investigator
NAI Lead Team: Ames Research Center
Fellowship Began In:

Project Report: The Evolution of Desiccation Tolerance in Cyanobacteria

NAI–NRC Postdoctoral Fellow : ***Tracy Norris***

Project Progress

The broad goal of this project is to investigate the ecological, physiological and genetic aspects of desiccation and freezing tolerance in cyanobacterial crusts and cryptoendolithic communities. The aim of the initial phase of this research project was to describe and identify the significant members of cryptoendolithic photosynthetic communities found in travertine terraces (calcium carbonate) originally deposited by hot springs now within Yellowstone National Park. Samples were collected from travertine formations of varying age, from as recent as 10 years ago to sites dating back over 300,000 years. In all cases, a cryptoendolithic community was present in the form of a 1–2–mm–thick greenish band just below the surface of the rock, which was composed primarily of cyanobacteria. Our hypothesis was that the species diversity of these photosynthetic communities would be low due to the extreme nature of this environment, which undergoes summer desiccation and winter freezing. Both molecular and culture based methods were used to investigate cryptoendolithic communities as well as microbiotic soil crusts in Yellowstone National Park . In the second year of this project we finished the molecular analysis of these communities, continued culture isolation efforts, and began work on physiological aspects of desiccation and freezing tolerance. From phylogenetic analysis we have learned that desiccation and freezing tolerance are distributed throughout the cyanobacterial radiation. Cultivated cyanobacterial strains from travertine communities were used in experiments on desiccation and freezing tolerance. Of the strains tested, 54% were able to recover from desiccation at 17% relative humidity, and 80% recovered from freezing at –15°C. The majority of strains were also able to tolerate salinities up to 24‰, probably a result of the overlap of adaptations for desiccation and osmotic stress. In addition to cold temperatures, 60% of the strains were able to recover from exposure to temperatures up to 45°C in the desiccated state, although they could not tolerate high temperatures in liquid culture.

Highlights

- Continued culture isolation efforts have resulted in the isolation of over 100 cyanobacterial strains from cryptoendolithic travertine environments. Comparison between sequences of culture isolates and

those of an environmental clone library suggest that we have isolated many of the ecologically relevant strains.

- Many new strains of cyanobacteria were isolated by enrichment culture from samples collected 2–3 years previously and kept under conditions of low humidity, demonstrating a high survival rate from desiccation.
- Phylogenetic trees were constructed to examine the relationships among the cultures and clone sequences within this study as well as among other cultured cyanobacteria. The overwhelming result from phylogenetic analysis is that desiccation/freezing tolerances are traits that are distributed in many cyanobacterial lineages.
- In almost all cases the nearest relative of clone library sequences from travertine communities was an uncultivated cyanobacterial sequence from wide ranging environments that included desert, Antarctic and other cryptoendolithic communities.
- Of the travertine cyanobacterial strains tested, 54% were able to recover from desiccation at 17% relative humidity, and 80% recovered from freezing at –15°C.
- In addition to cold temperatures, 60% of the strains were able to recover from exposure to temperatures up to 45°C in the desiccated state, although they could not tolerate high temperatures in liquid culture.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

Field Expeditions

Field Trip Name: Yellowstone Field Trip

Start Date: 06/30/03	***End Date:*** 7/18/03
Continent: North America	***Country:*** USA
State/Province: Wyoming	***Nearest City/Town:*** West Yellowstone, MT
Latitude: 44 N	***Longitude:*** 111 W
Name of site(cave, mine, e.g.): Yellowstone National Park	***Keywords:*** desiccation, cyanobacteria, microbial ecology, cryptoendolithic communities

Description of Work: Collection of travertine samples containing cryptoendolithic communities for culture isolation and molecular work.

Members Involved:

EPO: Ames Research Center

These are the Education and Public Outreach activities for the Ames Research Center.

Yellowstone National Park

Yellowstone National Park Offers the public a portal to astrobiology The Ames Astrobiology team is working with Yellowstone National Park (YNP) on a long term, public engagement program that includes exhibits, literature, field experiences, educator workshops, and "fireside chats" with astrobiologists that will reach the three million visitors of all ages who experience YNP each year. The NAI team is working with Yellowstone staff on several projects within the Park including the development of ten exhibits that will illustrate astrobiology throughout the trails in Yellowstone. The team is also developing chapters on astrobiology and microbiology for the Yellowstone Resources and Issues Guide, which is a training manual for the interpretive research staff used to develop hikes and talks for the public. The Guide will be published and available for purchase from the gift stores throughout the Park. It will also be available for virtual visitors through research libraries in the national park system, the Yellowstone National Park Web site and the NAI site.

The team is also developing exhibit ideas to go into a planned new visitor center at Old Faithful geyser basin. This partnership with YNP is helping the general public to enhance their knowledge and skills and to access NASA research in astrobiology, including geology, microbiology, and space missions.

Understanding how life began on Earth is a natural focal point for astrobiology. Yellowstone is providing insights into the origin and evolution of life and the potential for life to exist beyond Earth. Biochemical clues hint that early life might have lived in high–temperature environments, including hot springs. The park's hot springs provide a glimpse into the nature of the early biosphere. Ancient spring alcoves on the flanks of Martian volcanoes invite comparisons with YNP, whose fossil–rich sinter spring deposits may, in turn, resemble deposits on Mars.

Yellowstone Resource and Issues Guide

The National Park Service produced and published the Resources and Issues Guide to train their year–‘round interpreters in YNP. The NASA Ames NAI team specifically created the content for the astrobiology/microbiology chapter within the guide. We coordinated within our team and the YNP staff to provide the

images necessary to illustrate the content developed to tell the astrobiology story in the Park. Interpreters can use the content to develop specific hikes and tours for the public. NPS also publishes the manual its website, where it reaches millions of “remote visitors” to the Park. The Ames team has entered into a funding collaboration with Lockheed Martin Space Operations, The Thermal Biology Institute, the American Society for Microbiology and Agouron Institute to produce the Resources manual in color. The Guide is also available to the general public in the bookstores/gift shops in Yellowstone National Park. Earlier this year, the Lockheed Martin Corporation made an additional contribution of $12,000 to complete funding for the astrobiology interpretive exhibits as well as to colorize the Guide. In addition to telling the story of Yellowstone's hidden treasures and greatly improving the visitor experience in the world's first national park, this Yellowstone astrobiology project is a model for interpreting complex scientific information in other national parks and public spaces throughout the United States. Over fifty four additional national park interpreters have accessed the guide for use in their parks. It also demonstrates that science is not only important and accessible but also interesting and fun.

Yellowstone National Park Way Side Exhibit

The WaySide Exhibit project is a partnership project between the NASA Ames team and Yellowstone National Park. NASA and Yellowstone National Park have enjoyed a strong and effective partnership over the years based on supporting scientists and engaging Park visitors in the experience of exploration and scientific discovery. Approximately two years ago, The NASA Astrobiology Institute, Lockheed Martin Space Operations and the Ames NAI team took an instrumental step in furthering this partnership by donating funds for the development of outdoor astrobiology exhibits in several locations throughout the Park. These exhibits, located Park–wide at sites that best illustrate the most compelling aspects of astrobiology research in Yellowstone, will describe how the Park's hydrothermal features are extreme habitats for amazing life forms that may help explain the history our biosphere and also provide clues to assist our search for life on other planets. Ames team members who have major contributions include David Des Marais, David Ward, Tori Hoehler, Jack Farmer, Nancy Hinman, Linda Jahnke and Catherine Tsairides. The NASA Astrobiology Institute and Lockheed Martin Corporation have contributed partnership funding for as many as ten Way Side Exhibit signs.

Yellowstone National Park Planning Team

Dr. David Ward, Montana State University, represents the Ames NAI team on the YNP Planning Team. Diane Chalfant, Chief, Division of Interpretation at Yellowstone National Park invited an Ames team member to join the Science Advisory team as part of the development team for the Old Faithful Education Center. The 6–member Science Advisory Team included 5 geologists (Robert, Fournier (ret. USGS), Robert Smith (Univ. Utah), Duncan Foley (PLU), Lisa Morgan (USGS), Hank Heasler (YNP)) in addition to Dr. Ward. The Education Team consisted of various people experienced in museums and science education therein (Bonnie Sachatello–Sawyer, Native American Waters

Project; Deborah Perry, Visitor Studies Assoc., Bob Pickering, Buffalo Bill Historic. Center, Jaci Tomulonis, Monterey Bay Aquarium, and Diane Chalfant). The design team from Chadbourne and Associates (Boston) recently awarded the contract for OFEVC. A review of the front–end evaluation given by the Visitor Studies Association was part of this meeting. Overall, ultimately, our long term project goal is to be awarded significant floor space for interpreting extremophiles in the context of (i) what causes the colors in the hot springs, and (ii) their importance to the story of evolution of life on Earth and elsewhere in the Universe.

From Earth To Sky

Use NASA Space and Earth Science to highlight your park and its resources in an exciting new way!

“From Earth to Sky” is an innovative partnership between NASA and the National Park Service. This partnership has been formed as part of the Explorer Institute, which develops professional development opportunities for interpretive personnel nation wide.

NASA scientists and educators will team with NPS Interpretive Development Program facilitators to conduct weeklong professional development workshops. Two workshops will be held September 15–20, 2004 and October 18–22, 2004. One workshop will be held at NASA Ames Research Center and the other will be held in Harpers Ferry, West Virginia with a field trip to the NASA Goddard Space Flight Center.

The workshops will cover a variety of Space and Earth Science topics, including the night sky, the Sun, comparative planetology, remote sensing and astrobiology. Each of these topics can enhance how visitors experience the national parks and the unique resources found within them. During the workshops, NASA and National Park personnel will collaborate to identify NASA science that fits well with, and enhances, the compelling stories of the natural and cultural resources of our National Parks.

Join the Journey From Earth to Sky!

Astrobiology Science Conference

Dr. Lynn Rothschild has continued to coordinate the Astrobiology Science Conference hosted at NASA Ames Research Center. The meeting is highly focused on scientific results with hundreds of abstracts submitted in the field for presentation. The conference draws researchers from all over the world to participate in the lectures and array of break out sessions designed around specific themes. Included this year were sessions in Spanish, educator programs, integrated public outreach, poster sessions, and research presentations. Keynote speakers and panel discussions provided in–depth content and involvement from the participants. The week of Sunday, March 28th through Thursday, April 1st provided attendees with choices of up to eight breakout sessions to choose from with evening talks and events that complemented the science presentations.

Dr. David Ward presented “Microbiology/Astrobiology Outreach Education in Yellowstone National Park” at the 2004 Astrobiology Science Conference. The presentation was part of a series of talks by NASA Ames Astrobiology scientists that addressed their research and outreach programs. Dr. Ward’s talk summarized the comprehensive program being developed to exploit Yellowstone's colorful and charismatic extremophile microorganisms. A partnership involving the NASA Ames NAI team, Lockheed–Martin Space Operations and the Yellowstone Division of Interpretation has been formed to (i) develop a new chapter for the Yellowstone Resources and Issues Manual (the primary resource used to train interpretive rangers and park managers), (ii) develop new interpretive signs to be strategically placed along boardwalks, and (iii) revise trail guides to coordinate with new signs and provide another layer of learning. A partnership involving the Montana State University Thermal Biology Institute, the Yellowstone Division of Interpretation and the Yellowstone Park Foundation has been formed to (i) develop an electronic field trip and (ii) develop curricula for four K–12 formal education programs already in place in Yellowstone. Microbiology/astrobiology interpretation is also one of the main themes of a new Old Faithful Visitor Education Center being planned by the Yellowstone Division of Interpretation.

Valley Children's Museum

The Ames Astrobiology team serves on the Advisory Board of the Valley Children's Museum. We have developed a recent collaboration with The Valley Children's Museum, and the California Academy of Sciences. The focus is on exhibit research and development while creating educational program content for the VCMWoW! Museum Without Walls Interim Program. Through this innovative program, the VCM provides hands–on educational exhibits and programs at community events, local libraries, and schools. The California Academy of Sciences will transfer the Astrobiology exhibit on display at CAS to the Valley Children's Museum in the Spring of 2005. With community grants from Livermore, San Ramon, and Pleasanton the astrobiology exhibit will travel to local schools, libraries, malls, and outdoor festivals for the general public. The Astrobiology Educator Guide will be utilized along with the docent guide developed by CAS.

The Valley Children's Museum is a community–based, non–profit 501(c)(3) organization dedicated to bringing educational, play–based programs to children, families, and school groups located in the Tri–Valley and surrounding communities. Since its inception in 1999, the VCM has generated immense support throughout the region. The VCM continues to enhance its VCMWoW! Interim Program while working towards developing its permanent site. For more information about the Valley Children's Museum, please call 925–461–6574 or visit www.valleychildrensmuseum.org.

Wrigley Marine Science Center, Geobiology Course

This intensive summer course was sponsored by the Agouron Institute and the University of Southern California (USC) Wrigley Institute for Environmental Studies, and hosted by the Philip K. Wrigley Marine Science Center on Catalina Island, CA. For six weeks, the participants learned concepts and

methods for investigating how microorganisms interact with their environment and how these interactions have shaped the evolution of the Earth. The course focused on the following five key aspects of geobiology: Early Biomolecular Chemistry, Earth History, Earth Systems, Physiological Diversity of Microbes, and Microbial Evolutionary Ecology. A core team of biologists, chemists, geologists, and astrobiologists lectured on these topics and supervised field projects. Three mini–symposia addressed currently "hot" topics in geobiology. Dr. Dave Des Marais participated both as a mini–symposium lecturer and as an advisor to students pursuing projects relevant to astrobiology.

Scientists and Museum's Working Together

Science communication to the public is important for many reasons not the least of which is the need to educate the public about science. This is especially true for astrobiology, which involves the exploration of space for habitats that could support life. Science centers play an important role in presenting and interpreting science for their visitors and to inspire the next generation of scientists who may carry out the missions being planned today. While museum personnel are experts in developing programs and exhibitions, science centers often do not have astrobiology experts on their staffs. They rely on scientists from other institutions to help with science content interpretation. The partnership between scientists and science–center personnel create exciting and stimulating experiences for visitors. In order to encourage scientists to partner with science centers on exhibitions we created a workshop to provide understanding of the role between content expertise and exhibition and program development. This workshop was designed to take advantage of the presence of astrobiologists and to team them with experienced museum program developers in an astrobiology exhibit charette. This will provide scientists with insight and experience working with museum professionals. The invited museum professionals included (exhibit developers, designers and evaluators) from local science enters (The Tech Museum of Innovation in San Jose, The California Academy of Sciences and The Exploratorium both in San Francisco) to participate. We setup small groups containing scientists and science center personnel. The teams were charged with developing several different exhibits, which will be chosen to explore particular problems in exhibit development and content interpretation in astrobiology. Finally, the groups presented to the entire workshop for positive critiquing. This workshop model will be used at future informal education professional meetings.

Educational Film, Radio, Web, and Print Productions

The Ames Astrobiology Team is highly involved with public programming on television, radio, video, and publications. The distribution of astrobiology research, specific missions, and unique scientific events are shown nationally and internationally featuring any number of scientists on the Ames team. Team members have been involved in numerous diverse media events.

Dr. Tori Hoehler: Featured in Norwegian public television program "Schroedinger's Katt“. Science adviser and E/PO consultant for the forthcoming Disney IMAX film "Aliens of the Deep". Interview on Mars rovers & astrobiology for “Tech T.V.”

Dr. Norris: Community Conversations: “Astrobiology: Life in Space”

Dr. Ward: Yellowstone National Park Electronic Field Trips: “Hot Colors: ‘Windows Into the Hidden Worlds’”

Dr. David Des Marais: Mars Exploration Rover press conferences. Interviews for press and film. University of Colorado, Boulder Science Writer/Journalist Conference.

Dr. Lynn Rothschild: SETI Radio "Are We Alone" interview. Eyewitness News–interview. New York Hall of Science extremophile exhibit. BBC4 with Martin Rees, Astronomy Royal.

Educational Workshops/Classroom/Lab Experiences Educational Workshops/Classroom/Lab Experiences

The Ames Astrobiology team has developed and organized educational sessions and workshops at national conventions or site locations across the country and internationally. Team members participated as keynote speakers, lecturers, and presenters of hands–on workshops targeted at students of all levels, university professors, and educators. The team also develops and presents science lessons for local and international classroom experiences at various schools. The presentations occur in places where team members are conducting research on–site or involved in science conferences. The science team makes it a priority to present their research at universities, while providing a program for the K–12 school in the areas they are visiting. Because of return field experiences or invitations as speakers, the team does have more than a "one stop" experience with the local school districts. Students and educators are invited to various centers, universities, and field sites to participate with the science team. The experiences with the science team also include field expeditions, short courses, course series, and lesson development with the educators on site. The Camp Wilderness Curriculum and Park Kids programs at Yellowstone National Park and the Museum programs at the California Academy of Sciences involve scientists with students, teachers, docents, and interpreters. Science team members make themselves available after they return home to answer questions via e–mail from the students or educators that they had met. The themes usually addressed are the value of scientific training, participating in space exploration, as well as the exciting details of astrobiological research.

Astrobiology Academy

The NASA Ames Astrobiology research team participates in the Astrobiology Academy by presenting lectures to the students, offering lab tours, and hosting student interns from the Academy. The students have a research mentor from Ames who works with them as they develop their projects and meets with them to oversee the research developments.

Stanford University Course

The Ames Astrobiology researchers participate in the development of the

course presented at Stanford University to graduate students. Dr. Lynn Rothschild is the director of this program. The NASA Ames team collaborates each year on the design and content of the course. The researchers provide lectures, lessons, lab experiences, and projects for the duration of the semester long course. Each series of lecturers are responsible for preparing the mid term and final exams for their portion of the program.

Microbial Mat Samples

Microbial mat samples taken for research purposes from around the world are maintained by the Ames Research team. The team is routinely asked to provide samples for classrooms, educator workshops, museum exhibits, and other displays. The microbial mat samples sent to various locations are used for the general public, professional development programs, and classroom activities providing a hands−on experience with this vital research tool. The mats are selected, packaged, and maintained by the Ames team for these venues.

Yellowstone National Park News Release

“NASA Research Focuses on Yellowstone's Hot Springs and Compares Findings to Rocks from Mars”

Dr. David Des Marais of the NASA Ames team (NAI) provided interviews and was quoted in articles nationally and internationally due to the Associated Press article. This release was also featured on various websites nationally and internationally and featured on the NASA Astrobiology site due to the Yellowstone National Park article in newspapers across the world.

−−Washington Post −−Las Vegas Sun −−USA Today −−LA Times −−Arizona Republic (Phoenix) −−Seattle Post−Intelligencer −−Billings Gazette (MT) −−Pittsburgh Post−Gazette −−NASA Ames Astrogram −−Office of Space Science Newsletter −Voyages in Education and Public Outreach

Except from the published article: “Bozeman, Montana: How does life begin and evolve? Is there life elsewhere in the Universe? What is the future of life on Earth? These fundamental questions make up the science of astrobiology, and some of NASA's top scientists are trying to answer them in of all places Yellowstone National Park. Microscopic organisms that have inhabited Yellowstone's hot springs for billions of years tell the story of life on earth, and could eventually lead to the discovery of life on other planets.

While astrobiology−related studies have been taking place in Yellowstone for several years, a grant from Lockheed Martin Corporation and the NASA Astrobiology Institute will soon make this fascinating field of study accessible for the first time through permanent interpretive exhibits for park visitors. The $66,000 grant to the Bozeman, Montana−based Yellowstone Park Foundation will fund the development of outdoor exhibits in several locations throughout the Park. These exhibits will interpret Yellowstone's hydrothermal features as extreme habitats for amazing life forms that may help explain the origins of life on earth and provide clues in the search for life on other planets.”

Docent Field Guide To Exhibits

The California Academy of Sciences developed a docent field guide, which provides an introduction to the exhibits featuring “Astrobiology: Life in Extreme Environments.” The docent manual follows the same path as the exhibit floor by outlining the content in specific exhibit areas. This collaborative manual provides the docents with the content needed to provide public talks, small group discussions, and science on the floor demonstrations within the astrobiology exhibit space.

Content in the guide was coordinated by Dr. Carol Tang. What is Astrobiology? Astrobiology–Life in Extremes Astrobiology is the study of Life, it's Evolution and Distribution in the Universe How do we study life? Earth is unique in the solar system/universe. Where is life found? Life has been found in many of Earth's extreme environments. Extreme environments exist elsewhere in the solar system on other planetary bodies. Does Life exist elsewhere in the universe? The understanding and exploration of extreme environments, both on earth and elsewhere, guides our search for life.

Science Communication Group

The Science Communication group proposed to mobilize expertise from across the NASA Astrobiology Institute and the wider community toward the advancement of science communication in astrobiology. The founding group is consists of thirty science journalists, science communicators, television producers, museum specialists, education and public outreach experts, web specialists, academics, and key individuals who have led the quest to understand how to provide the public with an understanding of science. Our representation includes the NASA Ames NAI Team, NASA Astrobiology Institute, Time Magazine, US News and World Report, the Australian newspaper, international freelance science journalists, Pioneer Productions, the New York Hall of Science, the Powerhouse Museum, Space Science Institute, and universities in the United States, United Kingdom, and Australia. Dr Seth Shostak and Professor Paul Davies chaired a panel of experts from the NASA Astrobiology Institute Science Communication Group at the Astrobiology Science Conference at NASA Ames Research Center, California, in March 2004. It was open to all conference participants and led to a lively discussion on the communication of astrobiology via the mass media and ideas for future workshops.

California Academy of Science

The California Academy of Sciences (CAS) exhibit entitled "Astrobiology: Life in the Extremes" was developed and opened in downtown San Francisco during this past year. The NASA Ames Astrobiology team partnered with CAS to create the astrobiology exhibit. Dr. Carol Tang was the Co–Investigator for NASA Ames and lead on the design and development team, which included CAS curators, staff, and outside consultants (Pompei AD and Cinnabar, Inc.). This 2500 square foot exhibit focuses on extreme environments and the lessons they provide for astrobiology. Exhibit material was provided by NASA,

NASA ARC, CAS, VPL, and Penn State as well as members of the scientific community consisting of scientists from UC Davis, Portland State, and Woods Hole Oceanographic Institute. NASA–ARC provided the majority of images for the hot springs exhibit component––Colleen Howell compiled these from across the NAI team. Some of the research featured was from a project previously funded by NAI through Arizona State University (Cuatro Cienegas module). Attendance at this exhibit was about 5000 people during the preview opening alone (May 1–June 19).

ARC NAI team members also participated in development of the exhibit by providing input and ideas beyond images alone. These members include: Carol Tang, Tori Hoehler, Catherine Tsairides, Dave Des Marais, Max Bernstein, Charles Apel, Linda Jahnke, Lynn Rothschild, and Rocco Mancinelli.

Astrobiology Docent Trainings

In conjunction with the California Academy of Sciences the NASA Ames Research Center serves as a professional development site for the docents twice a year. The NASA Ames Education team provides tours of the NASA facility and introduction to the NASA materials designed to be used with educators, school children, and the general public. The Astrobiology science team invites the docents into their laboratories for tours, talks, and hands–on experiences that can be duplicated on the museum floor with small groups. The Astrobiology Educator Guide has been provided to the resource library at the California Academy of Sciences for formal education programs at the museum along with the card games set aside for the general public to use at tables and on the computers in the experience center.

Public Presentations/Sympsiums/Lecture Series

The Ames Astrobiology Science Team has been invited as guest speakers and lecturers for professional and public symposia. The science team is involved with undergraduate and graduate students as lecturers in courses, student societies, workshops, mentoring and intern experiences. NAI Ames team scientists have presented all over the world and have collectively given over 1200 hours to present astrobiology research to the community. A sample of these diverse events include:

Dr. Lou Allamandola: Lecture at Santa Clara Valley Chapter of the American Chemical Society: "From Astrochemistry to Astrobiology." Lectures at Chemistry/Physics/Biology departments at University of Missouri and Stanford University: "From Interstellar Molecules to Astrobiology."

Dr. Hector D'Antoni: San Jose State University NAFEO/MSi/NASA Ames Academy Mentoring guest student.

Dr. Greg Laughlin: Branson School Guest lecturer: "Stellar Evolution and Habitable Planets." The Museum of the Rockies: "Extrasolar Planets".

Dr. Maura Rabbette: Lecture at NASA Ames Earth Day Fair: "Runaway greenhouse research at NASA Ames." Lecture at San Jose State University:

“Mathematics Department Multivariate Statistical Analysis of Radiator Fin Theory and the Role of Wind on Greenhouse Atmospheres.”

Dr Bernstein, Dr. Apel, Dr. Hoehler, Dr. Des Marais, Dr. Linda Jahnke, Dr. Lynn Rothschild, Dr. Rocco Mancinelli, Dr. Carol Tang: contributed images for California Academy of Sciences web−site and museum exhibits.

Dr. Sandford: NASA Ames Randall Museum Junior Science and Humanities Symposium. Randall Museum Science Fair

Dr. Apel: Lecture at Santa Rosa Junior College: "Being a Scientist on NASA's Stardust Discover Mission"

Dr. David Des Marais: Astrobiology Academy/lab mentor. Lecturer for Space Biology Summer Course for Engineers. Foothill College Lecture Series: “The Mars Exploration Rovers.” Talk for National Academy of Sciences “Weird Life” study group. Astrobiology Science Conference: evening panel/career student talk. Talk for Cupertino Rotary Club: “Mars Exploration Rovers.” Lecture for Weizmann Institute (Bay Area Group): “Astrobiology.” Lecture at San Francisco Commonwealth Club: “Red Planet Mars.”

Dr. Lynn Rothschild: Skyline College “Women In Science” day

K−14 Classroom Presentations

The Ames Astrobiology Team has developed a rapport with our local Bay Area school districts. Our scientists are asked to complement the existing science program for California by coming into the formal education classroom to provide specific lectures or hands−on demonstration activities. The researchers incorporate their science into the content that is part of the local and national standards for the district. The science team also invites the classrooms to NASA Ames for onsite demonstrations, tours, and access to the laboratories. The team is often called upon for career day programs, science fair judging, and special event programming for scientific events scheduled at the schools. This classroom involvement is initiated by the science team members themselves because of their interest in K−14 classroom partnerships. This involvement occurs throughout the NASA Ames Research Center Education Office.

NASA's Mars Exploration Rover (MER) Mission

Dr. David Des Marais has contributed to the (MER) mission as a member of the Science Operations Working Group (SOWG). The SOWG investigates how liquid water has influenced rocks and soils at the two rover sites, Gusev Crater and Meridiani. Dr. Des Marais is one of the Leads of the Long Term Planning subgroup of the SOWG. LTP Leads link the tactical “day−to−day” operations to strategic planning for the twin rovers, Spirit and Opportunity. They coordinate activities between the rovers and the Mars orbiters. Dr. Des Marais has brought the Mars mission to the public eye by participating in a series of public and professional outreach events nationally and internationally. His contributions include professional and public lectures, interviews for the radio and

newspapers, television appearances and participating in large scale press releases, and serving on the MER exhibit committee at NASA Ames. He threw the ceremonial “first pitch” at a San Francisco Giants game on May 13, 2004.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Team Reports: Arizona State University

Arizona State University
Executive Summary
Principal Investigator: Jack Farmer

For information about the astrobiology research and activities being done at Arizona State University visit... http://www–glg.la.asu.edu/~jfarmer/index.html

Team Reports: Carnegie Institution of Washington

Carnegie Institution of Washington
Executive Summary
Principal Investigator: Sean Solomon

The NAI team led by the Carnegie Institution of Washington is studying the evolution of organic compounds from prebiotic molecular synthesis and organization to cellular evolution and diversification. Our program attempts to integrate the sweeping narrative of life's history through a combination of bottom–up and top–down studies. On the one hand, we study processes related to chemical and physical evolution in plausible prebiotic environments – the interstellar medium, circumstellar disks, extrasolar planetary systems, the primitive Earth, and other Solar System objects. Complementary to these bottom–up investigations of life's origin, we carry out field and experimental top–down efforts to document the nature of microbial life at extreme conditions and the characterization of organic matter in ancient fossils. Both types of efforts inform our development of biotechnological approaches to life detection on other worlds.

Our team's research activities focuses on life's chemical and physical evolution, from the interstellar medium, through planetary systems, to the emergence and detection of life, across seven integrated areas of research:

1. We are applying theory and observations to investigate chemical evolution in the interstellar medium, in circumstellar disks, during planetary formation, and on Solar System bodies.

2. We are carrying out analytical research on extraterrestrial samples, including meteorites and interplanetary dust particles, with an emphasis on organic molecules and evidence for water.

3. We are studying prebiotic chemical and isotopic evolution on Earth, with an emphasis on the sulfur cycle and the role of sulfur in prebiotic organic synthesis.

4. We are investigating possible mechanisms of prebiotic molecular selection and macromolecular organization, including the self–organization of amphiphiles and the selective adsorption of organic molecules onto mineral surfaces.

5. We are continuing to study life in extreme environments, with field

studies of hydrothermal microbial communities and laboratory studies of stress adaptation of microbes in high−pressure and high−temperature environments.

6. We are examining ancient fossils and microbes fossilized in the laboratory with a variety of analytical techniques to assess preservation mechanisms of molecular biosignatures, and we are studying modern geothermal systems to investigate preservation of biosignatures during silicification in these environments.

7. We are applying our enhanced understanding of life's chemical and physical evolution to develop new techniques in astrobiotechnology – procedures that will be applied to the design and testing of instruments for life detection, initially in terrestrial settings and eventually on spacecraft to be sent to other Solar System bodies.

Fuller understanding of life's origin, evolution, and distribution requires major advances on all these topics, as well as the extensive challenge of integrating these topics. During the past year we achieved significant progress in each of these research areas, and we devoted increased attention to the interfaces among these theoretical, experimental, and field approaches.

Among the highlights from the past year's research in the area of the evolution **from molecular clouds to habitable planetary systems** were the following:

- Observations of circumstellar disks in the TW Hydrae and Beta Pictoris associations show that evidence for inner disk clearing is not a simple function of the age of the association.
- Theoretical models of convective energy fluxes in circumstellar disks strongly support the idea that giant planets may form rapidly by the disk instability mechanism.
- Models for the delivery of water−bearing planetesimals to the growing terrestrial planets shows that the efficiency of this process depends sensitively on the presence of the giant planets.
- Continued radial velocity measurements of the 2,000 Sun−like stars within 50 parsecs have yielded a number of new extrasolar planet candidates, including a planet with a minimum mass twice that of Jupiter orbiting its Sun−like star (HD 70642) on a nearly circular orbit at a distance of 3.3. AU. The system is the closest analog of our Solar System discovered to date.
- New models for the atmospheres of hot Jupiters have laid the groundwork for understanding the results of future observations of hot Earths.

Highlights in the area of **extraterrestrial materials and the origin and evolution of organic matter in the Solar System** during the past year included the following:

- The first confocal Raman images of interplanetary dust particles permitted three−dimensional mapping of organic matter at the 200−nm scale.
- D/H isotopic imaging of carbonaceous chondrites demonstrates more extreme heterogeneity on the 1−2 µm scale than previously recognized. In general, however, the D/H ratio of organic matter in carbonaceous chondrites correlates strongly with the extent of parent body processing.

- Petrographic, isotopic, and transmission electron microscopy (TEM) measurements of a partially differentiated meteorite indicate that carbon isotope heterogeneity in graphite can be preserved during partial melting in meteorite parent bodies.

Highlights in the area of **prebiotic chemical and isotopic evolution on Earth** during the past year included the following:

- Sulfur fractionated by enzymatic catalysis has been harvested in the laboratory from living culture of sulfur–matabolizing microbes and analyzed for ^{32}S–^{33}S–^{34}S.
- A model that describes the mass–dependent sulfur isotope fractionations for sulfate reducers and sulfur disproportionators has been developed that shows how microbes may have played a crucially important dual role in both preserving but also diluting anomalous sulfur isotope fractions. As an agent of preservation, microbial enzymatic catalysis precipitates pyrite, a secure storage site for sulfur isotopes, but as an inhibitor, the full magnitude of isotope anomalies may not be preserved because of dilution.
- Many common transition–metal sulfides have been shown experimentally to catalyze organic reactions in a manner that mimics the carbon fixation pathways adopted by acetogenic and methanogenic microorganisms.

Highlights in the area of **prebiotic molecular selection and organization** during the past year included the following:

- The facile self–assembly and vesicle formation of amphiphiles was demonstrated during hydrothermal reactions of pyruvate.
- A novel hypothesis, dubbed the “PAH world,” provides a plausible chemical link from the random prebiotic “soup” to the RNA world. By the PAH world hypothesis, polcyclic molecules self–assemble into stacks and then selectively bind purines and pyramidines, the bases of nucleic acids.
- Atomic force microscopy measurements support the inference that electrostatic interactions dominate the selective adsorption of amino acids by mineral surfaces.
- More than a dozen common chiral mineral surfaces have been identified and characterized with respect to their potential for prebiotic selection of chiral molecules. Adaptation of DNA ChipWriter/ChipReader technology to the study of molecular adsorption on mineral surfaces promises to speed future such efforts.

Highlights in the area of **life in extreme environments** during the past year included the following:

- Bacterial groups were discovered that are unique to the hot environments of mid–ocean ridge hydrothermal vents and include new groups of microorganisms that can fix carbon dioxide in the absence of oxygen with hydrogen and sulfur.
- The Lost City hydrothermal field represents a new type of submarine hydrothermal system driven by exothermic chemical reactions in mafic oceanic crust and not as the result of cooling magma.
- Studies of microorganisms within sulfide chimneys at active hydrothermal vents suggest that biofilm formation on minerals may be associated with microbial growth or survival at extremely high temperatures.

- Laboratory experiments have demonstrated that microbes are able to survive at pressures where ice−VI is observed.
- Diamond anvil cells are being designed to allow manipulation of cells and organic material after exposure to extreme pressures.
- A possible connection has been uncovered between the isotopic composition of Fe and the degree of microbial Fe processing in Fe−bearing bacterial mats.

Highlights in the area of **biosignatures and abiosignatures** during the past year included the following:

- Molecular analysis of biofilms from the Enspel Formation reveals that within the aliphatic fractions there are distinct compositional differences between the biofilms and the sediment.
- Compound−specific isotope ratio mass spectrometric analysis of amino acids suggests that discrete metabolic pathways may have distinct isotopic signatures.
- A substantial database of C, N, O, and H isotopic biosignatures from the early Cambrian is being developed.

Highlights in the area of **astrobiotechnology** during the past year included the following:

- Life−detection instrumentation has been tested in a Mars analog environment on Svalbard. This environment will be used to test flight instrumentation proposed for Mars lander missions.
- Fossil collagens in 40,000−year−old bone samples have been characterized using the world's first antibody microarray to fossil compounds.
- High throughput has been achieved for the simultaneous screening of thousands of fluorescently labeled D and L amino acids for assessing their binding characteristics to mineral surfaces.
- Quantitative microfluidic cell lysis has been demonstrated for gram−negative, gram−positive, and archaeal cells.

In summary, our team's recent research, including discoveries and characterization of new planetary systems, investigation of the fates of carbon and water on planetary building blocks and other worlds, elucidation of robust pathways for prebiotic organic synthesis, documentation of novel microbial metabolic strategies, evaluation of possible biosignatures, and development of new technologies for astrobiological exploration, inform the central questions of astrobiology. Taken together, these discoveries are changing our views of life's origin and its possible distribution in the universe.

Project Report: From Molecular Clouds to Habitable Planetary Systems

Project Investigators:	***Alan Boss , R. Paul Butler , Sara Seager , Sean Solomon , Alycia Weinberger , John Chambers***

Project Progress

1. *Protoplanetary and Debris Disks*

   Co−I Weinberger pursued studies of young stars to assess the number with circumstellar disks as a function of age and to measure detailed properties of extant disks. Using the Keck Observatory, she searched for disks around stars of age 10 to 100 Million years (Myr) using sensitive 12− and 18−µm photometry. Each association of stars, composed of a few tens of stars that were formed from the same parent molecular cloud at the same time, provides a laboratory for the study of disk evolution. Work on the first of these associations, TW Hydrae, showed that terrestrial planet formation must never have happened or be nearly complete in these 8−Myr−old stars (Figure 1). Results from a second association, 12−Myr−old Beta Pictoris, showed that a larger fraction of stars had disks. Together, the two associations show that the progress of dust removal and planet formation is not a straightforward function of age.

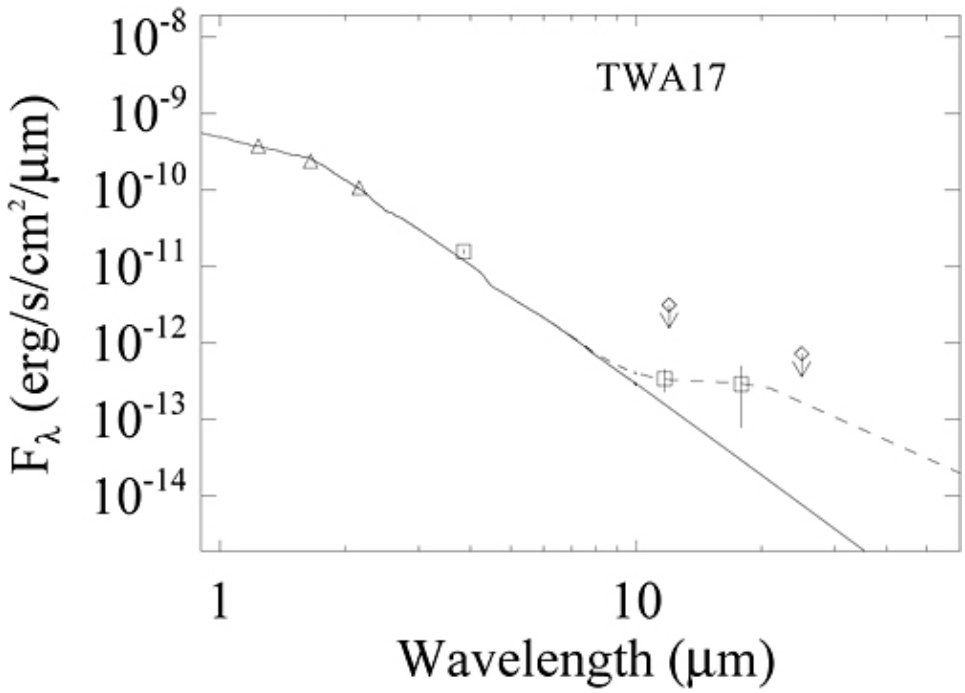

Figure 1. Discovery of a new but very tenuous disk around the 8−Myr−old star TWA 17. This spectral energy distribution shows excess radiation at 12 and 18 microns (open squares) above that expected from the stellar photosphere (solid line). Infrared excess is the signature of disk dust that absorbs stellar light, heats up, and reradiates it at longer wavelengths. TWA 17 was the only star in a survey of sixteen that had detectable dust. The rapid disappearance of large amounts of dust around these sample stars may mean that any planet formation in the terrestrial planet region was completed very quickly. The photosphere was fit to 1−2 micron data from the 2MASS catalog (triangles). The completeness level of the IRAS survey at 12 microns and extrapolated to 18 microns (diamonds) demonstrates that this disk is too tenuous to have been detected by IRAS. The infrared measurements are from the W. M. Keck Observatory. The dotted line shows a 170−K blackbody, the best fit (i.e., color temperature) to the excess measured, corresponding to an integrated dust luminosity relative to the star of L(IR)/L(*)=0.005. (From Weinberger et al., 2004).

Postdoctoral Fellow Aki Roberge and Weinberger have worked extensively to use the Hubble Space Telescope for "coronagraphic spectroscopy," i.e., spatially resolved optical spectra of circumstellar disks. They applied their reduction technique to spectra of TW Hydra and showed that the star's dust disk scatters blue light in the inner part of the disk but neutrally in the outer part of the disk. This is most easily understood if the size of the dust particles is smaller in the inner than the outer disk. They have successfully applied for Hubble Space Telescope time to study HR 4796A's disk with the same technique.

Roberge is also using far−ultraviolet (UV) spectroscopy to study three young stars surrounded by circumstellar dust disks using the orbiting

Far Ultraviolet Spectroscopic Explorer (FUSE) satellite. The observations sensitively probe for small amounts of circumstellar gas in the disks, in an effort to set a limit on the timescale for gas giant planet formation and also to investigate the composition of the planetary bodies producing the observed dust disk. One of three targets was observed this year; the other two remain to be scheduled.

The only way one can currently examine the chemistry of extrasolar cometary systems is to look for such systems around carbon−rich AGB stars, where they will be vaporized by their aging star. In carbon−rich environments, one expects no oxygen−containing molecules other than CO and small amounts of SiO and HCO^+. Postdoctoral Fellow Saavik Ford attributes any other oxygen−containing molecules found in carbon−rich environments to a vaporizing cometary system, analogous to the Solar System's Kuiper Belt. So far, one extrasolar cometary system has been discovered around a carbon−rich AGB star, specifically IRC+10216, through the detection of water vapor by Ford and her colleagues. Ford has searched for two other interesting oxygen−containing molecules around IRC+10216, formaldehyde (H_2CO) and methanol (CH_3OH). Both may have played a role in pre−biotic chemistry on the early Earth. She has successfully detected formaldehyde around IRC+10216, at abundances comparable to those found in Solar System comets; however, her observations failed to detect methanol and set a stringent upper limit on the abundance of methanol which is more than an order of magnitude lower than the typical methanol abundances found in Solar System comets.

Ford has looked at possible observations of other extrasolar cometary systems using the Atacama Large Millimeter Array (ALMA), which will exceed the sensitivity of current instruments by factors of 20−100. ALMA should be capable of conducting a chemical survey of a large (~10−15) number of extrasolar cometary systems. Ford is planning to search for HDCO (singly deuterated formaldehyde) around IRC+10216, as detection would be exciting evidence supporting the existence of comets around that object. Ford is also planning to map the formaldehyde emission around IRC+10216, since she has preliminary evidence of a non−spherically symmetric distribution of cometary bodies. Ford, along with Postdoctoral Fellow Nader Haghighipour, is also supervising an undergraduate student who is running dynamical models to examine the possibility that the non−uniform distribution of cometary bodies around IRC+10216 is caused by the gravitational influence of a planet.

2. *Formation of Habitable Planetary Systems*

Co−I Boss is widely recognized as the leading advocate of the disk instability mechanism for the rapid formation of gas and ice giant planets. The rapid formation of self−gravitating clumps of gas and dust in a marginally gravitationally unstable disk requires a reasonably efficient means of cooling the disk gas. Clumps form on the dynamical time scale of a few orbital periods in the disk instability scenario.

Radiative transfer is not able to cool the midplanes of optically thick protoplanetary disks fast enough to permit the disk instability mechanism to form dense clumps. However, vertically−oriented convective cells, driven by the temperature gradient between the disk's midplane and surface, appear to be capable of cooling the disk midplanes on the desired timescale. Boss demonstrated this possibility by analyzing in detail the vertical convective energy fluxes in the first three−dimensional (3−D) radiative hydrodynamics model of clump formation by disk instability. Transient convective cells can be seen in all simulations to date, with vertical velocities (about 0.1 km/sec) and energy fluxes large enough to cool the outer disk at the desired rate (Figure 2). These models strongly support the idea that giant planets may form rapidly by the disk instability mechanism. Boss has also shown that gravitational torques and convective flows are able to transport material across the solar nebula, possibly accounting for the outward transport of thermally annealed grains that are observed in comets.

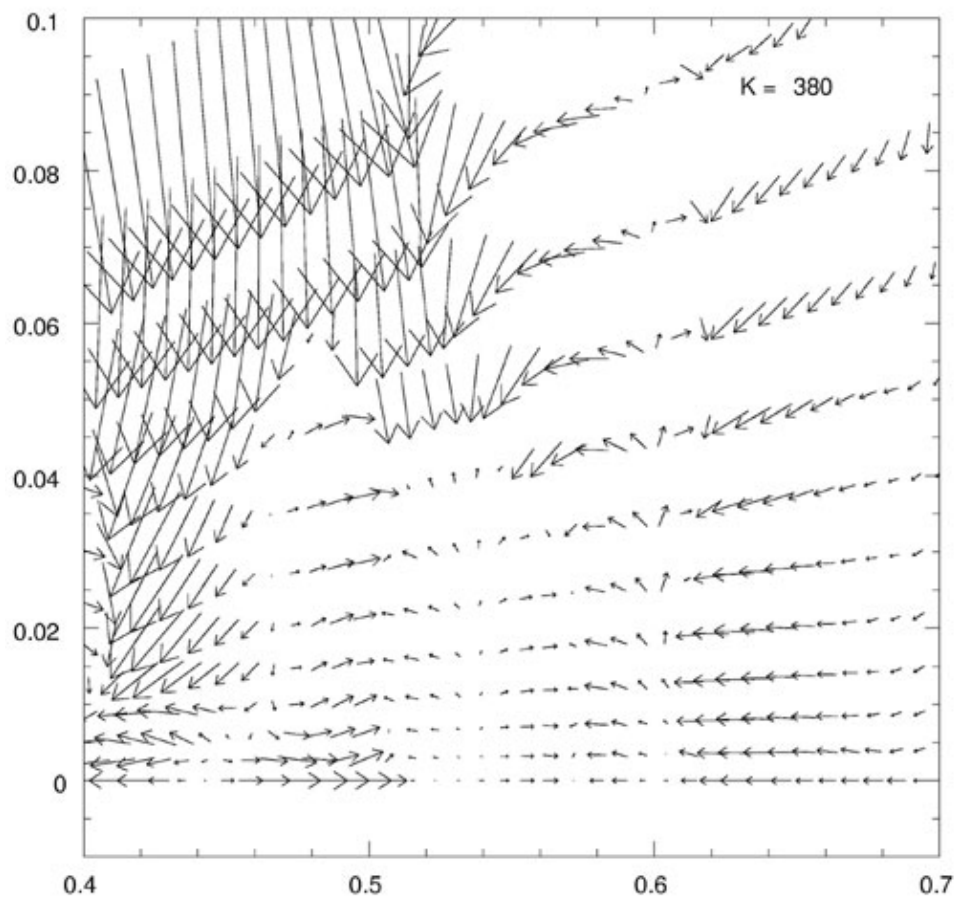

Figure 2. Convective cells can be seen in this vertical cross−section of a planet−forming disk modeled in three spatial dimensions. These cells carry thermal energy away from the disk's midplane to the disk's surface, allowing the disk to remain cool while forming self−gravitating gaseous protoplanets by the disk instability mechanism. A vertical plane at azimuthal grid cell number K = 380 (out of a total of 512 azimuthal

grid points) is shown. The region shown extends from a distance of 8 AU to 14 AU from the central solar−mass protostar. The vertical axis has been expanded by a factor of three to make the convective motions more apparent. The top of the plot is located at 2 AU above the disk midplane, which lies close to the bottom edge of the plot. Symmetry through the midplane is assumed in the calculation, so that the vertical velocities are forced to vanish at the midplane. The maximum velocity vector plotted has a speed of about 2 km/s (From Boss, 2004).

Haghighipour continued his research on the formation of cm−sized objects in the vicinity of off−axis pressure−maxima in a marginally gravitationally unstable disk, and he also studied the dynamical evolution and long−term stability of habitable planets in multi−gas giant extrasolar planetary systems. Results on the first subject indicate that small dust grains, while sweeping up the sub−micron particles of the background, undergo gas−drag−induced migration toward the location of pressure maxima, where they quickly accumulate and create a turbulent layer of cm−sized objects. The study included the effect of the evolution of the disk through changes of the disk's physical parameters on the rate of the formation of the dust grain layer, and also the collision and coalescence of dust grains in such an environment.

Haghighipour also studied the long−term stability of the Gamma Cephei system, where a Jupiter−like planet revolves around the primary star of a binary star system, the dynamical stability of a planetary system embedded in the Beta Pictoris debris disk, and the dynamical evolution and stability of the extrasolar planetary systems Upsilon Andromedae, 47 Ursa Majoris, 55 Cancri, and GJ 876. The latter work was performed in collaboration with Postdoctoral Fellow Eugenio Rivera and with Ferenc Varadi and William Moore of the University of California, Los Angeles (UCLA) NAI team.

Rivera performed dynamical fits to the radial velocity data of stars hosting at least two extrasolar planets. Planet−planet perturbations were included in modeling the data. Ideally, this fitting algorithm could be used to constrain the planets' masses and their orbital inclinations. The method has been used primarily to fit the radial velocity data for the star GJ 876. So far, the GJ 876 planetary system is the only one for which the inclusion of the planet−planet perturbations produces a very significant improvement in the fits to the radial velocity data. This is due to the strong perturbations between the planets, which are in a 2:1 mean motion resonance. Additionally, the code has been used to generate the initial conditions used in long−term stability studies of several extrasolar planetary systems. These initial conditions have also been used to identify regions in multi−planet extrasolar planetary systems that could harbor terrestrial planets.

Co−I Chambers is developing a new numerical model for the delivery of water and organic material to the early Earth. Current thinking is that the Earth initially formed under conditions that were too hot for such materials to condense, so that the planet probably received most of its

current inventory from external sources such as asteroids and comets. The new model updates an earlier model for planet formation developed by Co−I Wetherill and makes it possible to study the delivery of water and organics to Earth−like planets in extrasolar systems. Early results suggest that the water content of extrasolar Earth analogues depends sensitively on the orbits and masses of gas giant planets in these systems.

3. *Searching for Extrasolar Habitable Planetary Systems*

Co−I Butler and his group invented the iodine−cell precision radial velocity technique used by most of the world's planet hunting teams, discovered two−thirds of the known extrasolar planets, and achieved the world's best measurement precision. Over the past year the "California & Carnegie Planet Search" program has found 20 planets with the 10−m Keck, 3.9−m Anglo−Australian, and 3−m Shane telescopes in Hawaii, Australia, and California respectively. Among these discoveries is an approximate Solar System analogue (Figure 3), four new multiple planet systems, and two new sub−Saturn mass planets.

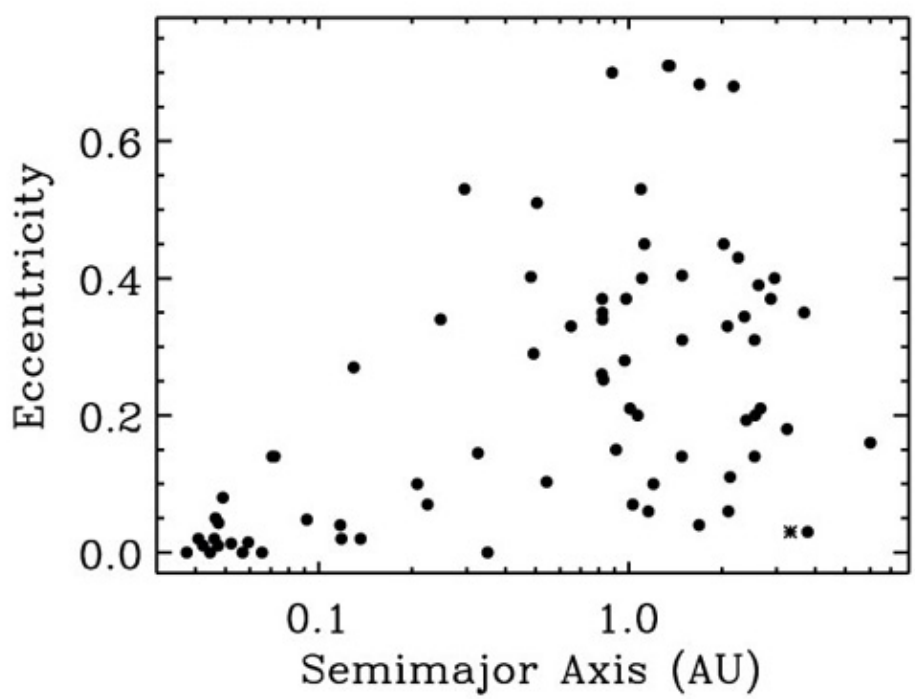

Figure 3. A plot of semimajor axis versus orbital eccentricity for known extrasolar planets highlights the best solar system analog discovered to date from radial velocity measurements. The planet around HD 70642 is in a circular orbit with a 5.8−year period. This discovery is from the Anglo−Australian (AAT) planet search.

Butler's major remaining goals are the detection of true Solar System analogs (Jupiter− and Saturn−mass planets orbiting beyond 5 AU in

circular orbits), and sub−Neptune−mass planets in short−period orbits. In both cases achieving higher spectroscopic precision is critical. Butler and his group are currently surveying all Sun−like stars out to 50 parsecs (pc), a total of about 2,000 stars.

Postdoctoral Fellow Kaspar von Braun continued to pursue the EXPLORE/OC planet transit search program. In the past year, he and his colleagues observed three new open star clusters, bringing the total observed to five. Setting up the EXPLORE/OC survey involved selecting target open clusters using known astrophysical data (available for only a fraction of the Milky Way open clusters) and testing data taken in 2002−2004. Specifically, target clusters have to be centered at the zenith in the middle of the night during a given observing run, and they need to be located nearby (within about 1 kpc) in order to achieve a high signal−to−noise ratio for small stellar radii, which increases the chances for detection of a transiting planet. von Braun and a colleague analyzed the photometric data of the open clusters NGC 2660 and NGC 6208 and conducted the preliminary reduction of test data of about seven target open clusters for future observing runs. Although von Braun's work has not yielded a detection of an extrasolar planetary transit, it has shown the ability to do so, given the observing cadence and relative photometric precision.

In addition to this effort, von Braun has been involved in the analysis of EXPLORE and OGLE data to test different transit−finding and light−curve−phasing algorithms. This analysis includes modeling light curves (together with Co−I Seager) to obtain the period, depth of transit signal, total transit duration, and duration of the flat part of transit (i.e., inside of ingress and egress). Combined with Kepler's third law and the assumption of a stellar mass−radius relation, these observable quantities yield a unique solution of the physical system parameters: stellar mass, stellar radius, planetary radius, orbital radius, and system inclination angle.

4. *Characterizing Extrasolar Habitable Planetary Systems*

In order to understand extrasolar terrestrial−type habitable planets, we must first understand the simpler giant planets. Co−I Seager, together with NAI JPL colleagues Y. L. Yung and C. D. Parkinson, and Caltech graduate student M. C. Liang, studied photochemistry on the hot Jupiters, addressing a major question that relates to observational signatures of hot Jupiters. Jupiter and Saturn have low albedos and muted spectral features blueward of 600 nm due to photochemical hazes. The hazes are produced from CH_4 photodissociation from solar UV radiation and recombination to higher hydrocarbon hazes. One might naively expect that the hot Jupiters, 100 times closer to their star than Jupiter is to our sun, would have vigorous photochemical haze production due to the 10^4 times higher UV flux. Seager and her colleagues found the opposite, namely that hydrocarbons are negligible on hot Jupiters, resulting from the high temperatures—10 times Jupiter's temperature. Despite the high UV flux, the high temperatures

allow faster recombination to CH_4 at the expense of hydrocarbon production. In addition, the high temperatures cause a lower CH_4 reservoir to begin with CO as the dominant carbon–bearing molecule at high temperatures. In addition to the photochemical haze result, Seager found that H_2O becomes photodissociated at high altitudes resulting in a huge atomic H reservoir (without UV radiation, all H would be in H_2 at the local temperature). This H reservoir is related to the escape of hydrogen detected by Vidal–Madjar and colleagues. Since hot Earths will probably be detected someday, Seager's work will form the basis for further photochemical studies of extrasolar planet atmospheres.

Seager has continued to interpret extrasolar planet data and make model predictions used by ground– and space–based proposals. Seager and collaborator James Cho have developed a general circulation model for Earth to address Earth's observational signature under different conditions. If Earth had a different rotation rate, obliquity, or continental arrangement, what would the cloud cover fraction and pattern be, and how would this affect either the planet's brightness or its spectral signature? The code is developed, and these questions will be addressed in the coming year.

5. *Habitable Environments in the Solar System*

One of the long–term goals of the CIW NAI team is to assess the likelihood, timing, and physical and chemical characteristics of potential habitable environments on Solar System objects other than Earth. PI Solomon's efforts on this project during the past year have focused on hydrothermal systems on Mars as such candidate environments, primarily because of the influx of important new data from the Mars Global Surveyor (MGS), Mars Odyssey, Mars Express, and Mars Exploration Rover missions. A first step in that evaluation was a synthesis of what can be inferred about the role of water in the early geophysical, geochemical, and geochemical evolution of the planet.

For its first billion years, the planet Mars was at its most active stage, and water linked interior and surface processes. Global differentiation segregated core, mantle, and crust within about 50 Myr of solar system formation; a magnetic dynamo in a convecting fluid core magnetized large areas of the ancient crust; and the Tharsis province became a focus for volcanism, deformation, and outgassing of water and carbon dioxide, possibly in quantities sufficient to induce episodes of global climate warming. A substantial early water budget contributed to widespread erosion, sediment transport, and chemical alteration of crustal material. A more massive early atmosphere was shielded against solar wind stripping by the global magnetic field. Deep hydrothermal circulation of water in the Martian crust likely accelerated crustal cooling and the preservation of variations in crustal thickness. Such circulation chemically altered the carriers of crustal magnetization, likely rendering any residual crustal magnetization beneath the lowest areas of major drainage basins undetectable from orbit, an inference that permits a Martian dynamo to have persisted for as long as one

billion years. Such deep penetration of water would also have provided a large volume of crust within which oxidation–reduction reactions at water–mineral interfaces may have yielded energetically favorable environments for organic synthesis and potentially for microbial habitability. Cessation of the dynamo, widespread reduction in the crustal field, and waning of interior outgassing allowed the early atmosphere to dissipate and the planet's surface to cool; substantial quantities of subsurface liquid water may persist to the present.

Highlights

- Weinberger's observations of circumstellar disks in the TW Hydrae and Beta Pictoris associations show that evidence for inner disk clearing is not a simple function of the age of the association.
- Boss's analysis of convective energy fluxes in circumstellar disks strongly supports the idea that giant planets may form rapidly by the disk instability mechanism.
- Chambers's work on the delivery of water–bearing planetesimals to the growing terrestrial planets shows that the efficiency of this process depends sensitively on the presence of the giant planets.
- Butler's spectroscopic survey of all 2,000 Sun–like stars within 50 parsecs yielded a number of new extrasolar planet candidates, including a planet with a minimum mass twice that of Jupiter, orbiting its Sun–like star (HD 70642) on a nearly circular orbit at a distance of 3.3 AU. This system is perhaps the closest analog to our Solar System discovered to date.
- Seager's work on the atmospheres of hot Jupiters has laid the groundwork for understanding the results of future observations of hot Earths.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 2.1:*** Mars exploration

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Kepler	Science Team Member
1	FUSE	Data Analysis
1	MOST	Science Team Member

2	TPF	Planning Support
3	SIM	Planning Support
2	Mars Global Surveyor	Co−Investigator
1	MESSENGER	Principal Investigator
1	Hubble Space Telescope	Data Analysis

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Co−I Boss is on the Science Team for NASA's Kepler mission, which is planned for launch in 2007. Kepler's photometric observations will permit the detection of numerous Earth−like planets in Earth−like orbits around stars in the disk of our Galaxy.

Boss is a member of the Navigator Program Independent Review Team (IRT), reporting to NASA Headquarters, which has oversight responsibility for all elements of the Navigator Program, including the Keck Interferometer, Large Binocular Telescope Interferometer, Space Interferometry Mission, and Terrestrial Planet Finder. Boss chaired a sub−group of the IRT that assessed the TPF Science Roadmap. This assessment led in part to a redefinition of the entire TPF mission concept in 2004.

Co−I Butler is involved with the Space Interferometry Mission, launch date ~ 2009.

Co−I Seager was involved as a Support Scientist on the Microvariability and Oscillations of Stars (MOST) microsatellite (Canadian Space Agency, launched June 2003). Seager was also involved in the NASA Origins Probe study proposals Fourier Kelvin Stellar Interferometer (FKSI) to characterize known planets at IR wavelengths (PI Bill Danchi, NASA Goddard) and Origins Billion Star Survey (PI Ken Johnston, U.S. Naval Observatory).

A member of the NASA Terrestrial Planet Finder Scientific Working Group, Seager contributed as part of a three−person subteam that led the preparation of the science requirements document for TPF.

PI Solomon is a Co−Investigator on the Mars Orbiting Laser Altimeter experiment on Mars Global Surveyor. He is also the Principal Investigator for the MESSENGER mission to orbit Mercury.

Co−I Weinberger was principal investigator on a cycle 9 Guest Observer program for the Hubble Space Telescope entitled "Imaging and Spectroscopy of Dusty Circumstellar Disks."

Field Expeditions

Field Trip Name:	
Start Date: June 2003	***End Date:*** July 2004
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Monthly trips to Chile (Magellan Baade Telescope, Las Campanos Observatory), Hawaii (W. M. Keck Telescope), and Australia (Anglo−American Telescope).	
Members Involved:	

Field Trip Name: W. M. Keck Telescope I	
Start Date: 7 December 2003	***End Date:*** 9 December 2003
Continent:	***Country:*** USA
State/Province: Hawaii	***Nearest City/Town:*** Waimea
Latitude: 19° 49.7'	***Longitude:*** 155° 28.7'
Name of site(cave, mine, e.g.): Keck Headquarters	***Keywords:***
Description of Work: Mid−infrared imaging of young stars to detect their dusty disks and spectroscopy to study their composition	
Members Involved:	

Field Trip Name: W. M. Keck Telescope I	
Start Date: 5 May 2004	***End Date:*** 9 May 2004
Continent:	***Country:*** USA
State/Province: Hawaii	***Nearest City/Town:*** Waimea
Latitude: 19° 49.7'	***Longitude:*** 155° 28.7'
Name of site(cave, mine, e.g.): Keck Headquarters	***Keywords:***

Description of Work: Mid–infrared imaging of young stars to detect their dusty disks and spectroscopy to study their composition

Members Involved:

Field Trip Name: Baade Telescope (Magellan I)

Start Date: 26 May 2003	***End Date:*** 31 May 2003
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:*** La Serena
Latitude: –29° 0.2'	***Longitude:*** 70° 42.1'
Name of site(cave, mine, e.g.): Las Campanas	***Keywords:***

Description of Work: Molecular hydrogen imaging of young stellar outflows.

Members Involved:

Field Trip Name: IRAM 30 m

Start Date: Winter 2004	***End Date:*** Spring 2004
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***

Description of Work: Observations of formaldehyde around IRC+10216.

Members Involved:

Field Trip Name: Magellan 1

Start Date: 25 September 2003	***End Date:*** 26 September 2003
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Las Campanas	***Keywords:***

Description of Work: Spectral type determination of EXP4 and NGC 2660 candidates and stars in fields of view.

Members Involved:

Field Trip Name: Magellan I	
Start Date: 27 July 2003	***End Date:*** 28 July 2003
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Las Campanas	***Keywords:***
Description of Work: Spectral type determination of EXP4 and NGC 6208 candidates and stars in fields of view.	
Members Involved:	

Field Trip Name: Swope 1 m telescope	
Start Date: 5 March 2004	***End Date:*** 26 April 2004
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Las Campanas	***Keywords:***
Description of Work: Open cluster survey (IC 2714 & NGC 5316).	
Members Involved:	

Field Trip Name: DuPont 2.5 m telescope, Las Campanas Observatory	
Start Date: 11 May 2004	***End Date:*** 17 May 2004
Continent: South America	***Country:*** Chile
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Las Campanas	***Keywords:***
Description of Work: Spectral type determination of candidates and stars in field of IC 2714, NGC 5316, and NGC 6208.	
Members Involved:	

Cross Team Collaborations

Co–I Boss continues his collaboration with the NASA Ames scientists working on the Kepler mission.

Co−I Chambers is collaborating with Jonathan Lunine (University of Arizona NAI team).

As Chair of Astronomy Focus Group, Co−I Seager completed the "Astrobiology and the James Webb Space Telescope" recommendation to NASA. This effort involved participants both inside and outside of NAI. From NAI were Jonathan Lunine, co−chair (University of Arizona), Alan Boss (CIW), Tom Greene (NASA Ames), Joe Nuth (NASA Goddard), and Alycia Weinberger (CIW). Additional workshop participants from the NAI included Nader Haghighipour (CIW), Michael Mumma (NASA Goddard), and Maggie Turnbull (University of Arizona).

Seager also has ongoing collaborative work with Yuk Yung (JPL NAI team) and Drake Deming (NASA Goddard NAI team).

PI Solomon is collaborating with Bruce Jakosky (University of Colorado NAI team) on the history of Martian water.

Co−I Weinberger collaborated with Eric Becklin, Ben Zuckerman, and Andrea Ghez of the UCLA NAI team on observations of young circumstellar disks.

Project Report: Extraterrestrial Materials: Origin and Evolution of Organic Matter and Water in the Solar System

Project Investigators:	***Conel Alexander , George Cody , Marilyn Fogel , Timothy McCoy , Larry Nittler , Andrew Steele , Ed Vicenzi***

Project Progress

1. *Organic Carbon in Meteorites and IDPs*

   Interplanetary dust particles (IDPs) are typically several microns in diameter and contain carbon and other materials with structure on a scale of tens– to hundreds–of–nanometers across. A heterogeneous distribution of carbon crystallinity and chemical composition has been inferred from other studies using standard micro–Raman techniques, but until now IDP structure had not been directly imaged. A group led by Postdoctoral Fellow Marc Fries conducted the first confocal Raman imaging of interplanetary dust particles in order to better characterize the organic matter they contain. Three particles were shown to have chemical variability, especially in terms of the degree of disorder in their organic matter, on a ~200–nm spatial scale. Unfortunately, the particle with the highest degree of heterogeneity was lost before isotopic measurements could be performed. Future work will attempt to correlate Raman spectra with D/H and $^{15}N/^{14}N$ ratios in IDPs, as well as with synchrotron XANES data.

   Co–Investigators Nittler and Alexander also used isotopic imaging to characterize the D/H spatial heterogeneity of fragments of the Tagish Lake (unique carbonaceous chondrite) and Al Rais (CR2) meteorites. They found that D/H is highly variable on a 1–2 µm scale in both meteorites, with D/H ratios in some C–rich hotspots approaching the highest values previously observed in IDPs. Transmission–electron–microscopy (TEM) analysis of several D–rich fragments by Co–I Stroud is underway.

   Using the focused ion beam workstation at the Naval Research Laboratory, Co–I Stroud has developed techniques for preparing ultra–thin sections of isotopically characterized interplanetary dust particles (Figure 1). These techniques will be applied to analyzing the

structure and chemical composition of the IDPs showing large isotopic variations in D/H, in order to determine any association with particular organic carriers.

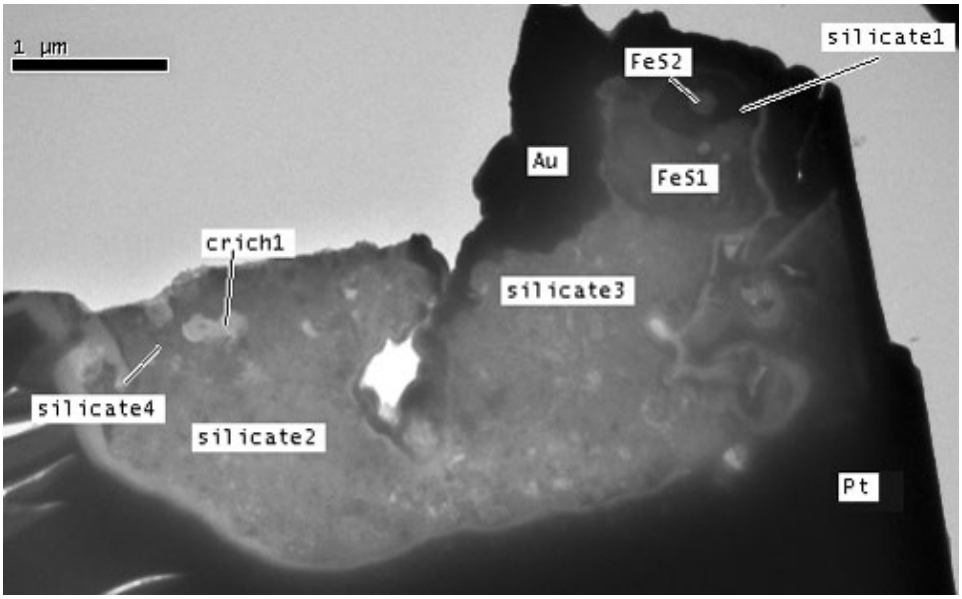

Figure 1. Transmission electron micrograph of an ultra−thin section of an interplanetary dust particle prepared by focused ion beam lift−out.

On the basis of stable isotope and solid−state nuclear magnetic resonance measurements by Co−Is Cody, Alexander, and Fogel, the D/H ratio of organic matter in carbonaceous chondrites correlates strongly with the extent of parent body processing. In particular, the insoluble macromolecular material in Tagish Lake appears much more hydrothermally processed than CR2 chondrites and apparently has lost much of its aliphatic component that was originally present. The lower bulk D/H of Tagish Lake compared to Al Rais supports this conclusion in general, but the presence of organic−rich hotspots with very high D/H ratios indicates that some very primitive organic matter has survived on small scales.

Ion microprobe analysis of organic residues has shown that at least some of the heterogeneities seen in the analyses of the bulk meteorites survive the process of making the residues. This work also suggests that ion microprobe measurements may underestimate the D anomalies in the organic material by up to a factor of two.

One of the aims of our work on meteorite organics is to provide standards for the development of microanalytical techniques that will be applied to IDPs and the Stardust mission samples. We have recently determined the bulk elemental and isotopic compositions of the insoluble organics from a number of primitive meteorites. We have also acquired high−resolution XANES spectra of insoluble organics at the Advanced Light Source (ALS) at the Lawrence Berkeley Laboratory. Transmission electron microscopy is generally the technique of choice

for studying IDPs and, probably, will also be for studying Stardust samples. We have begun a quantitative comparison of the XANES spectra acquired at ALS with electron energy−loss spectra obtained by TEM (Figure 2). The features associated with C, N, and O are clearly resolved. The C (1s) near−edge fine structure is similar to amorphous carbon. We are currently analyzing several other CM chondrites to determine the degree of heterogeneity in composition and bonding character of C.

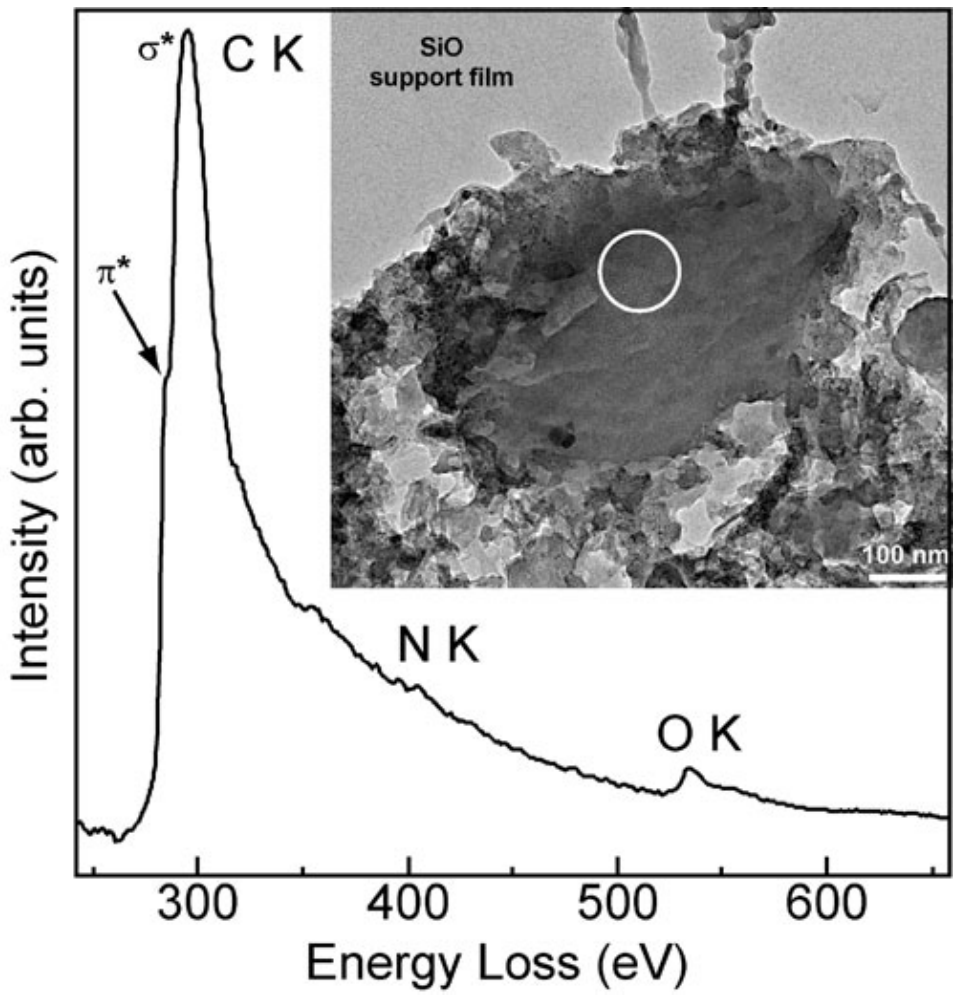

Figure 2. Electron energy−loss spectrum from an organic residue of the Murchison CM chondrite acquired by Zega and Stroud. TEM image (inset) shows the grain from which the spectrum was acquired. The white circle indicates the size of the electron beam used for the analysis.

2. *The Fate of Carbon during Planetary Differentiation*

In the first year of funding for this subtask, Co−Is McCoy, Nittler, and Stroud continued their collaboration on the Iodranite GRA 95209, in which carbon isotopic anomalies in a partially−differentiated meteorite were first discovered. Combining the petrographic observations of McCoy, the isotopic measurements of Nittler, and TEM observations of

graphite morphology by Stroud, it is now clear that isotopic anomalies were preserved in graphite during melting of enveloping metal in GRA 95209, but once melt began to migrate and graphite agglomerated, these isotopic anomalies were destroyed.

A major focus of this research effort is experimental melting of primitive achondrites to examine the temperature to which isotopic anomalies in graphite persist. To this end, Co−I McCoy and collaborators G. Benedix (research scientist, Washington University), T. Rushmer (faculty member, University of Vermont), R. Ford (master's degree student, University of Vermont), and C. Corrigan (postdoctoral fellow, Smithsonian Institution) spent much of the past year developing the techniques for melting primitive achondrites at appropriate temperatures and fO_2.

In the past year, the team also secured additional samples of GRA 95209 from the Meteorite Working Group, which will be used in the planned experiments.

3. *The Martian Hydrosphere: Clues from Meteorites*

Co−I Vicenzi has continued his study of the microchemistry of preterrestrial alteration products in Martian meteorites. He is developing a new technique, using hyperspectral X−ray microanalysis, to investigate the possibility of a chemical linkage between complex low−temperature aqueous assemblages formed in the Martian subsurface and global surface dust. Elli Pauli (George Washington University), who has a pre−doctoral appointment at the Smithsonian Institution, is using a variety of microscale spectroscopic methods to characterize sulfate−bearing alteration in Martian meteorites. The disposition of Fe, S, Cl and other astrobiologically important elements, and the suitability of these once watery microenvironments to sustain microbial life, are clearly important areas of exploration with regard to possible extant life on Mars.

With the addition in January 2004 of Detlef Rost as a postdoctoral fellow in the Smithsonian Institution group, work has initiated on measuring relative sensitivity factors for time−of−flight secondary ion mass spectrometry (ToF−SIMS) on a set of deep−sea volcanic glasses. These data are required to quantify the submicrometer−resolution, secondary ion images collected from Martian secondary mineral−filled veinlets. Data analysis is underway to evaluate the mechanism of formation of the low−temperature alteration materials, e.g., hydrothermal versus evaporitic precipitation.

Highlights

- The first confocal Raman images of interplanetary dust particles permitted three−dimensional mapping of organic matter at the 200−nm scale.

- D/H isotopic imaging of carbonaceous chondrites demonstrates more extreme heterogeneity on the 1–2 µm scale than previously recognized. In general, however, the D/H ratio of organic matter in carbonaceous chondrites correlates strongly with the extent of parent body processing.
- Petrographic, isotopic, and TEM measurements of a partially differentiated meteorite indicate that carbon isotope heterogeneity in graphite can be preserved during partial melting in meteorite parent bodies.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Cross Team Collaborations

Co–Investigators Conel Alexander, George Cody, and Larry Nittler are collaborators on the NAI team at NASA Goddard Space Flight Center.

Project Report: Prebiotic Chemical and Isotopic Evolution on Earth

Project Investigators:	***Jay Brandes , George Cody , James Farquhar , Robert Hazen , Douglas Rumble***

Project Progress

1. *Unravelling Earth's Sulfur Cycle*

   Sulfur fractionated by enzymatic catalysis has been harvested in the laboratory from living cultures of sulfur–metabolizing microbes and analyzed for ^{32}S–^{33}S–^{34}S. The species *Archhaeoglobus fulgidus*, *Desulfovibrio gigas*, *Thermodesulfovibrio yellowstonii*, *Desulfobacter hydrogenophilius*, *D. jorgensenii*, *D. autotrophicum*, *D. thiozymogenes*, *D. sulfodismutans*, and a culture of sulfur disproportionators from Gulfo Dulce, Costa Rica, all have mass–dependent sulfur isotope fractionations. A model that describes the mass–dependent sulfur isotope fractionations for sulfate reducers and sulfur disproportionators has been developed. In that model, as has been demonstrated in studies of oxygen isotope fractionation, mass dependent reactions transfer non–mass dependent signatures from reactants to products, albeit diminished in magnitude by dilution. Microbes may have played an important dual role in both preserving but also diluting anomalous sulfur isotope fractionations. As an agent of preservation, microbial enzymatic catalysis precipitates pyrite, a secure storage site for sulfur isotopes, but as an inhibitor, the full magnitude of isotope anomalies may not be preserved because of dilution.

   Applying these ideas to sulfur isotope measurements on single pyrite grains from a single bed of 3.5–Ga chert from the North Pole district, Western Australia (Figure 1), indicates behavior expected from the microbial metabolism of sulfur. The North Pole microbes accepted ambient sulfur with a non–mass dependent fractionation of ^{33}S, metabolized it mass dependently, and left behind a linear array of δ^{33}S versus δ^{34}S values offset from bulk Earth by –0.3 per mil in Δ^{33}S.

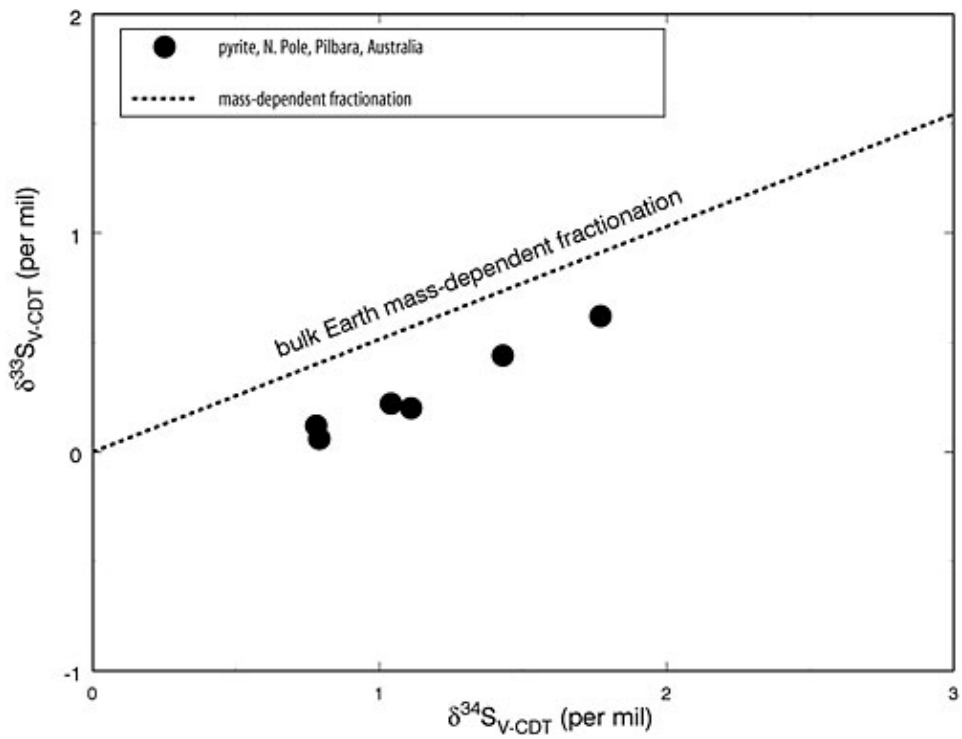

Figure 1. Sulfur isotope composition of pyrite grains from a single sedimentary bed of chert from the North Pole District, Pilbara, Western Australia. The dashed line gives compositions for bulk Earth.

2. *The Critical Role of Sulfur in Prebiotic (Protometabolic) Organic Chemistry*

Over the past year Co−Investigator Cody and his colleagues have been focusing on a potentially important set of prebiotic reactions. Following up on their earlier work with hydrothermal reactions with citric acid they began exploring similar chemistry in the presence of NH_3–NH_4^+ and in the presence of transition metal sulfides. They previously demonstrated that metal sulfide catalyzed reactions could provide a source of citric acid under reduced hydrothermal conditions. Citric acid is a useful source of alpha−keto acids (oxalacete and pyruvate) via reaction path α (Figure 2). The natural question arises as to whether one can convert these alpha−keto acids to their respective amino acids (aspartate and alanine) via a meta−sulfide−catalyzed reductive amination. The use of heterocatalysis (i.e., surface catalysis) offers the tantalizing possibility that regioselective reduction of the imine intermediate might be topologically controlled on the mineral surface and lead to enantiomeric excesses.

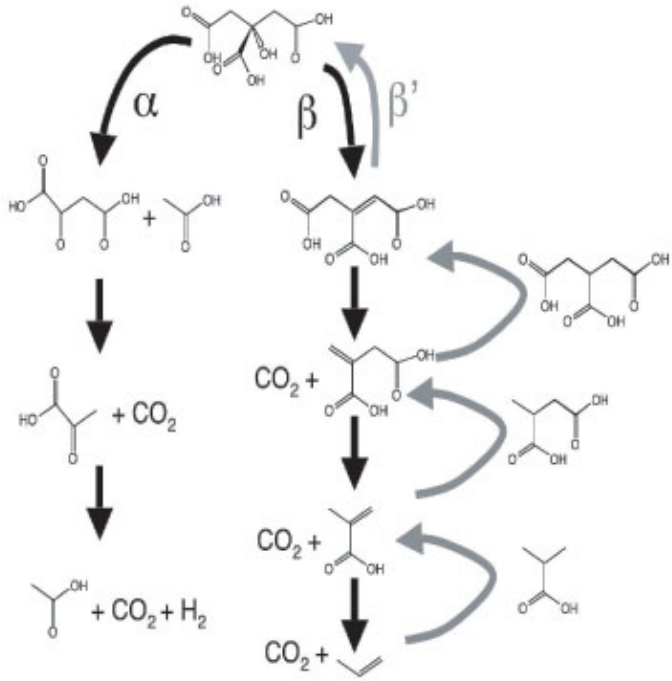

Figure 2. The principal degradative pathways of citric acid in hot water. Reaction pathway α mimics the branch point in the reverse citrate cycle, i.e., the retro Aldol reaction that leads to the formation of oxaloacetate and acetate. Oxaloacetic acid undergoes a facile decarboxylation to yield pyruvic acid and CO_2. Pyruvic acid undergoes an oxidative decarboxylation yielding acetic acid, CO_2 and H_2. A separate degradation pathway, ß , involves citric acid eliminating water to form aconitic acid, which undergoes a decarboxylation to form itaconic acid and CO_2 (note that itaconic acid exists in equilibrium with two other unsaturated isomers as well as the hydroxylated dibasic acid, citramalic acid). Itaconic acid decarboxylates to yield methacrylic acid and CO_2, which in turn can decarboxylate to form propene. Abiotic reversal of the α pathway does not appear probable. However, under reducing conditions and in the presence of effective catalysts (such as NiS) a pathway, ß ', exists that can plausibly lead from propene up to citric acid.

The team has been extensively exploring a range of reaction conditions that might be favorable for the transformation of citric acid to aspartate and alanine. They have found that alanine synthesis is highly favorable, but aspartate synthesis is not. Evidently the rate of decomposition of oxalacetate to pyruvate occurs too rapidly to favor reductive amination. They have found only one set of conditions that produce trace quantities of aspartate. These difficulties aside, they discovered other reactions that were unanticipated and may be of importance to prebiotic chemistry. Toward this end they are now refining their understanding of the reaction space through numerous (hundreds to date) experiments of varying T, P, and composition.

In addition to these experiments they completed the synthesis of ^{34}S–labeled metal sulfides to explore the extent of sulfur exchange accompanying hydrothermal reactions with alkyl thiols. In particular they are focusing on the metal–sulfide–promoted synthesis of citric acid, wherein a number of thiol intermediates form via a redox reaction with the metal sulfide. Cody and colleagues intend to explore further metal–sulfide–catalyzed reductive amination reactions, and they are particularly interested in identifying metal sulfide phases that will promote this reaction at lower temperatures. If they can obtain reasonable yields of amino acids at temperatures less than 100 °C, there is a chance that any enantiomeric excesses formed via regioselective reductions on the catalytic surfaces could be preserved against the long–term probability of racemization.

Finally, the group has moved and re–installed the high–pressure flow reactor into their hydrothermal laboratory. This summer they will replumb the system and begin long–term studies using the flow reactor and fluorescent molecular probes to detect products at extreme dilution.

Highlights

- Sulfur fractionated by enzymatic catalysis has been harvested in the laboratory from living cultures of sulfur–metabolizing microbes and analyzed for ^{32}S–^{33}S–^{34}S.
- A model that describes the mass–dependent sulfur isotope fractionations for sulfate reducers and sulfur disproportionators has been developed that shows how microbes may have played a crucially important dual role in both preserving but also diluting anomalous sulfur isotope fractionations. As an agent of preservation, microbial enzymatic catalysis precipitates pyrite, a secure storage site for sulfur isotopes, but as an inhibitor, the full magnitude of isotope anomalies may not be preserved because of dilution.
- Many common transition metal sulfides have been shown experimentally to catalyze organic reactions in a manner that mimics the carbon fixation pathways adopted by acetogenic and methanogenic microorganisms.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Field Expeditions

Field Trip Name: Archean Surface Processes

Start Date: 23 June 2004	***End Date:*** 2 July 2004
Continent: Africa	***Country:*** South Africa
State/Province: Mpumalanga	***Nearest City/Town:*** Barberton
Latitude: 25° 47'S	***Longitude:*** 31° 03'E
Name of site(cave, mine, e.g.): Barberton Greenstone Belt	***Keywords:*** early Archean geology

Description of Work: Field trip organized by Don Lowe (Stanford University) and Gary Byerly (Louisiana State University) and sponsored by NAI. Objective was to explore geology and geochemistry of the early Archean in the context of evolution of early life.

Members Involved:

Project Report: Prebiotic Molecular Selection and Organization

Project Investigators: ***David Deamer , Robert Hazen , Andrew Steele***

Project Progress

Life emerged on Earth as a geochemical process, the consequence of ancient interactions among rocks, water, and gases. More than a half–century of research has demonstrated the facile synthesis of biomolecules in many prebiotic environments, from deep space to Earth's deep interior. However, the processes by which that diverse prebiotic collection of molecules were selected, concentrated, and organized into the essential macromolecules of life constitute a significant gap in our understanding of life's origins. During the past year our studies of prebiotic molecular selection and organization have focused on two aspects of this history: (1) molecular self–organization, and (2) molecular selection and organization on mineral surfaces.

1. *Molecular Self–Organization*

   Lipids. Deamer, Hazen, and colleagues continued their studies of amphiphile self–organization with investigations of the self–assembly of molecules produced when an aqueous solution of pyruvate is subjected to high–pressure (to 400 MPa) and temperature (to 300°C). The group observed facile amphiphile synthesis and subsequent self–assembly of products that mimic those from carbonaceous chondrites and vacuum–ultraviolet (UV) experiments (Figure 1).

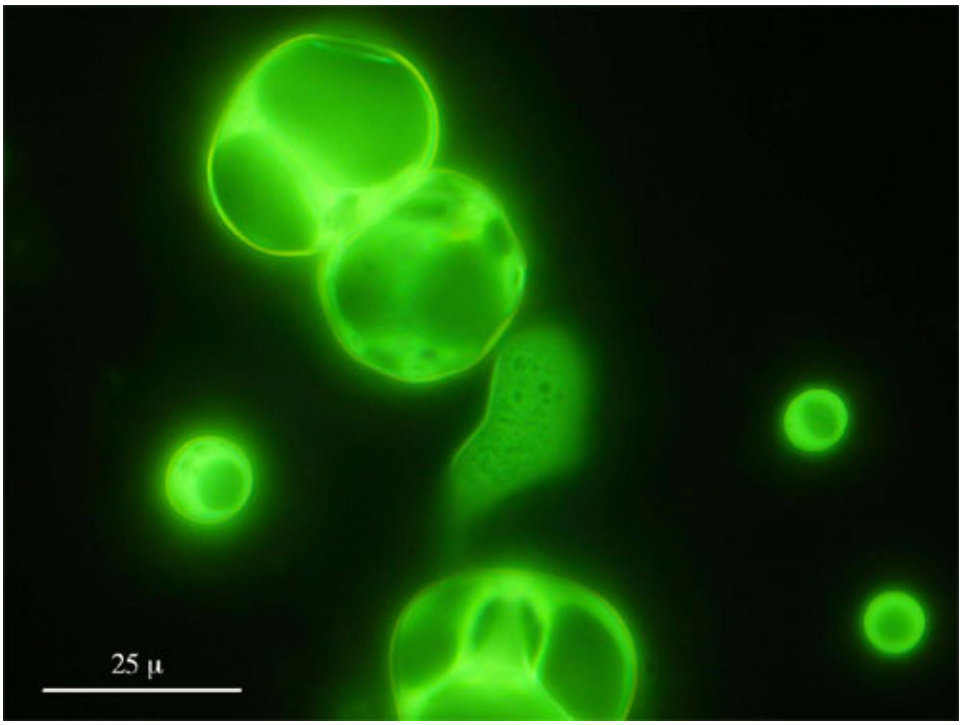

Figure 1. A key step in life's origin is the selection and organization of macromolecular structures from an aqueous solution. Deamer and Hazen have demonstrated that when a drop of pyruvic acid hydrothermal products is placed in a phosphate–buffered (pH = 8.5) aqueous solution, amphiphile molecules self–assemble into fluorescent vesicles in the size range 5 to 50 microns. Photo by David Deamer.

The "PAH World." In a related effort, Carnegie Predoctoral Fellow Nicholas Platts (Renssalaer Polytechnic Institute) proposed a novel hypothesis, dubbed the "PAH world," related to prebiotic molecular selection and organization. He suggested that the chemical behavior of polycyclic aromatic hydrocarbons (PAHs) provides a plausible solution to a central problem in origin–of–life science: the link between the dilute prebiotic mixture of small molecules on the one hand, and the formation of molecules with capacity to carry genetic information on the other. In his proposal the dilute "prebiotic soup" contained abundant PAHs, which could have spontaneously self–assembled into stacked, or discotic, arrangements. Under this scenario, PAH molecules of roughly similar size and shape stack one above the other, thus bringing their edges into approximate alignment. Lateral and rotational relative motions of individual stacked PAH molecules would effectively select a random distribution of small, flat, edge–bound molecules (i.e., the nucleotide bases) from the random aqueous environment (Figure 2). This proposed "PAH world" logically precedes the "RNA world" for the origin of life. The model makes a sequence of testable predictions related to the self–assembly of derivatized PAHs, the chemical selectivity for edge–bound bases, and the subsequent oligomerization of these units. Experiments to test these predictions are underway.

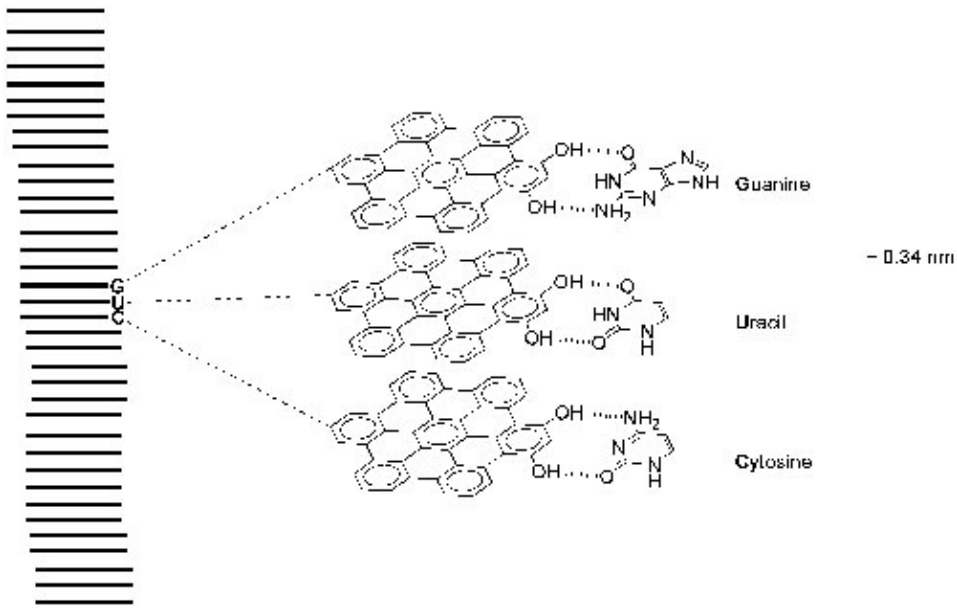

Figure 2. This diagrammatic figure conveys the essential features of the "PAH world" hypothesis of Platts and others. Three prebiotic nucleobases are shown hydrogen bonded to hydroxy functions in the edge structures of some derivatized and neighboring PAH molecules, which are themselves disposed in a stacked and discotic array. The exemplar polynuclear aromatic compound being envisaged here is 1,3–dihydroxy hexa– *peri* –hexabenzocoronene ($C_{42}H_{18}O_2$). The hydroxy functionalities are merely meant to be illustrative of the general chemical principle of derivatization at the edges of PAH molecules; other types of organic functionalization/derivatization (*e.g.*, –COOH, C=O) are certainly possible, especially given the typical productive richness of organic photochemistry. The PAHs shown here are partially hydroxylated, and are thus also partially oxidized relative to the parent aromatic hydrocarbons. The interplanar (*i.e.*, inter–PAH) spacings would be expected to be approximately 0.34 nm (*cf.* 0.335 nm in graphite, and the 0.34–nm inter–residue helical rise in the B crystallographic form of DNA). The three nucleobases are being shown in their keto tautomeric forms (*i.e.*, with protonated ring nitrogens), so as to be consistent with the seemingly reasonable assumption that prebiotic Hadean (*i.e.*, > ca. 3.85 Ga) surface and rain waters were probably acidulous [*e.g.*, an otherwise inert Hadean atmosphere with a $P_{CO_{2(g)}}$ of 0.10 bar (*i.e.*, ~271.0 PAL $CO_{2(g)}$) would equate to pH ~4.4 (298.15 K) for rain/surface waters]. The keto tautomers bear the pro–glycosidic purine and pyrimidine secondary amine nitrogens (*i.e.*, the NH functions at N(9) and N(1), respectively) disposed outwards, and thus chemically accessible, to the surrounding solution. The derivatized PAH edge structures effectively represent something of an electronic phase boundary between the discotically arrayed aromatic cores of the PAHs and the surrounding aqueous media of Darwin 's "warm little pond." The phenomenon of life can thus be seen as deriving from what is effectively a phase separation between the discotic aromatic cores of the PAHs *versus* the surrounding aqueous based phase. It seems probable to us that the essentially regular ($2p_z$)

inter–base plane–parallel spacing distance of 0.34 nm was inherited by molecular biology as a chemical memory of this unique mode of origin, and that this structural molecular fossil has been conserved in the essentially semi–discotic dispositions of the heterocyclic bases in the secondary and higher order structures of extant nucleic acids.

2. *Molecular Selection and Organization on Mineral Surfaces*

Selection of Amino Acids. Of special interest are the mechanisms by which molecules are selectively adsorbed from an aqueous solution. Hazen and colleagues characterized the surfaces of calcite, quartz, and feldspar using atomic force microscopy and demonstrated that maximum adsorption of amino acids occurs when the mineral's point of zero charge and the amino acid's isoelectric point differ significantly. They also initiated a project to model molecule–crystal interactions from first principles with density functional theory.

Chiral Selection. One of life's most striking biochemical characteristics is its preference for chiral, or handed, molecules. All known cells use predominantly left–handed amino acids and right–handed sugars, for example. However, all prebiotic synthesis pathways yield equal amounts of left– and right–handed molecules. A key step in understanding the origin of life, therefore, is how the chiral selection process occurred.

Hazen, Asthagiri, Maule, and Steele continued investigations of the possible roles of chiral mineral surfaces, which are ubiquitous in nature. They began a systematic characterization of the most common chiral surfaces of rock–forming minerals, including quartz, calcite, feldspar, pyroxene, and amphibole (Figure 3). They found that surfaces featuring both positive and negative charge centers, including calcite, pyroxenes, and feldspars, have a greater intrinsic ability to adsorb selectively left– and right–handed molecules from solution.

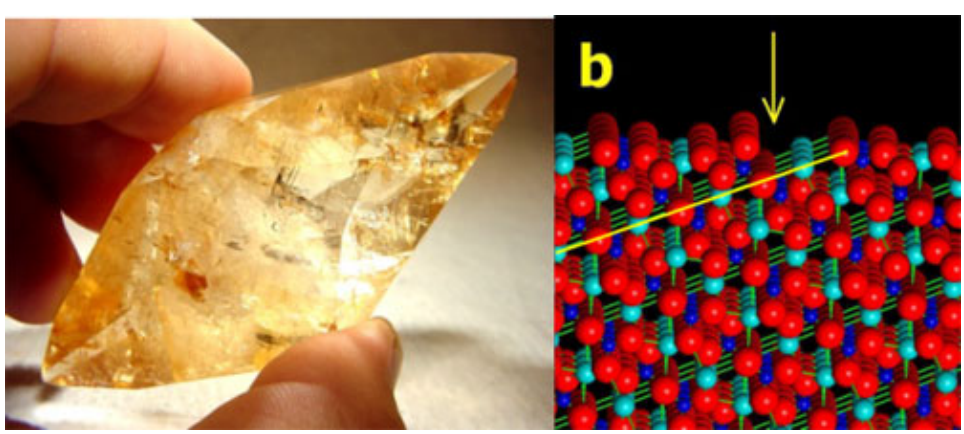

Figure 3. A distinctive characteristic of life is handed, or "chiral," amino acids, but how did life select for these molecules? The common rock–forming mineral calcite ($CaCO_3$) often displays chiral crystal faces. These handed surfaces have the potential to adsorb selectively left–

and right−handed molecules. The atomic structure of these faces (b) reveals irregularities that provide binding sites for molecules (from Hazen, 2004).

In an important new direction, they applied DNA ChipWriter/ChipReader technology to study the adsorption of chiral molecules on a variety of mineral surfaces. They decorated mineral surfaces with small droplets of various solutions. Initial results demonstrate strongly selective adsorption of some chiral amino acids onto quartz and calcite crystal surfaces.

These results point to a viable mechanism for the prebiotic selection, concentration, and ordering of chiral molecules. The new data, furthermore, are proving of great interest to the pharmaceutical industry. The often−difficult chiral separation of molecules costs consumers billions of dollars annually, and mineral surfaces point to new strategies for the safe and efficient chiral purification of drugs.

Highlights

- Deamer and coworkers demonstrated facile self−assembly and vesicle formation of amphiphiles produced from hydrothermal reactions of pyruvate
- Platts devised a novel hypothesis, dubbed the “PAH world,” by which polycyclic molecules self−assemble into stacks and then selectively bind to purines and pyrimidines (the bases of nucleic acids). This hypothesis provides a plausible chemical link from the random prebiotic “soup” to the RNA world.
- Hazen and coworkers determined that electrostatic interactions dominate the selective adsorption of amino acids by mineral surfaces.
- Hazen and colleagues identified and characterized more than a dozen common chiral mineral surfaces with the potential for prebiotic selection of chiral molecules.
- Maule and coworkers successfully applied DNA ChipWriter/ChipReader technology to the study of molecular adsorption on mineral surfaces.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Project Report: Life in Extreme Environments

Project Investigators:	John Baross , George Cody , David Emerson , Marilyn Fogel , Erik Hauri , Russell Hemley

Project Progress

Our team is interested in examining (1) the diverse mechanisms utilized by life to survive extremes of temperature, pressure, salinity and nutrient limitation, (2) the response of life to fundamental changes in the properties water, and (3) how the unique biochemistry associated with extremes can be used for life detection.

1. Life in Deep−Sea Hydrothermal Vents

The astrobiology research objectives of Co−Investigator John Baross and his group are focused on understanding the microbial ecology of the subsurface at hydrothermal vent environments. His research group is also interested in examining the microbial communities that colonize in crust that is millions of years old, and the role that microbial/mineral associations in these environments have on the growth and survival of microorganisms under the most extreme temperature and pH conditions found in vent environments. During the past year a study in subsurface environments at volcanically active sites on the Juan de Fuca Ridge has been launched that has utilized a range of molecular techniques. These approaches allowed Baross's group to isolate and characterize bacteria unique to these hot environments. Among the novel groups of microorganisms isolated were organisms that can fix carbon dioxide anaerobically utilizing hydrogen and sulfur as reductants. These organisms also form biofilms on mineral surfaces and produce copious amounts of exo−polysaccharides as part of the biofilm process. These organisms, which use a novel, and yet characterized, metabolic pathway for carbon dioxide reduction, are believed to be key components of the primary producers in these environments. Other organisms isolated from these environments include a new genus of thermophilic, anaerobic iron reducers that couple iron reduction with the oxidation of simple organic acids and four new species of halophilic bacteria that are uniquely adapted to grow at high salinities and high pressures. It was also found that a very high diversity of the subsurface microbial community has the capacity to fix gaseous nitrogen using genes referred to as nifH. Some of the nifH gene sequences from these environments are unique and point to a much higher diversity of nitrogen−fixing archaea than previously

reported. These results are important because other forms of nitrogen such as ammonia and nitrate are present in low concentrations or at non−detectable levels in these environments. The subsurface associated with hydrothermal systems harbors a diverse microbial community that includes organisms that have novel metabolic and physiological traits that allow for growth in the absence of nutrients derived from photosynthesis.

Baross's research group recently completed a study of the microbial community in a subseafloor environment at Baby Bare Seamount, a well−described basaltic outcrop located on 3.5−Ma oceanic crust in the northeast Pacific. Using a new sampling technique that involved piercing stainless steel darts into the crust, they were able to collect crustal fluid that was not contaminated with seawater. Preliminary culture and molecular phylogenetic data show the presence of a small but active microbial population dominated by bacteria including thermophiles. This microbial community is different from subseafloor communities near hydrothermal vents and includes unique groups not found in seawater or sediments.

The Lost City hydrothermal field represents a new type of submarine hydrothermal system driven by exothermic chemical reactions in ultramafic oceanic crust and not as the result of the cooling of magma. Lost City hydrothermal field is hosted on 1.5−Ma ultramafic oceanic crust approximately 15 km from the axis on the Mid Atlantic Ridge. The analytical results from samples gathered during cruises in December of 2000 and May of 2003 show that the physical conditions come together to form a hot, highly reducing, alkaline environment. Furthermore, this environment produces high concentrations of hydrogen, methane, and other low−molecular−weight hydrocarbons. The highly alkaline fluids cause the precipitation of seawater carbonate that results in the formation of massive carbonate chimneys on the seafloor. The microbial communities associated with these carbonate structures were dominated by a single group of methane−metabolizing archaea. The predominant phylotype, related to the Methanosarcinales, formed tens of micrometer−thick biofilms in regions adjacent to hydrothermal flow. These results are in contrast to the extremely high diversity of bacteria and archaea found in active, hot sulfide structures. These findings expand the range of known geological settings that support biological activity to include submarine hydrothermal systems that are not dependent upon magmatic heat sources. The early history of Mars may have included liquid water and exposures to ultramafic rocks that would have favored geochemical processes similar to those at Lost City. It should be noted that the recent discovery of atmospheric methane and the confirmation of hematite and other iron−bearing minerals on Mars indicates that the conditions for such processes to occur on Mars are present.

2. Stress Adaptation on Microorganisms and Expansion of Habitability

The research of Co−I Scott and colleagues is focused on understanding the response of life to extreme−pressures (> 0.3 Gpa) and a variety of temperatures. Their initial work focused on the ability of two piezo−sensitive bacteria, *Shewanella oneidensis* MR1 and *Escherichia coli*, to survive at pressures at which water undergoes fundamental changes in its ability interact

with organic material, and to stabilize non−covalent interactions such as hydrogen bonding and van der Waals interactions. Van der Waals interactions or forces are temporary fluctuating dipole and dipole−dipole interactions that cause attractions between individual molecules. Because of water's polar nature, it plays a key role of mediating van der Waals interactions and hydrogen bonding between biological materials. These interactions are profoundly affected by changes in the ordering properties of water due to phase transitions.

Both *Shewanella* MR1 and *E. coli* were able to survive in a phase stability field imposed using diamond anvil cells (DAC) designed and manufactured by the high−pressure group at the Carnegie Institution of Washington (CIW). DACs have become a ubiquitous method for imposing pressures on minerals approaching those observed at the center of the planet. Unlike traditional cold−seal pressure systems and pressurized growth vessels, DACs allow real−time observation and interrogation by a range of microscopic and spectrometric techniques. The group demonstrated the utility of using the DAC as a way of examining the effects of GPa−pressures on *Shewanella* MR1 and *E. coli*. For example, they showed through Raman spectroscopy that formate oxidation by *Shewanella* MR1 continued after cells were exposed to pressures above 1 GPa. Furthermore, because of their transparency, DACs provide an ideal optical platform for microscopic examination. The group is developing a range of techniques utilizing epi−fluorescent dyes (Figure 1) to examine the viability and metabolic activity of cells at pressures where water can form dense ices (e.g., ice−VI and ice−VII) at temperature well above 4°C.

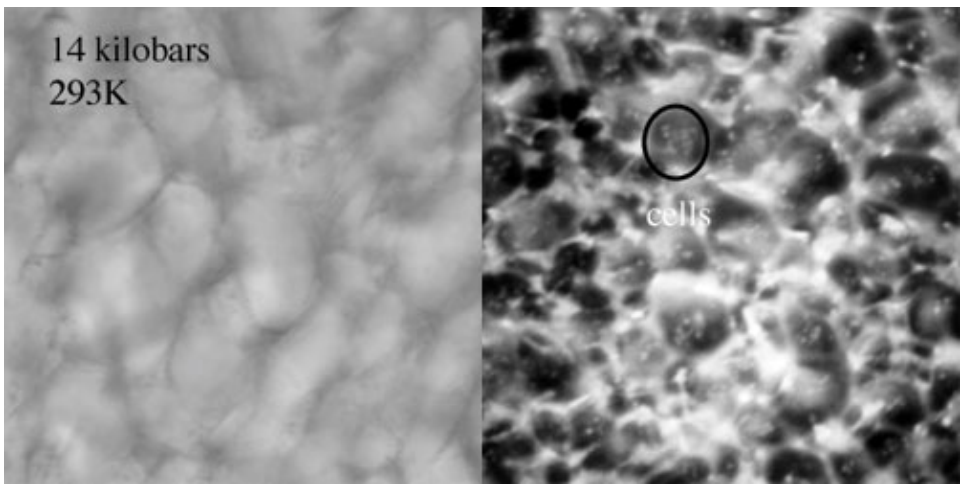

Figure 1. Co−I Scott and his colleagues are developing fluorescent assays that will allow them to visualize intact and viable cells. On the left is a field of high−density ice−VI examined by simple light microscopy at a magnification of 450x. On the right is a contrasting panel of the same ice field examined using the epi−fluourescent DNA−dye DAPI (4, 6−Diamidino−2−Phenylindole), which binds to AT base pairs of DNA by electrostatic interactions. These assays allow them to visualize and identify intact cells under eutectic conditions.

Co−I Hemley and colleagues are developing DACs that can hold larger volumes to allow the recovery of cells and other biological materials after exposure to GPa pressures. Scott is presently developing techniques for

measuring the metabolic activity of cells while in the DAC and for the recovery and culturing of cells when grown at pressures where ice−VI and ice−VII are formed. He has been able to recover and culture *E. coli* cells exposed to pressures between 0.3 and 0.4 GPa in one of several cold−seal pressure systems at CIW (Figure 2). He and his collaborators are at the initial stages of utilizing genomic arrays to examine gene expression in *E. coli* and *Shewanella* in response to the extreme conditions in an environment where ice−VI and ice−VII are stable. As part of this goal Scott was a collaborator and co−author on the recently completed sequencing of *Shewanella* MR1's genome. During the past year there has been an effort to develop the molecular and other tools to determine if there are genes that are preferentially expressed in response to changes in pressure.

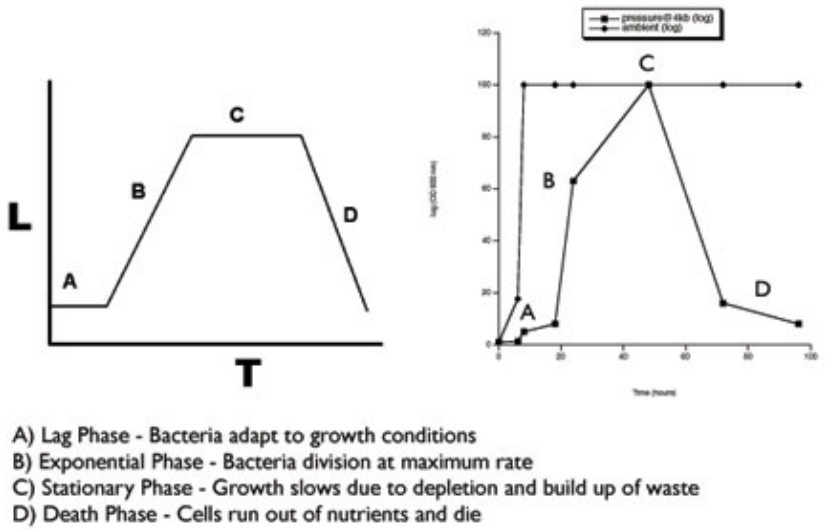

Figure 2. Characteristic pattern of growth, stasis, and death of bacteria at high pressure. At right is an illustrative experiment in which the cellular density of E. coli in Luria broth at 0.4 GPa was monitored by means of the optical density of light at 600−nm wavelength as a function of time at pressure. At left is a schematic view of the stages in this and similar experiments. A denotes a lag phase, during which bacteria adapt to growth conditions after onset of pressure. B denotes an exponential phase, characterized by bacterial division at a high rate. C denotes a stationary phase, during which growth slows due to depletion of nutrients and build−up of waste. D denotes a death phase, when cells run out of nutrients and die. These stages are labeled in the experiment at right.

Despite speculation that ice−VI and −VII may be stable in deep subduction zones it is very likely that there are no ecosystems on the modern Earth where an ice−VI and −VII zone can be found. However, the subsurface of the Jovian satellites, in particular Europa, likely contain zones where ice−VI and −VII are plentiful. This work, therefore, may provide insight into the nature of habitability deep within such a body. It has been suggested that organic veins in ice−VI on

a young Solar System body might have facilitated life arising in a cold icy organic soup by concentrating prebiotic solutes and decreasing the kinetic barriers to advantageous reaction pathways. However, most laboratory work in support of this idea was done at the eutectic where ice−Ih is formed at ambient pressures. Under such conditions there is a significant kinetic barrier due to the low temperatures. By doing the experiments at the eutectic where high densities such as ice−VI and −VII are formed, the activation energy for the formation of the biologically useful macromolecules such as amino acids is significantly reduced. Scott is presently designing experiments for examining the kinetics of reaction mechanisms for forming amino acids and organic molecules at such conditions.

3. Iron−based Metabolic Strategies for Microbial Life

Iron isotopes in natural samples exhibit a range of compositions, plausibly reflecting abiotic equilibrium exchange reactions and kinetic effects, as well as mediated chemistry by microbial activity. Having developed a technique to measure precisely the stable isotope variations of Fe using cold plasma ICP−MS, Co−Is Hauri and Emerson have continued to examine samples from specific settings in which Fe isotopic fractionation may occur. Their work presently focuses on Fe precipitated in bacterial mats near hydrothermal vents on the Loihi seamount near Hawaii collected by Emerson during several field expeditions.

Emerson and colleagues previously identified lithotrophic Fe−oxidizing bacteria in Fe−oxide−rich colonies around hydrothermal vent sites on the Loihi summit. Although some of the Fe oxides present may result from abiotic oxidation of ferrous Fe in the vent water, the morphologies of the precipitated Fe oxides strongly suggest at least partial microbe−induced Fe oxide deposition. Ongoing Fe isotope measurements of bulk precipitates show –0.2 ‰ < δ^{56}Fe < +0.5 ‰ (Figure 3). These values are well within the range of fractionations measured in both natural abiotic precipitation of ferrihydrite from aqueous ferrous iron and equilibrium fractionation between ferrous−iron and ferric−iron−bearing compounds in the laboratory. The four marginally isotopically light samples (which are essentially indistinguishable in composition from the terrestrial basalt standard, within uncertainties) possess the highest fraction of amorphous Fe oxide precipitate compared with non−amorphous morphotypes. In contrast, the isotopically heavy mats tend to possess larger fractions of sheath and filament morphologies, whose structures are presumed to result from precipitation reactions mediated by microbial activity. The meaning of this tentative association is unclear, but it could represent a connection between isotopic composition and the degree of microbial Fe processing in the mats. In addition to further characterizing the range of Fe isotope compositions in the Loihi samples, Co−I Scott and colleagues continue to explore connections between isotopic composition and markers of biological activity. Since any extant or past life would have interacted with the iron cycle of the planet, iron isotope fractionation is of interest as a potential biomarker in the search for evidence of past and present life on Mars.

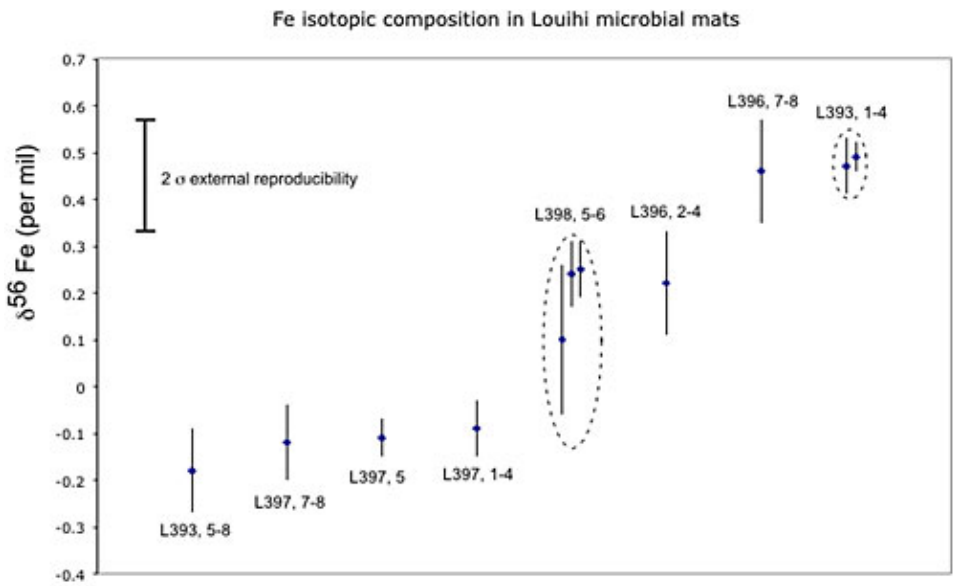

Figure 3. Fe isotopic compositions of microbial mats from the Loihi seamount relative to the Kil1919 Hawaiian basalt standard. Replicate analyses are grouped with a dashed oval. Error bars represent the 2–sigma in–run statistical uncertainties. External reproducibility is indicated by the error bar on the upper left.

A parallel project by Co–I Emerson involves the source of carbon for neutrophilic Fe–oxidizing bacteria that grow under microaerobic conditions. While this should be a relatively trivial exercise, for these Fe–oxidizers it has not been so. Circumstantial evidence, growth in very oligotrophic environments, has always suggested that they are autotrophs; furthermore, acidophilic Fe–oxidizers are known autotrophs. Standard ^{14}C–uptake assays suggest that Emerson's strains are autotrophs; however, cell yields are also low, and signals are weak. To confirm autotrophy, he has carried out stable isotope ^{13}C–uptake studies with Co–I Fogel. Results for the Fe–oxidizers using this assay have consistently been negative for autotrophy. A number of different controls have worked appropriately. One finding from this work is the Fe–oxidizers appear to require certain amino acids for growth, suggesting that these could be their source of carbon. However, feeding them with labeled amino acids yielded negative results. Further investigation suggests that amino acids may have been exerting a small buffering effect, which may have enhanced growth. The question remains unresolved, but another round of experiments is underway to solve this riddle.

In collaboration with George Luther's group at the University of Delaware, Emerson used nonselective microelectrodes that employ scanning voltammetry to measure iron species. This work has shown that ferrous iron is required for growth and has allowed the team to measure Fe oxidation rates more precisely than has been done before. The group has also made field measurements on *in situ* ferrous iron concentrations and iron ligands. An interesting finding from this work was a novel form of FeS that appears to exist in the natural habitat. Greg Druschel, formerly a postdoctoral researcher in Luther's lab, was able to synthesize and further characterize this compound.

An ancillary project in Emerson's laboratory, not supported by NAI but of general interest, is the development of two rapid, universal methods for aiding in the identification of archaea. One of these is a phenotypic method that uses whole cell maxtrix−assisted laser desorption/ionization time−of−flight mass spectrometry (MALDI−TOF−MS) to compare mass spectral patterns of cell wall components. This method requires a minimum of cell preparation beyond growing the cells, is rapid and accurate, and yields strain−level differentiation. The other method is the use of repetitive primer PCR (repPCR) to genotype archaea. This procedure, available as a kit from Bacterial Barcodes (which Emerson helped to optimize), works well for strain−level differentiation.

Highlights

- Bacterial groups were discovered that are unique to the hot environments of mid−ocean ridge hydrothermal vents and include new groups of microorganisms that can fix carbon dioxide in the absence of oxygen with hydrogen and sulfur.
- The Lost City hydrothermal field represents a new type of submarine hydrothermal system driven by exothermic chemical reactions in mafic oceanic crust and not as the result of cooling magma.
- Laboratory experiments have demonstrated that microbes are able to survive at pressures where ice−VI is observed.
- Diamond anvil cells are being designed to allow manipulation of cells and organic material after exposure to extreme pressures.
- A possible connection has been uncovered between the isotopic composition of Fe and the degree of microbial Fe processing in Fe−bearing bacterial mats.

Roadmap Objectives

- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

Field Expeditions

Field Trip Name: Loihi Seamount	
Start Date: December 2003	***End Date:***
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Study Fe−mats associated with hydrothermal venting. Mat speciments were brought back for comparative analysis with samples collected previously.	
Members Involved:	

Field Trip Name: Soufriere Hotsprings/Volcano	
Start Date: June 2004	***End Date:***
Continent:	***Country:*** St. Lucia, West Indies
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Sample collection; results yielded abundant evidence for neutrophilic Fe−oxidizing bacteria growing at 50°C.	
Members Involved:	

Field Trip Name:	
Start Date: May 2003	***End Date:***
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Participated on 4 cruises to submarine hydrothermal vent environments and to seamounts on old oceanic crust. The vent cruises were at the Lost City peridotite−hosted hydrothermal environment at the Mid−Atlantic Ridge, the Axial Volcano site on the Juan de Fuca Ridge, and the "Pacific Rim of Fire" cruise that studied volcanoes along the Pacific Rim and particularly at subduction zones. A seamount in the NE Pacific called Baby Bare was sampled last summer using stainless steel darts that penetrated into the crust to obtain crustal fluids. Baby Bare was recently discovered to be a recharge site where seawater penetrates into the crust, one of the first to be discovered.	
Members Involved:	

Cross Team Collaborations

John Baross and his group (University of Washington) are discussing possible collaboration with Mitch Sogin and the NAI team at the Marine Biological Laboratory to look at genomic and functional diversity in subsurface environments associated with hydrothermal vents.

James Scott is collaborating with Antonio Salgado Serrano (Centro de Astrobiologia) and with Gene McDonald and Kenneth Nealson (formerly of the NAI team at JPL).

David Emerson has collaborated with Jill Banfield (Berkeley NAI team).

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: Carnegie Institution of Washington

Project Report: Biosignatures and Abiosignatures

Project Investigators:	***Conel Alexander , David Emerson , Marilyn Fogel , Robert Hazen , James Scott , Noreen Tuross***

Project Progress

1. Preservation of Molecular Biosignatures

Rare samples from the Upper Oligocene Enspel Formation in Germany have previously been shown to contain exceptionally well−preserved bacterial fossils. These bacterial fossils are associated with macrofossils such as fish and tadpoles, where they replaced the soft tissues of those organisms while degrading the original organic matter. In some cases, the bacterial biofilms are sufficiently substantial that milligram quantities can be separated from the rest of the fossils and the sedimentary matrix. This distribution implies that molecular biomarkers can be studied in direct association with the morphological fossils, allowing insights into quasi−*in situ* biomarker formation. The fossil biofilms contain up approximately 50% total organic carbon and approximately 7% nitrogen. Initial studies by Co−I Steele and Postdoctoral Fellow Jan Toporski using time−of−flight−secondary ion mass spectroscopy (ToF−SIMS) have suggested that molecular biomarkers are directly associated with the bacterial fossils. To test this observation we conducted standard gas chromatography−mass spectroscopy (GC−MS) experiments on a sample where sufficient biofilms material could be separated from the sediment. For comparison, a sample from the sedimentary matrix was also analyzed. The materials were extracted using dichloromethane and methanol mixtures assisted by sonication. The extracts where then separated into six different fractions (e.g., aliphatic, aromatic, ketone, alcohol, organic acids) by silica column separation using organic solvents of different polarities and prepared for GC−MS analyses.

Preliminary data analysis of the first fraction, the aliphatic fraction, shows that there are distinct compositional differences between the biofilms and the sediment. This inference is based on three observations: the distribution of the n−alkane fraction, the presence of branched alkanes in the biofilms that are not present in the sediment, and the composition of the hopane/hopene fraction of both samples. ToF−SIMS investigation of the distribution of the biomolecules in each of the extracted samples is continuing.

Laboratory investigations of the experimental silicification and fossilization of microorganisms and viruses are being carried out in parallel. Microorganisms chosen for these experiments include *Escherichia coli* strain K−12, *Bacillus subtilis*, and *Pseudomonas putida* MnB1, as well as the filamentous bacteriophage M13. The purposes of this work are to explore potential biomarkers remnant from the fossilization process and to follow the degradation of biomarkers over time. A thorough understanding of the degradation of biomarkers over time can yield important information about what to look for in the ancient geological record, and potentially on other Solar System bodies. To date, these studies have focused on morphological studies of microorganism degradation over time (Figure 1), degradation of DNA over time with exposure to a silicifying or fossilizing solution, microbial viability with exposure to a silicifying or fossilizing solution, biomineral formation, RNA degradation over time, and changes in protein expression over time with exposure to a silicifying or fossilizing solution.

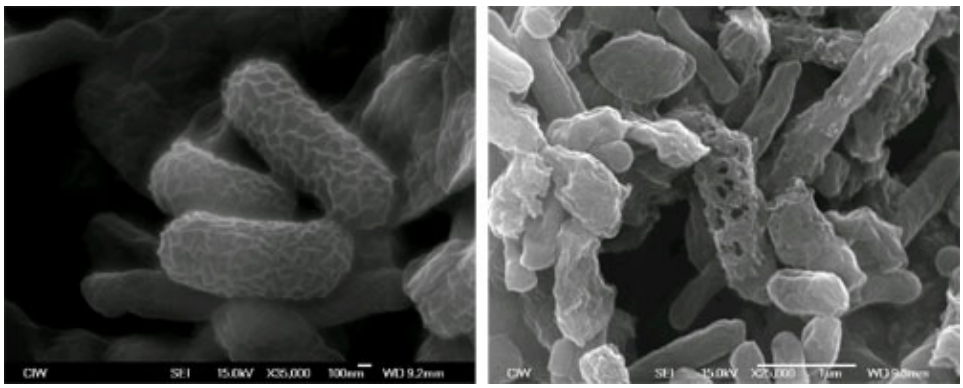

Figure 1. Scanning electron microscope images of *E. Coli* display morphological degradation during experimental silicification. The image to the left is of *E. Coli* after 3 days of exposure to 3000 ppm SiO_2. The image on the right is of *E. Coli* after 31 days of exposure to 3000 ppm SiO_2 . This contrast highlights the considerable morphological changes to the cells that occur during exposure to Si. SEM images by Rachel Schelble.

2. Stable Isotope Biosignatures

The stable C, N, O, and H isotopic compositions of a wide variety of rocks, organic materials, and living organisms are being systematically analyzed to establish the temporal and global variation in biologically−produced isotopic signatures in order to establish statistical criteria distinguishing biological from abiological signatures.

Co−I Fogel and her group have analyzed the stable C, N, O, and H isotopic compositions of a large number of Precambrian rock samples. Among these are ancient black shales, quartzites, and cherts from early Precambrian localities in western Australia sampled by collaborator John Lindsay of NASA Johnson Space Center. Postdoctoral Fellow Andrey Bekker has been conducting organic carbon analyses of Archean carbonates collected from Siberia that contain unusually heavy C isotopic ratios of +28‰. For these analyses the group developed a modified method to dissolve bulk carbonate with ultra−clean acid directly in a silver sample analysis tube. Postdoctoral

Fellow Shuhei Ono concentrated on the isotopic analysis of early Precambrian charts and shales obtained during a field trip to the Barberton formation in South Africa. Princeton University graduate student Bianca Mislowack analyzed the N abundances and isotopic content of deep subsurface rocks collected as part of a larger NAI project in collaboration with her advisor, Tullis Onstott, a member of the Indiana NAI team. These rocks contain extremely low N contents, raising critical questions as to how they sustain deep crustal microbial life. Co−I Hazen has been analyzing a suite of Precambrian stromatolite samples for carbon content and isotopic composition to determine whether the carbon is biogenic. The product of all of these efforts will ultimately be a substantial database of early Precambrian isotopic biosignatures.

In collaboration with Hans Amundson of University of Oslo, Fogel and Steele are exploring biosignatures in volcanic rocks recently erupted on Svalbard, a potential Mars analog site. Organic carbon has been discovered in vacules contained within igneous rocks. This carbon has δ^{13}C values of –12 ‰; it is thus isotopically heavier than other local sources of organic carbon, e.g., surface lichen or microbes. It is currently believed that this organic carbon must be abiologically derived. The C and O isotopic values of co−existing carbonates in both large veins and within microscopic globules indicate that these carbonates must have precipitated from glacial meltwater. A second field trip to Svalbard is planned for the coming summer. In related work carried out with Postdoctoral Fellow Marc Fries, Fogel has analyzed the isotopic composition of Antarctic meteorites. This pilot study is intended to provide background material for a larger effort to study the signatures of terrestrial contamination of meteorites that occurs during their time in and on Antarctic ice.

Co−Is Scott and Fogel have been using compound−specific isotope ratio mass spectrometric analysis of amino acids to establish isotopic signatures of discrete metabolic pathways (Figure 2). This work has been extended to studying the isotopic signatures of amino acids derived from hydrothermal vent microorganisms and abiotically synthesized amino acids produced by Miller−Urey experiments. Co−I Scott has been analyzing hypolithic microbial communities from the Mojave Desert to determine whether there are unique biosignatures associated with life in extreme dry and hot environments. Postdoctoral Fellows Jennifer Eigenbrode and Shuhei Ono initiated experiments with Fe−oxidizing microbes cultured in Winogradsky columns in anaerobic chambers with a focus on simulating the atmospheric and surface chemical characteristics of the Hadean Earth. Carbon, nitrogen, oxygen, and sulfur isotopic biosignatures will be explored as functions of time and simulated environmental conditions. Postdoctoral Fellow Albert Colman initiated studies of phosphatic minerals from the Lost City hydrothermal vent field to determine whether there is evidence of an oxygen isotope biosignature in these minerals.

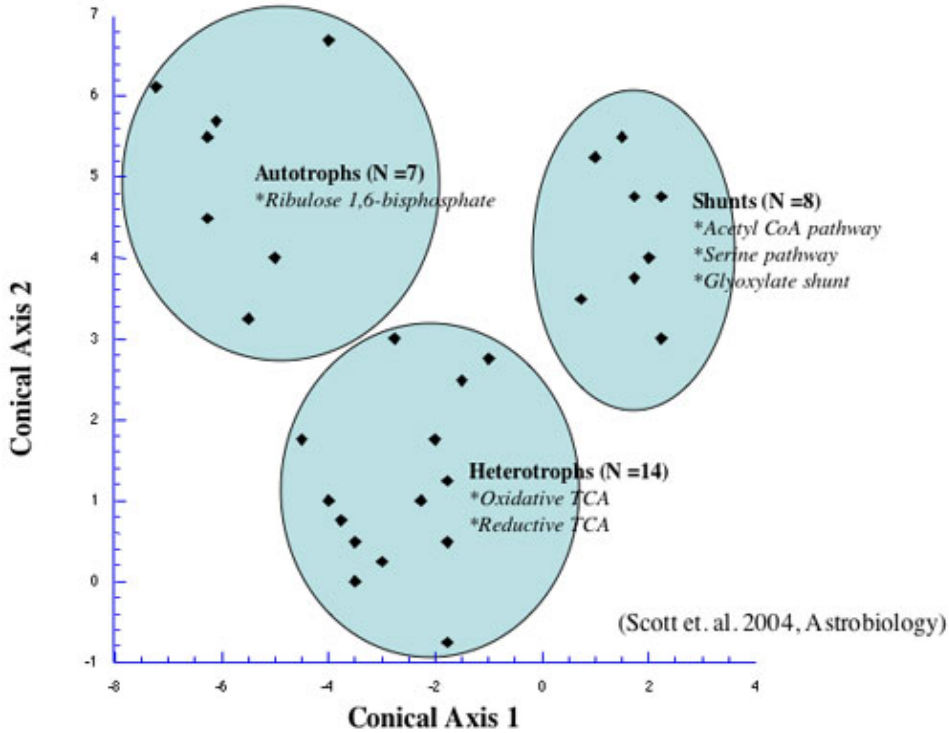

Figure 2. The δ^{13}C abundances of individual amino acids reveal functional relationships between different biosynthetic pathways utilized by prokaryotic organisms. When analyzed via discriminant function analysis, various discrete metabolic pathways can be distinguished in a two−dimensional variance representation of the correlation distances among eleven different amino acids. The conical axis 2 is dominated by the variance of the δ^{13}C of alanine with the δ^{13}C of amino acids that come directly from the TriCarboxylic Acid cycle (TCA) cycle. Conical Axis 1 is dominated by the relationship between the δ^{13}C concentrations of alanine and aspartic acid, where the degree of variance reflects differences in how the biochemical intermediates oxaloacetate, pyruvate, and alpha ketoglutarate are replenished for use by biosynthetic pathways.

3. Studies of Organic Compounds and Silicified Microbial Remains Associated with the Kamchatka Hydrothermal Region

A field trip to the silicified hot springs on the Kamchatka peninsula is planned for the late summer of 2004. The results from this field trip will be reported in the next progress report.

4. Scanning Transmission X−ray Microscopy and in situ Chemical Analysis of Organic Fossils

In March 2004 co−I Cody and colleagues traveled to the Advanced Light Source to learn how to use the scanning transmission X−ray microscope at beam−line 5.3.2. This is a state−of−the−art facility that allows for fine−scale (20−nm) spatial imaging utilizing soft X−ray absorption fine structure on the carbon, nitrogen, and oxygen K (1s) absorption edges. The group focused on the analysis of meteoritic organic matter, but in experiments planned for this fall they will focus on sub−micron−scale chemical analysis of ancient fossils. The

materials to be targeted involve relatively young fossils from the Enspel Formation in collaboration with Steele and Toporski, ancient fossils derived from Precambrian cherts in collaboration with Ono and Bekker, and Cambrian materials in collaboration with collaborators Andrew Knoll (Harvard University) and Kevin Boyce (University of Chicago).

Highlights

- Molecular analysis of biofilms from the Enspel Formation reveals that within the aliphatic fractions there are distinct compositional differences between the biofilms and the sediment.
- A substantial database of C, N, O, and H isotopic biosignatures from the early Cambrian is being developed.
- Compound−specific isotope ratio mass spectrometric analysis of amino acids suggests that discrete metabolic pathways may have distinct isotopic signatures.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Cross Team Collaborations

Co−I Fogel collaborates with John Lindsay (former NAI team at JSC); Bianca Mislowack, Princeton University (Indiana University NAI team); Hans Amundson (potential NAI international partner); and Pamela Conrad (former NAI team at JPL)

Co−I Cody collaborates with William Schopf and Andy Czaja of the UCLA NAI team.

Project Report: Astrobiotechnology

Project Investigators:	***Robert Hazen , Wesley Huntress , Timothy McCoy , James Scott , Andrew Steele , Ed Vicenzi***

Project Progress

The development of new technology to carry out *in situ* experiments to address astrobiological questions is an important goal of NAI, underscored this year by the formation of an Astrobiotechnology Focus Group. An early action by the Focus Group was to secure funding to hold a workshop at the Carnegie Institution of Washington (CIW) this fall (8–10 September 2004). Further activities of this focus group are provided in a separate report to NAI. Within the CIW team, efforts in astrobiotechnology have focused on several aspects of life detection instrumentation for remote missions to Mars and other solar system bodies.

1. Development of Flight Instrumentation

With support from the NASA Astrobiology Technology for Instrument Development (ASTID) program, Co–I Steele and his collaborators have initiated work on a prototype instrument to detect prebiotic molecules and biosignatures, the Modular Assays for Solar System Exploration (MASSE). In this past year prototyping was completed for microfluidic chips to lyse gram–negative, gram–positive, and archaeal cells (Figure 1), perform clean–up and concentration of targeted biomarkers, and inoculate these onto a protein microarray. This work is being undertaken at Marshall Space Flight Center (MSFC) by the Lab–on–a–chip Development (LOCAD) group. A prototype sample preparation system has been built and is currently being tested at CIW. Optical systems to interrogate the inoculated array have been prototyped and built and tested at Montana State University, and advanced concept designs have been conceived and are currently being fabricated. A final flight design is currently being developed by Oceaneering Space Systems of Houston.

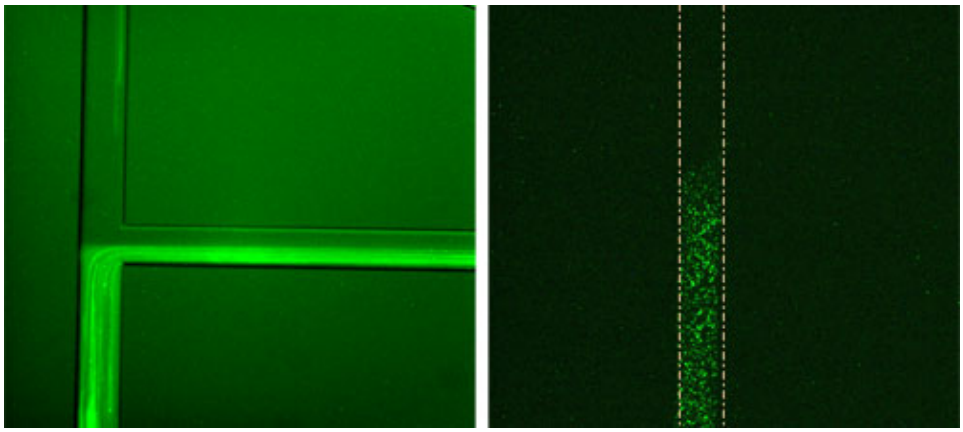

Figure 1. (a) Brightfield and fluorescence imaging combined to illustrate the NS145 chip T−junction and pathway of SYTO−9 stained *E. coli*. (b) Mixing of H. marismortui with the lysing agent Solution B causes complete lysis of the archaeal cell wall and a decrease in fluorescence.

The definition of protein microarray chips that contain antibodies to extinct and extant life biomarkers continued during the past year. The ability of an antibody microarray to search for hundreds of different biological molecules simultaneously, using only a few microliters of sample (all within an area of a few square millimeters on a glass slide), renders it an appealing method for *in situ* detection of “biomarkers” on the Martian surface. Largely used to investigate patterns of gene expression, this method has yet to be fully developed for microbial detection in geological samples. To test the suitability of antibody microarrays for such a purpose, we designed a microarray to detect two common bacterial antigens, lipopolysaccharide (LPS) and groEL (chaperonin 60). To evaluate possible effects of a geological sample upon the efficiency of antibody binding (e.g., changes in pH or high Fe_3^+), we spiked simulant Martian regolith with LPS, added directly to the microarray surface without filtering, showing that LPS−specific detection was not inhibited. A more complex microarray was then developed to detect eleven biomarkers (LPS, DNA, peptidoglycan, collagen, groEL, β−galactosidase, mycoplasma, K−99 pilus protein from *Escherichia coli*, free fatty acids, and nitrate reductase) in a single sample of simulant Martian regolith spiked with lyophilized *E. coli*. Further experiments including long−term monitoring of antibody stability over the time it takes to travel to Mars was instigated using a variety of active surfaces. Testing of antibodies to small molecules and fossil antigens continued, including antihopane and sterane antibodies and collagens within fossilized bones.

The group has also been testing rock crushers designed for flight onboard the Mars Science Laboratory mission. Testing for mineral carry−over from sample to sample has been completed, and testing for bacterial carry−over is being carried out by spiking basalt samples with *E. coli* and measuring the amount of cells left on the crusher after operation. The team is using real−time polymerase chain reaction (PCR), Limulus amebocyte lyase (LAL) test (supplied by N. Wainwright of the Marine Biological Laboratory), and adenosine triphosphate (ATP) assay. Results suggest that a small amount of carry−over occurs, but further testing is underway.

2. Laser−Induced Breakdown Spectroscopy (LIBS)

As a collaborative effort with Gregory Bearman of the Jet Propulsion Laboratory, Co−I Steele, Postdoctoral Fellow Fries, and others have investigated the use of laser−induced breakdown spectroscopy (LIBS) for astrobiology projects. They assembled a small LIBS device using a 337−nm N_2 laser. LIBS utilizes a focused laser pulse to ablate a small (~100−µm diameter) spot from a sample surface and excite that material briefly into a plasma. Since that plasma is effectively a small sample of the bulk material that is converted to a hot but rapidly cooling gas, the light emitted is effectively an atomic emission spectrum from the bulk material. This technique has been used to examine a sample of hot springs carbonate from a Mars analog location in Svalbard. The carbonate rocks are host to a photosynthesizing cryptoendolithic microbial community, which lives inside the rock at a depth of about a millimeter where it is protected from dessicating winds and ultraviolet radiation. LIBS was employed on this sample using both cryptoendolith−containing and heat−sterilized samples to test whether LIBS is useful to measure directly the presence and/or abundance of the organisms. It was determined that, for the small ultraviolet system used here, LIBS was unable to detect conclusively the presence of the organisms. However, LIBS was able to distinguish clearly the presence of even very small carbonates against basaltic groundmass. Since LIBS can be made into a very small system with no logistical requirements other than a relatively small amount of electrical power, it will likely be very useful as a triaging technique. In this role it will complement the MASSE project nicely. Relative to LIBS, MASSE will require a substantial time per sample and will deplete its store of expendable reagents with each test. LIBS can therefore be used to search for sampling locations for MASSE.

3. Fieldwork at Mars Analog Sites

The Arctic Mars Analog Svalbard Expedition (AMASE) involved the participation of 18 scientists on an ice breaker for two weeks to visit the world's northernmost terrestrial hot springs and the site of the only analog to the carbonate globules found in ALH84001. This site (79° 23.294´N, 13° 26.392´E) is near the Sverrefjell volcano. Co−I Steele joined a multidisciplinary group including Tori Hoehler (of the NAI team at NASA Ames Research Center) to field test protocols and instruments for characterizing the presence of microbes in both the hot−springs and the volcanic basalts. These techniques included polymerase chain reaction (PCR) and hand−held instruments to conduct the Limulus amebocyte lyase (LAL) test (supplied by N. Wainwright, Marine Biological Laboratory) and adenosine triphosphate (ATP) assay, as well as a hand−held digital microscope. The successful field testing enabled field PCR to be conducted for the first time in the Arctic to confirm the presence of functional genes for bacterial sulphur metabolism in the Trollolsen hot springs. ATP luminometry was conducted on relic carbonate hot springs that showed the presence of cryptoendolithic communities (Figure 2). Samples returned to the laboratory have been analyzed by many techniques in order to prepare the Svalbard area to serve as a Mars analog for field testing of instrumentation for the Mars Science Lander (MSL). A second expedition will be mounted this year.

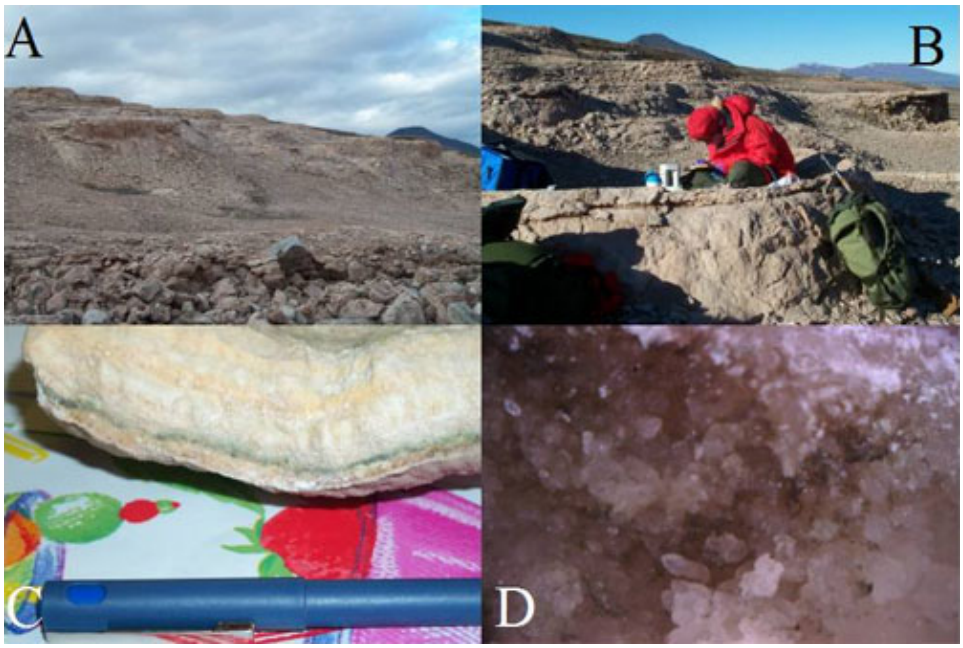

Figure 2. (A) An image of relic terraces at the AMASE site in Svalbard. (B) Picture of the ATP analysis being undertaken on the lower terrace by undergraduate M. Schweizer. (C) Image of a sample of the terrace showing the layering the carbonate and the presence of a layer of cyanobacteria typical of a cryptoendolithic community. (D) x30 magnification digital image showing the presence of dark green cyanobacterial colonies through the matrix of the sample shown in (C).

4. Application of Astrobiotechnology for Origin of Life Issues

Co−Is Steele and Hazen and Postdoctoral Fellow Jake Maule applied biotechnology to improve the protocol for testing crystal surfaces for chiral selectivity. Using the unique capability of the Telechem Spotbot microarrayer to print on uneven surfaces, the group printed small volumes (0.7 nL) of fluorescently L− and D−amino acids onto feldspar, calcite, and mica surfaces, at up to 20 different dilutions, each in quintuplicate to allow for surface variation. The surfaces were then scanned for fluorescence with a Genepix 4000B scanner, washed with saline solution, and then scanned again to observe any preferential binding post−wash. In addition, “left” and “right” faces of quartz were printed with fluorescently labeled L−lysine and fluorescence quantified pre− and post−wash (Figure 3). There appears a significant and quantifiable retention of L−lysine on the right face of the crystal.

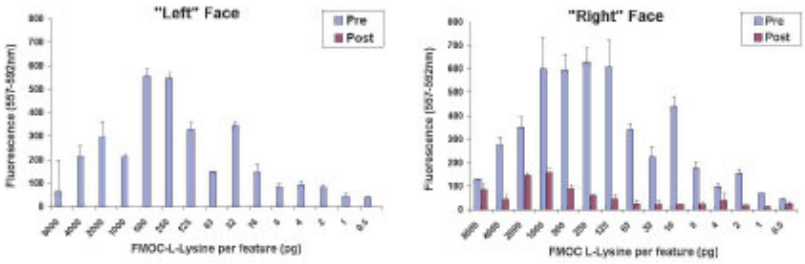

Figure 3. Preferential binding of fluorescently labeled amino acids on the left and right faces of quartz.

Highlights

- Life–detection instrumentation has been tested in a Mars analog environment on Svalbard. This environment will be used to test flight instrumentation proposed for Mars lander missions.
- Fossil collagens in 40,000–year–old bone samples have been characterized using the world's first antibody microarray to fossil compounds.
- High throughput has been achieved for the simultaneous screening of thousands of fluorescently labeled D and L amino acids for assessing their binding characteristics to mineral surfaces.
- Quantitative microfluidic cell lysis has been demonstrated for gram–negative, gram–positive, and archaeal cells.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	MSL	Planning Support
2	MSL	Instrument/Payload Development
2	ExoMars	Planning Support
2	ExoMars	Instrument/Payload Development

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Co−I Steele is actively advising the Mars Exploration Program. He serves on the Organic Contamination Science Steering Group, the Mars Icy Science Team, and the MEPAG Goals Committee. Steele chairs and Postdoctoral Fellow Toporski serves on the Astrobiology Field Laboratory (AFL) Science Steering Group, a committee commissioned by MEPAG and the NASA Mars Office to define the science objectives and mission architecture for a proposed follow−on mission to MSL in 2013.

Several team members are involved in proposed experiments on MSL. Co−I McCoy is involved in a proposal for a gamma−ray spectrometer to search for H − either as ice or bound in hydrated minerals − and other elements that are concentrated by biogenic processes or a necessary agent for such processes (e.g., P, Mn, Ca). Co−Is Huntress, Scott, and Steele are involved in a proposal for a Surface Analysis for Mars (SAM) instrument. Steele is also a participant on two other proposed instruments. One is the Mars Ultraviolet Science Experiment (MUSE), designed to triage samples using deep−UV fluorescence spectroscopy to detect organic and mineral signatures at a high level of sensitivity. The other is the Rocklab experiment package, which combines a thermal evolved gas analyzer, X−ray diffraction, and high−resolution microscope to examine samples for carbon content and isotope signature, mineralogy, and imaging.

Steele and Toporski are advising ESA on the Pasteur exobiology payload and rover for the ExoMars mission. They are also collaborating on a proposal for an instrument, Molecular Biology Instrument for Life Detection (MoBILD).

Field Expeditions

Field Trip Name: Arctic Mars Analogue Svalbard Expedition (AMASE)

Start Date: 10 August 2003	***End Date:*** 22 August 2003
Continent: Arctic	***Country:*** Svalbard
State/Province:	***Nearest City/Town:*** Longyearbyen
Latitude: 79° 23.294'N	***Longitude:*** 13° 26.392'E
Name of site(cave, mine, e.g.): Troll Springs Sverrefjell	***Keywords:***

Description of Work: Field testing of protocols and instruments for characterizing the presence of microbes in hydrothermal and volcanic analogs to sites on Mars.

Members Involved:

Cross Team Collaborations

Co−I Steele maintains collaborations with N. Wainwright (MBL), Tori Hoehler (ARC), and V. Parro Garcia (CAB).

EPO: Carnegie Institution of Washington

These are the Education and Public Outreach activities for the Carnegie Institution of Washington.

Capital Science Lecture Series

To make science more accessible to the general public, the Carnegie Institution of Washington began the Capital Science Lectures in the fall of 1990. These free public talks are designed to help nonscientists understand scientific thinking and to appreciate the importance of basic research in our lives today. For the past five years, speakers have been chosen to focus on the Institution's interest in astrobiology. The 2003/2004 series featured talks by such scientists as Dr. Wendy Freedman of the Carnegie Observatories who presented a talk entitled 'Exploring the Universe in the New Millennium.' The series is also attended by students of local high schools. They meet with the presenter before the lecture to discuss the research and to have personal interaction with the scientist. Students from several area schools have been attending since the inception of the lecture series.

Astrobiology Presentations for the General Public and Special Interest Groups

The Carnegie Institution of Washington offered the following presentations for the general public and special interest groups:

–Sara Seager presented invited talks to the Third Harvard–Smithsonian conference on Theoretical Astrophysics: Astrophysics of Planetary Systems, in Cambridge, MA, and to the 14th Annual Maryland Astrophysics Conference: The Search for Other Worlds, in College Park, MD. She also presented at colloquia and gave seminars at Harvard University, University of Maryland, and Fermilab. Her public talks were given at the National Air and Space Museum and at the National Science Foundataion (NSF) Symposium, 'The Universe from the Ground Up,' both in Washington, DC. –Alan Boss presented many invited talks, presentations, and posters on planetary formation to special interest groups, both nationally and internationally. These groups included the Division of Planetary Sciences, University of Delaware, Gordon Conference on the Origins of Solar Systems, American Society for Gravitational and Space Biology, Australian National University and Australian Academy of Science, and Lunar and Planetary Science Conference. He presented public lectures at the 2004 Carnegie Evening in Washington, DC, and at the Frontiers of Astronomy Series at the Cleveland Museum of Natural History in Ohio. –John Baross presented invited talks on the subject of Geobiology to many groups

both nationally and internationally. These groups included: The American Astronomy Society, American Society for Limnology and Oceanography, American Society for Microbiology, American Geological Society, American Association for the Advancement of Science, National Research Council, University of Brest, France, and the Goldschmidt Conference in Denmark. –Doug Rumble presented several seminars on the history of Earth's atmosphere at the following institutions: Stanford University, University of California, Berkley, and the Carnegie Institution of Washington in Washington, DC. –NASA Astrobiology Institute members and alumni participated in a symposium on mass–independent isotope effects at the Goldschmidt Conference in Kurashiki, Japan. –Rick Carlson gave keynote lectures at the Gordon Conference on the Earth's Interior in MA and at the South American Symposium on Isotope Geology in Brazil. –Alycia Weinberger gave invited talks at the Gordon Conference on the Origins of Solar Systems.

Astrobiology in the Popular Media

Carnegie Institution of Washington astrobiologists appeared in or on radio, television, and the national press during 2003–2004. –Alan Boss appeared in a televised press conference entitled 'The Oldest Planet' for NASA's Space Science Update Series; he was interviewed live for the The News Hour with Jim Lehrer on the same topic and gave a taped interview on National Public Radio. He was interviewed by the Australian Broadcasting Commission on the topic 'Looking for Earths: The Kepler Mission.'. He also participated in a televised press conference from NASA headquarters entitled 'Youngest Planet and Ingredients for Life Found in Forming Solar Systems.'. His work has also been quoted or described in Sky & Telescope, Science News, Mercury and the Washington Post. –Paul Butler was one of the five winners of the Discover Magazine Award for Innovation in Science and Technology for his work on identifying extrasolar planets. A profile was published in the November 2003 issue of Discover.

Carnegie Seminar Series

The Department of Terrestrial Magnetism (DTM) and the Geophysical Laboratory each hold weekly scientific seminars. Speakers include visitors and members of the staff, with topics ranging from astrophysics and planetary sciences to geochemistry and seismology. The seminars are announced to the community with monthly schedules sent to 214 institutions and individuals in the Washington metropolitan area. The following seminars were given by scientists associated with the NASA Astrobiology Institute, and by speakers on subjects related to astrobiology.

a. Department of Terrestrial Magnetism

7/23/03: DTM's Eugenio Rivera, "The Dynamical Evolution of the Earth–Moon Progenitors."

9/10/03: DTM's Michael Smoliar, "Asteroidal cores: Crystallization history recorded in PGE patterns."

11/12/03: Laurie Leshin, Arizona State University, "Carbon on Mars: Reservoirs, Processes and Implications for Biosignatures."

11/18/03: Phillip A. Ianna, University of Virginia, "A Brief History of the Astrometric Search for Extrasolar Planets."

1/21/04: Yongsong Huang, Brown University, "Compound−specific D/H Ratios in Monocarboxylic Acids and Macromolecules in Carbonaceous Meteorites: Implication for the Origin and Formation Pathways of Meteoritic Organic Compounds."

3/31/04: David Wilner, Harvard Smithsonian Center for Astrophysics, "Debris Discs Around Nearby Stars."

4/21/04: Adrian Melott, University of Kansas, " Did a Gamma−Ray Burst Initiate the Ordovician Extinction?"

5/5/04: Scott Gaudi, Harvard University, " Microlensing Searches for Extrasolar Planets."

5/13/04: Pascale Ehrenfreund, Leiden Observatory, The Netherlands, "A Voyage from Dark Clouds to the Early Earth."

5/26/04: Bill Herbst, Wesleyan University, "Around KH15D, a Solar−like Star of Planet−forming Age."

6/30/04: Thomas Zega, Naval Research Laboratory, "Mineralogic Signatures of Aqueous Alteration in the Early Solar System."

7/7/04: Sara Seager,DTM, "Towards a Physical Characterization of Extrasolar Planets and the Search for Biomarkers."

b. Geophysical Laboratory

9/29/03 Huiming Bao, Louisiana State University, "Sulfate O−17 Anomalies in Ancient Ash Beds."

10/6/03 Alex Pavlov, University of Colorado at Boulder, "Methane, Oxygen and Sulfur in the Archean Atmosphere: Organic and Sulfur Aerosols as UV−Shield, 'Food' and Climate Driver in the Archean Environment."

10/17/03 Lisa Faithorn, NAI, NASA Ames Research Center, "NAI as Virtual Institute − An Anthropological Perspective − Current Goals and Available Resources."

10/20/30 Becky Alexander, Harvard University, "Understanding the Present and Paleo Record of the Oxygen Isotopes of Sulfate."

10/27/03 T. G. Waddell, University of Tennessee, Chattanooga, "Prebiotic Organic Chemistry Related to the Origin of Metabolic Pathways."

11/10/03 Shuhei Ono, Geophysical Laboratory, "Multiple Sulfur Isotope Records in Archean Australia and their Implications for Early Earth's Atmosphere and Biosphere."

11/17/03 Ed Young, University of California, Los Angeles, "Oxygen Isotope Heterogeneity in the Solar System – A Signature of Water? Astrochemical and Geological Evidence for the Role of Water in the Rock–Forming Process in the Solar Nebula."

12/12/03 Hans Amundsen, University of Oslo, "Searching for Life in a Mars Analogue Environment."

12/15/03 Cari Corrigan, Smithsonian Institution, "ALH 84001: Life After Life on Mars."

1/26/04 Albert Colman, Geophysical Laboratory, "Phosphate Oxygen Isotopes, Marine Biogeochemistry, and the Detection of Ancient and Extraterrestrial Nutrient Cycling."

2/3/04 Veronica Vaida, Harvard University, "Atmospheric Aerosols as Prebiotic Chemical Reactors."

3/1/04 Peggy Ostrom, Michigan State University, "Biomolecular Preservation: New Possibilities and Perspectives."

Astrobiology in the Classroom

Carnegie astrobiologists participated in the following classroom activities: –James Scott, Andrew Steele, and Saavik Ford spent a morning each at Maury Elementary School in Washington, DC, talking about their work in astrobiology and how to become a research scientist. –Nader Haghighipour participated in NASA's 'Journey Through the Universe' program and gave four talks at four schools to sixth graders entitled 'Is the Sun the Only Star With Planets?' –Vera Rubin introduced and moderated a press conference at the National Press Club to introduce NEC Extreme Science, a science program for middle school students and teachers. The program will bring leading scientists into classrooms.

Committees, Editorial Boards, and Advisory Boards

–Robert Hazen served on the AAAS Committee on Public Understanding of Science and Technology and the Advisory Boards of several organizations that bring science to the public including NOVA, Encyclopedia Americana, Earth & Sky, and the Carnegie Council. He was also Vice President of the Mineralogical Society of America in 2003–2004. –John Baross performed the following professional activities: Organized and convened American Society for Microbiology (ASM) Colloquium entitled 'Novel Organisms and Novel Metabolisms; What More Can We Expect to Find?' Washington, DC, May, 2003. Co–Organized and Co–Chaired Geological Society of America (GSA) session entitled 'Submarine Hydrothermal Systems: The Emergence of Geobiology,' Seattle, WA, November, 2003. Co–organized and Co–Chaired

The American Association for the Advancement of Science (AAAS) session on The Lost City Hydrothermal System, Seattle, WA, February, 2004. Chair, National Research Council (National Academy of Sciences) Task Group 'The Limits of Carbon Life on Earth and Elsewhere,' 2004–2005. Organized National Research Council (National Academy of Sciences) Workshop 'The Limits of Carbon Life on Earth and Elsewhere' Washington, D. C., May 10–11, 2004. Lecturer and co–organizer of Vatican Observatory Summer School (VOSS) on Astrobiology, June 15–July 14, 2005, Vatican, Rome. His current editorial positions are: Editorial Board and editor in charge of mini–reviews, Astrobiology Journal, Mary Ann Liebert, Inc. Publishers. Co–Editor (with A. Brack, M. Mayor, and G. Horneck) of Advances in Astrobiology and Biogeophysics Series, Springer–Verlag Press. Co–Editor (with W. Sullivan) 'Planets & Life: The Emerging Science of Astrobiology,', Cambridge University Press (scheduled for publication in 2004). Co–Editor (with W. Wilcock, D. Kelley, E. DeLong and G. Cary) of AGU Monograph: Deep Subsurface Biosphere at Mid–Ocean Ridges (scheduled for publication in 2004).

Scientific Texts

–Robert Hazen is completing a book on the theory of emergence and the origin of life for the National Academy's Joseph Henry Press (to be published in 2005). He also completed work on an undergraduate science textbook that incorporates many astrobiology themes.

Traveling Astrobiology Exhibit

A portable, interactive version of the award–winning poster, Astrobiology: Discovering New Worlds of Life (published in 2002), was produced in 2003. The kiosk is available to all members of the NAI scientific and education and public outreach (E/PO) teams to be displayed at conferences, schools, universities, and public lectures, as well as museums, science centers, and libraries for public display on a rotational basis. The kiosk has been displayed at NAI's Astrobiology Science Conference (AbSciCon) (NASA Ames, March–April 2004), University of Tennessee (April 2004), and Pennsylvania State University (May–July 2004).

Carnegie Summer Intern Program

The Carnegie Summer Intern Program in Geoscience brings about 20 college students, competitively selected, to our campus every summer for an intensive 10–week experience in original scientific research. At a symposium held at the end of the program, students report on the results of their research. Several interns have been lead authors of related articles later published in scientific journals.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: Harvard University

Project Report: The Planetary Context of Biological Evolution

Project Investigator:	***Andrew Knoll***

Project Progress

The Harvard NAI team was constituted in 1998 as an interactive group of biogeochemists, paleontologists, sedimentary geologists, geochemists, and tectonic geologists assembled with the common goal of understanding the coevolution of life and environments in Earth history. In Year 6, the final year of NAI activity for the Harvard group, the team completed research in its core areas of inquiry: environmental evolution in the early Paleoproterozoic (2400–2200 Ma) when oxygen began to accumulate in the atmosphere and surface ocean; the terminal Proterozoic and Early Cambrian intervals (750–525 Ma) when animal life radiated; the Permo–Triassic boundary (251 Ma) when mass extinction removed some 90 percent of Earth's species diversity, permanently altering the course of evolution; the recognition and interpretation of molecular and isotopic biomarkers; and the astrobiological evaluation of a terrestrial analog for iron oxide and sulfate rocks recently discovered at Meridiani Planum, Mars. Our efforts in Earth history and evolution highlight the importance of Earth's physical development for the course of biological evolution –– the planetary context of evolution is likely to be a major theme of astrobiological inquiry wherever life may be found. Our paleobiological and geochemical analyses of ancient rocks and our research on the generation of molecular and isotopic biosignatures further provide the tools by which the search for life beyond the Earth will be conducted. Finally, our research on iron/sulfate rocks on Earth will help to guide continuing astrobiological investigation of the Martian surface, including projected sample return.

Highlights

- Analyses of mass independent sulfur isotopic fractionation in radiometrically calibrated sedimentary successions from South Africa show that Earth's atmosphere and surface oceans first began to accumulate oxygen between 2.45 and 2.32 billion years ago.
- Analyses of Mo–isotopes in mid–Proterozoic sedimentary rocks show that oxygen levels in the oceans remained low 1.5 billion years ago, with anoxic deep waters exhibiting a broader distribution that they have in oceans of the past 500 million years.

- Analyses of sulfur isotopes in stratigraphically well constrained sedimentary successions from southern Africa, Canada, and Australia indicate that levels of oxygen and sulfate in the oceans increased substantially ca. 580 million years ago, just before the initial appearance of large animals.
- Radiometric analyses of ash beds in key sedimentary successions calibrate the climatic and biological history of the Neoproterozoic and Cambrian Earth. Dates of 635+/– 1.2 million years, 580 +/1 million years, and 575+/1 million years constrain the ages of the younger global Neoproterozoic ice age, a further regionally distributed ice age, and the evolution of large animals, respectively.
- Combined stratigraphic and isotopic geochemical research have yielded a new understanding of Earth's Neoproterozoic and Cambrian carbon cycle, providing an important means of understanding the relationships among life, climate, and biogeochemical cycles 800–530 million years ago.
- Geochemical and paleobiological analysis of modern and Neogene iron deposits of the Rio Tinto basin, southwestern Spain, demonstrate the astrobiological potential of sample return from Meridiani Planum, Mars.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars MER	Science Team Member
2	Mars Sample Return	Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF,

Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Knoll and Grotzinger are memebrs of the MER science team. Work by a number of team memebrs (Knoll, Grotzinger, Hayes, Holland, Summons, and Anbar will feed directly into the choice of site and choice of analyses for Mars sample return.

Cross Team Collaborations

See submitted report. Collbaorations ending this year include work with memebrs of Penn State, Carnegie, and NASA Ames teams, as well as the Spanish CAB and the Australian Centre for Astrobiology.

Fellowships: Harvard University

The NAI–NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Peter Sazani
Project Title: Directed Evolution of an RNA Polymerase Ribozyme that Utilizes Highly Activated Monomers
Advisor: Andrew Knoll, Project Investigator
NAI Lead Team: Harvard University
Fellowship Began In:

Project Report: Directed Evolution of an RNA Polymerase Ribozyme that Utilizes Highly Activated Monomers

NAI–NRC Postdoctoral Fellow :	Peter Sazani

Project Progress

The goal of this proposal is the directed evolution from random pools of RNA of a polymerase ribozyme that utilizes highly activated nucleotide monomers as substrates. The successful identification of a ribozyme with these properties will represent a step towards the evolution of a self–replicating RNA and will provide insights into how simple replicating systems could have lead to the emergence of life on earth. This work also represents a potential advance in the synthesis of artificial life. Such a system would require replicable genetic information and a lipid vesicle to separate it from its external environment. Using highly activated nucleotide monomers as substrates for polymerization is advantageous in that they are less polar than nucleotide triphosphates (NTP), thus facilitating their diffusion through lipid vesicles. Furthermore, highly activated nucleotide monomers such as 5'–phosphorimidazolides have a 500–fold greater ability to polymerize on a template than NTP. Using these substrates will therefore reduce the rate enhancement required of the ribozyme to efficiently polymerize the monomers, which should simplify it.

The initial round of selection for the polymerase ribozyme requires a great initial expenditure of resources, the final preparations for which have occurred in the last 6 months. These preparations have included large–scale production of a random RNA pool from which the polymerase ribozyme may be selected, and smaller synthetic RNA molecules used in the selection scheme. Biological enzymes that will be used in the selection, including T4 DNA ligase and MMLV reverse transcriptase, were also produced. In addition, many small–scale pilot experiments were performed in order to ensure that the selection will yield the functional RNA molecules we desire. To date, all pilot experiments have shown positive results and the first round of selection for the RNA polymerase is scheduled to begin within 1 month of this report.

Highlights

- Pilot experiments have been performed to validate the ability of the selection scheme to enrich for RNA molecules with the ability to synthesize new RNA from nucleotide monomers.

- All materials necessary to begin selection of the polymerase ribozyme have been prepared.
- Round 1 of the RNA polymerase ribozyme selection is ready to begin.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Publications: Harvard University

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: Harvard University

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Indiana University
Executive Summary
Principal Investigator: Lisa Pratt

Introduction. During the first six months of funding from the NASA Astrobiology Institute (NAI), three major research projects were initiated by the Indiana–Princeton–Tennessee Astrobiology Initiative (IPTAI) Team: 1. Geomicrobiology and hydrogeochemistry of intra– and sub–permafrost water intersections in a deep gold mine, Kinross Luipn Mine, Nunavat Territories, Canada; 2. Partitioning of sulfur isotopes during pyrite oxidation coupled to radiolytic water cleavage; and 3. Whole–genome sequencing of an uncultured *Desulfotomaculum*–like organism from hydrothermal waters in deep gold mines, Witwatersrand basin, South Africa. Each of these projects requires a high degree of collaboration among IPTAI laboratories and involves two to four principal investigators, one to three post–doctoral associates, and two to five graduate and undergraduate students.

The central focus of the IPTAI team is investigation of psychrophilic microbial communities in a deep gold mine located near the Arctic Circle in northern Canada.

Figure 1. Headframe and living quarters (red buildings) at Kinross Lupin Gold Mine, Nunavat Territories, Canada. View of the mine from the winter haul road in May 2004.

This project involves highly instrumented field and laboratory activities (Figure 2) that build on expertise developed during 5 years of work on thermophilic microbial communities in the deep and ultra−deep gold mines of South Africa. Intra−permafrost/sub−permafrost brines from Arctic and Antarctic regions are important terrestrial analogues for Martian groundwater. Delineating biogenic signatures in analogue environments is crucial for designing life−detection probes for deployment on future Mars exploration missions.

Figure 2. Tullis Onstott (IPTAI–Princeton) and Monique Hobbs (Ontario Power Generation) working to install a noble gas diffusion sampler at the 890 meter level, Lupin Mine.

1. Geomicrobiology and hydrogeochemistry of intra– and sub–permafrost water intersections in a deep gold mine, Nunavat Territories, Canada. PIs Onstott, Pratt, Sherwood–Lollar, Clifford, and Pfiffner. Distinct microbial communities are anticipated in brines associated with continuous permafrost but uncontaminated samples of permafrost brines are rarely available for scientific study. The main shaft, ore workings, and exploration drifts at Lupin mine allow controlled study of both intra– and sub–permafrost waters. Water intersections at Lupin are located in fracture zones hosted by low–permeability Archean metagraywacke, phyllite, and banded iron formation. An initial field trip to assess the scientific potential at Lupin was conducted in May 2004 when Pratt and Onstott from IPTAI and Corien Bakermans from Michigan State University (MSU) joined an international team of permafrost investigators for collection of water and rock samples (Figures 3 and 4). A second sampling trip is planned for fall 2004. Samples from the May 2004 field trip will be given to the Marine Biological Laboratory (MBL) for assessment of eukaryotic activity. It is particularly exciting to link IPTAI's deep–subsurface expertise with MSU's resources as a center for research on psychrophilic microorganisms from Siberian permafrost and Antarctic lake ice and MBL's resources as a center for research on extremophile eukaryotes.

Figure 3. Tullis Onstott (IPTAI–Princeton) innoculating iron–reducing media with subsurface brine at the 1130 meter level, Lupin Mine.

Figure 4. Corien Bakermans (MSU lead team) injecting subsurface brine into a sterile serum vial filled with nitrogen, Lupin Mine.

With the assistance of Timo Ruskeeniemi (Geological Survey of Finland) and Monique Hobbs (Ontario Power Generation), brines of widely varying salinity were collected from 11 subsurface sites in May 2004. Brines below the permafrost were collected from six drill holes outfitted with valves and pressure gauges and located at the 1130− and 880−m levels. Dripping water from open fractures in the roof was collected at the 1130− and 250−m levels. Dripping water at the 250−m level is within the current permafrost. Water recirculated within the mine for drilling activities (service water) was sampled from an open drain at the 1130−m level. The following types of aliquots were collected:

a. Filters for DNA analyses.
b. Filters for enrichment of cultivable, anaerobic and aerobic psychrophiles.
c. Anaerobic media (sulfate reducers, fermenters, Fe (III) reducers and

methanogens) inoculated with borehole water.
d. Gas samples for isotopic analyses and measurement of dissolved H_2 and CO.
e. Water sample for isotopic analyses, including N isotopes of NH_4^+ (Waterloo)
f. Noble gas samples (Ottawa).
g. Dissolved sulfate/sulfide samples for isotopic analyses.
h. Samples for FISH (Fluorescent In Situ Hybridization) and flow cytometer (cell density)
i. Multiple samples for analyses of cations, anions, and short–chain fatty acids.

Field parameters, pH, Eh, dissolved O_2, temperature and conductivity were measured on site. Conductivity ranged from 4.9 to 60.4 mS/cm. Temperatures varied from 13.4 to 1.5°C. The pH ranged from 7 to 9. Visible ZnS precipitates were observed in the sulfur isotope syringes after one day of storage at room temperature indicating the presence of significant sulfide concentrations. Although Eh values as low as –143 mV were measured, Eh values were higher than expected for a sulfate/sulfide redox couple at the observed pH and temperature. One possible explanation is that mixing of water with different reduction potentials from separate fractures is occurring within boreholes. Televiewer logs indicate the presence of multiple fractures, and fracture water chemistry seems highly variable based upon observations of seeps.

The integrity of borehole installations at Lupin is a tribute to the technical ability of the Finish/Canadian collaborators on the Permafrost at Lupin Project. We know of no equivalent borehole array available for scientific study at a deep mine. Of particular interest for sampling deep subsurface microbes, there are high *in situ* water pressures (300 to 700 psi), sulfide is present, dissolved O_2 is absent, and the boreholes have been isolated for time periods up to 14 months. These are important positive indicators that the borehole microbial communities represent indigenous organisms in the rock formation. Over the next several months, the sulfur isotopic and DNA analyses combined with the results of microbial enrichments will allow assessment of the extent of potential mining contamination of the environment and to target specific boreholes for more detailed sampling via a borehole packer system.

2. Partitioning of sulfur isotopes during pyrite oxidation coupled to radiolytic water cleavage. PI's Ripley, Sherwood–Lollar, Pratt, and Onstott. A series of experiments are designed to investigate sulfur isotopic effects that may accompany the oxidation of sulfide minerals initiated by reaction with products formed during the radiolysis of water molecules. Radiolysis produces elevated H_2 concentrations in waters, as well as strong oxidants such as H_2O_2 and O_2. Both H_2O_2 and O_2 may react with sulfide minerals as S^o, $S_2O_3^{2-}$, or SO_4^{2-}. Thiosulfate ($S_2O_3^{2-}$) can undergo disproportionation to produce both oxidized (SO_4^{2-}) and a reduced (S^{2-}) sulfur species. Because of the isotopic fractionation between reduced and oxidized species, large)(sulfate–sulfide) values may be a result of radiolytic oxidation processes. Sulfate–reducing bacteria could utilize the oxidized sulfur species with the ultimate production of sulfide minerals. However, the generation of sulfide minerals from the reduced species liberated from thiosulfate could be characterized by $*^{34}S$ values that are similar to those produced in sulfide minerals where the reduced sulfur is of biologic origin. We must understand the

potential sulfur isotopic effects that are associated with each of these processes.

To this end we have been involved in designing a methodology to recover both reduced and oxidized sulfur species from thiosulfate. To date, 32 experiments to evaluate the sulfur isotopic mass balance in the disproportionation of $Na_2S_2O_3$ have been completed. A thiosulfate solution is formed by mixing powdered sodium thiosulfate ($Na_2S_2O_3$) with deoxygeneated, nanopure water under a N_2 atmosphere. The thiosulfate solution has been reacted with silver nitrate ($AgNO_3$) for periods varying from 1 to 2 hours; this step leads to the recovery of reduced sulfur as Ag_2S. After the removal of Ag_2S (Figure 5) by filtration, the residual solution is heated to $80^{E}C$ and $Ba(NO_3)_2$ is added to produce $BaSO_4$. Initial experiments utilized BaCl, but excessive amounts of AgCl were formed and prevented a quantitative recovery of $BaSO_4$. Isotopic measurements are in progress to determine the most efficient protocol to accurately characterize the distribution and isotopic fractionation of sulfur species. This work constitutes a portion of the Ph.D. research of Irene Arango at Indiana University.

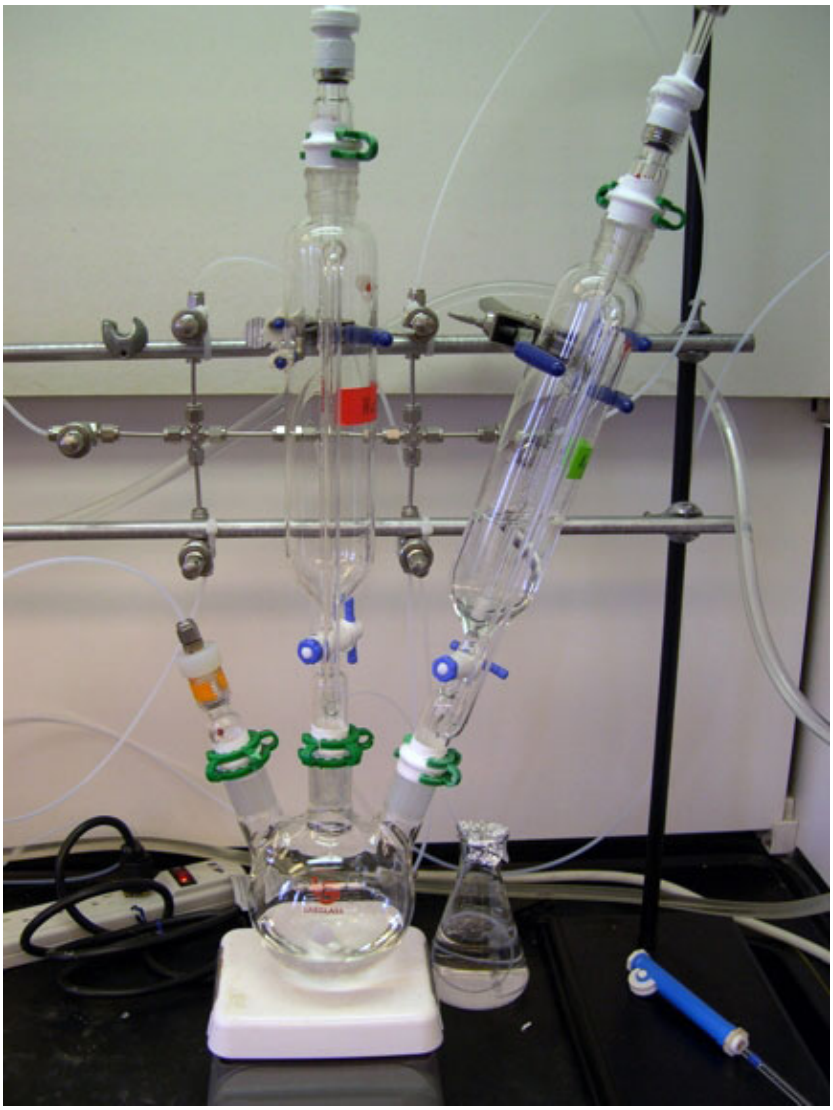

Figure 5. Nitrogen–purged extraction apparatus for quantitative recovery of dissolved and volatile sulfur species, Biogeochemical Laboratories, Indiana University.

In addition to the experiments on thiosulfate and its disproportionation products we will load our first closed–system pyrite oxidation experiments in July. Hydrogen peroxide will be syringed through a septum into a Pyrex tube containing finely ground pyrite. The tube will be sealed and the experimental charge heated for a 1– to 2–week period. Various temperatures will be utilized to evaluate the kinetics of the pyrite oxidation reaction.

During the past six months, Indiana University advertised for our post–doctoral position. Several excellent candidates responded, and our evaluation and interview process was necessarily thorough. The position was offered to Ms. Lili Lefticariu who has recently completed her Ph.D. dissertation involving stable isotopic geochemistry at Northern Illinois University. Lili will be in Bloomington in early July to discuss the project and will begin her work in mid–August. Over the coming year, experiments running at Indiana will be coordinated with similar experiments running at Toronto in order to study

carbon isotope effects on oxidized and reduced carbon species.

3. Whole−genome sequencing of an uncultured *Desulfotomaculum*−like organism (DLO) from hydrothermal waters in deep gold mines, Witwatersrand basin, South Africa. PI's Brockman, Hazen, and Onstott. A deep−branching clade of nearly identical DLO sequences (>99% homology) has been identified in 6 boreholes in 4 mining complexes separated by as much as several hundred km. The DLO has been the dominant bacterium (>90−100% of clones) present in clone libraries from very high quality sample sets in two different mines, and their dominance was retained throughout a several month time series in one case, and a 648−m vertical depth profile in the other case. Sulfate reduction appears to be the dominant terminal electron accepting process in these sample sets based on sulfate and sulfide levels, sulfur isotope geochemistry, and Gibbs free energy calculations. While prediction of physiology from phylogeny is not straight−forward in this case, the environmental chemistry, the DLO's strong dominance in the community, and the DLO's affiliation with cultivated *Desulfotomaculum spp*. that are sulfate−reducers all speak to the likelihood that it is a sulfate−reducer. The closest cultured relative is *Desulfotomaculum kuznetsovii* (90% similarity) and the closest sequence in Genbank is an environmental clone recently recovered from oceanic crustal fluid (95% similarity). Multiple attempts by different laboratories to culture the DLO have been unsuccessful.

To gain an understanding of the capabilities and degree of genetic novelty of the DLO, we have filtered large quantities of fissure water from a sample dominated by the DLO in order to provide adequate biomass for community DNA sequencing. The Department of Energy Production Genomics Facility will conduct the sequencing in collaboration with Pacific Northwest National Lab and Lawrence Berkeley National Lab. A total of 35,000 liters containing 4x10^4 cells per ml were filtered through a large area filter cartridge. This filter should yield 280 micrograms of DNA assuming a genome size of 2 Mbp/cell and 10% extraction efficiency. A minimum of 10 micrograms is needed for shotgun sequencing

DNA was extracted from 15% of the filter and quantified by spectrophotometry and gel electrophoresis. DNA yield was poor with only 400 nanograms of DNA recovered from 15% of the filter, indicating an extraction efficiency of only 0.1%. In addition, only 25% of this DNA was of the size (10 kb or larger) needed for shotgun sequencing. To preserve as much filter as possible, two other extraction protocols were used (as a screen) on smaller aliquots of the filter to determine if they would produce detectable DNA. No DNA was detected with these methods. These results indicate that DNA extraction efficiency is much poorer than expected.

In an effort to optimize the extraction efficiency, 1 x 10^12 *Arthrobacter* cells (a difficult to lyse Gram positive bacteria used as a model for the DLO) were filtered through an identical filter cartridge. A different extraction protocol (using lysozymeàsodium dodecyl sulfate/Proteinase Kà guanidine isothiocyanate, with a liquid nitrogen and mortar and pestle grinding pretreatment) was used and compared against the previous extraction method. DNA extraction efficiencies were 11% with the new method and 0.5% with the original method. In addition,

all DNA was greater than 10 kb in size. The new protocol will be tested on a small fraction of the filter containing the DLO, and once its performance has been confirmed to be adequate, one half of the remaining filter containing the DLO will be extracted.

Education and Public Outreach (EPO). Outreach for the IPTAI Team is centered at the University of Tennessee and is under the direction of Susan Pffifner. Funds from NAI were used to match funds from the National Science Foundation to support a seven–week Research Experience for Undergraduates (REU) held in South Africa and targeted toward minority students. The purpose of the South African REI is to engage students in geomicrobiological research and to encourage students to think about scientific careers. American students work side by side with South African students under the joint supervision of U.S. and South African faculty. One Taiwanese, ten American, and six South African students participated in the summer 2004 program. In addition to REU activities, eight lectures and seven media interviews were handled by Pratt, Onstott, and Pfiffner during the first six months of NAI funding for IPTAI . Additional information on EPO activities is available on the IPTAI website at http://www.indiana.edu/~deeplife .

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: Indiana University

Project Report: Biosustainable Energy and Nutrient Cycles in the Deep Subsurface of Earth and Mars

Project Investigators:	***Fred Brockman , Steve Clifford , Kimberly Davis , Charles Dismukes , James Fredrickson , Terry Hazen , Satish Myneni , Tommy Phelps , Lee Riciputi , Edward Ripley , David White , Gary Hieftje***

Project Progress

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.3:*** Origins of energy transduction
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Mars exploration	Project Investigator

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:

1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Principal investigators and collaborators with the IPTAI team are involved in the design and construction of two instruments intended for future exploration of Mars. Tullis Onstott (IPTAI−Princeton) is working with Kevin Lehmann in the Chemistry Department at Princeton on space exploration application for Cavity Ring Down Spectrometry (CRDS). Using a tunable laser, CRDS allows absorption lines for trace gases to be determined with a precision approaching that of isotope mass spectrometry. Consequently, the Princeton group proposes to measure carbon and hydrogen isotopic compositions of Martian methane at ambient atmospheric concentrations (about 1 ppb) using a CRDS instrument mounted on a rover platform. This type of instrument could also be used to look for other trace gases, such as ethane and formaldehyde which are photolytic products of UV breakdown of methane. The sensitivity of CRDM for methane is theoretically sufficient to detect one methanogenic microbe in 10 ml of fluid. As a laboratory proof−of−concept, the Princeton group will determine the isotopic composition of methane produced by a psychrophilic methanogen.

Gary Hieftje in the Chemistry Department at Indiana University is working collaboratively with Lisa Pratt (IPTAI−Indiana) on a life detection probe utilizing a luciferin/luciferace reaction. Luciferin is the basic substrate of all bioluminescence reactions including organisms as diverse as fireflies and marine dinoflagellates. The Indiana luciferin/luciferace probe is based on a reaction that specifically requires ATP as co−factor and is an indicator of bio−available energy or life. A series of initial experiments have been completed and an abstract on this research has been submitted to the Astrobiotechnology Workshop being held at the Carnegie Institution in summer 2004.

Field Expeditions

Field Trip Name: Kinross Lupin Mine

Start Date: 5/10/04	***End Date:*** 5/21/04
Continent: North America	***Country:*** Canada
State/Province: Nunavut Terrotory	***Nearest City/Town:*** Yellowknife
Latitude: 65deg 46min N	***Longitude:*** 111deg 14min W

Name of site(cave, mine, e.g.): Kinross Lupin Mine	***Keywords:*** microbial, water interaction, permafrost

Description of Work: Scientists from two NASA Astrobiology Institute teams, IPTAI and MSU, participated in an initial field trip to the Kinross Lupin gold mine in May 2003. Protocols for sampling anaerobic and aerobic eukaryotes will be developed for the Lupin project by a third Astrobiology team which is directed by Mitch Sogin at the Marine Biological Laboratory, Woods Hole Oceanographic Institution. We anticipate scientists from all of these teams participating in a second field trip to Lupin which is tentatively schedule for fall 2004. With the assistance of Timo Ruskeeniemi (Geological Survey of Finland) and Monique Hobbs (Ontario Power Generation), brines of widely varying salinity were collected from 11 subsurface sites in May 2004. Brines below the permafrost were collected from six drill holes outfitted with valves and pressure gages and located at the 1130 and 880 m levels. Dripping water from open fractures in the roof was collected at the 1130 and 250 m levels. Dripping water at the 250 m level is within the current permafrost. Water recirculated within the mine for drilling activities (service water) was sampled from an open drain at the 1130 m level. Samples of water, rocks, biofilms, and microbial mats collected during the May 2004 field trip have been distributed to numerous laboratories and the following research activities are in progress: 1. Growth, isolation and characterization of psychrophilic aerobic and anaerobic microorganisms from environmental (i.e. filter or permafrost cores) samples (Bakermans–Michigan State and Amaral–Marine Biological Laboratory). Characterization of isolates would include phylogenetic identity, membrane lipid composition (Pfiffner–Tennessee), temperature tolerance (including freezing tolerance), salt tolerance, pH range, utilization of substrates (i.e. short chain fatty acids and H2) for carbon and energy sources and stable isotope fractionation (Pratt–Indiana and Sherwood–Lollar–Toronto). 2. DNA (both 16SrDNA and functional genes) analyses of environmental (i.e. filter or permafrost cores) samples and flow cytometry of water samples (Onstott–Princeton) to determine biodiversity and biomass of all microorganisms including those noncultivatable. 3. Phospholipid fatty acid (PLFA) analyses of environmental (i.e. filter or cores) samples (Pfiffner–Tennessee) to determine biodiversity, stress level and biomass of cultivable and noncultivatable. 4. Sulfur isotope analyses of both sulfide and sulfate species (Pratt–Indiana) will be combined with 35S activity measurements and DSR and APS reductase gene analyses to delineate the microbial S cycle in environmental (i.e. both water and rock core) samples. 35S microautoradiography could be performed on freshly obtained rock/permafrost core to determine the spatial distribution of this activity with respect to mineralogy and physical properties. These results of these analyses would also complement the S and O isotopic analyses of sulfate being performed by Frape (Waterloo) to identify the sources of sulfate. 5. Organic chemistry of environmental (water and rock core) samples (Pratt–Indiana) to establish important electron donors and carbon substrates for microbial respiration and growth. The results of these analyses would also complement the inorganic aqueous chemistry being performed by Frape (Waterloo) and Ruskeeniemi (Geological Survey Finland). 6. Dissolved H2 and CO by residual gas analysis water samples (Onstott–Princeton) to establish abundance of these important electron donors for microbial

respiration and growth (CO). These results would also complement the gaseous chemistry analyses being performed by Frape (Waterloo). 7. N−cycle. Concentration and N isotopic composition of dissolved NH4+ (if any) of environmental samples (water and permafrost core) to constrain the origin of N for microbial growth. DNA analyses of functional genes (e.g., NAR, NIR, NOR, NIF, and AMO) utilized by nitrate reducers, N2 fixers and nitrifiers (Onstott−Princeton). These results would also complement the nitrate and N2 isotopic chemistry being performed by Frape (Waterloo). 8. Depending upon the success of 1 and 2, perform microbial activity measurements under in situ conditions and determine the S and C isotopic fractionation associated with microbial sulfate reduction and methanogenesis at low temperatures (Pratt−Indiana, Sherwood−Lollar−Toronto, Bakermans−Michigan State, Pfiffner−Tennessee). These data can be combined with qPCR of the methanogenic gene (MCR) to assess in situ rates of methanogenesis. The results of these studies would complement ongoing characterization of stable isotopic composition of aqueous, gas and rock pore species by Frape (Waterloo). 9. Examine the adaptations of microorganisms to low temperature with depth (which corresponds to time of exposure to low temperatures) to understand the evolution of these low temperature adaptive traits (Bakermans−Michigan State). Examine changes in the composition of the microbial community with depth to determine how low temperatures are selecting for and against individuals within the community. 10. Ground penetrating radar (GPR) survey at low frequencies using the European Space Agency (ESA) Netlander GPR, a version of which is currently deployed around Mars on ESA Mars Odyssey Orbiter. This GPR device is designed to penetrate ~1 km into Martian subsurface, but has not been tested at all on Earth, let alone in a terrain analogous to Mars like that present at Lupin. The subsurface characterization permits unprecedented ground truthing and will constrain interpretations of the current Mars orbiter (Clifford−Universities Space Research Association). An important component of this research project is the development of devices and instruments for borehole analyses, fluid management, life detection, and autonomous drilling in permafrost terrain with low water/rock ratios. Additional funding for instrument development and testing will be sought from NASA by US collaborators and could be sought from the Canadian Space Agency and the Canadian Institute for Advanced Research by Frape and Sherwood−Lollar Another important aspect of coring in permafrost will be the testing of alternative drilling fluids, such as gases, that will minimize contamination, preserve ice and methane clathrates and could be adapted to Martian drilling conditions. Initial time frame for NASA Astrobiology activities at Lupin mine is 3 years.

Members Involved:

Cross Team Collaborations

Scientists from two NASA Astrobiology Institute teams, IPTAI and MSU, participated in a field trip to the Kinross Lupin gold mine in May 2003 for collection of deep subsurface brines from within and below the zone of permafrost.. Protocols for sampling anaerobic and aerobic eukaryotes from

these brines will be developed by Mitch Sogin at the Marine Biological Laboratory. We anticipate scientists from all three of these NAI teams to participate in a second Lupin field trip scheduled tentatively for fall 2004.

Tullis Onstott (IPTAI−Princeton) is working closely with Bruce Jakosky (Colorado) on an agenda for the NAI Subsurface Life Splinter Group. An initial meeting was held in conjunction with the AbSciCon meeting in March 2004 and a second informal meeting of the subsurface group will occur at the MEPEG meeting in July 2004.

Lisa Pratt (IPTAI−Indiana) is a member of the five−person Management Committee for the recently funded (NSF) Field laboratory for Study of Subseafloor Life at the University of Rhode Island. This new facility will strongly enhance NAI activities directed by Steven D Hondt at Rhode Island.

EPO: Indiana University

These are the Education and Public Outreach activities for the Indiana University.

Research Experience for Undergraduates: Biogeochemical Education Experience – South Africa

Education and Public Outreach (EPO) for the Indiana–Princeton–Tennessee Astrobiology Initiative (IPTAI) Team is centered at the University of Tennessee and is under the direction of Susan Pffifner. Funds from NAI were used to match funds from the National Science Foundation to support a seven–week Research Experience for Undergraduates (REU) held in South Africa and targeted toward minority students. The purpose of the South African REU is to engage students in cross–disciplinary research and to encourage students to think about scientific careers. Students experience hypothesis–driven research from sampling in gold mines, to designing and performing research experiments, to writing manuscripts and presenting a public lecture. American students work side by side with South African students under the joint supervision of U.S. and South African faculty. Ten American, seven South African, and one Taiwanese undergraduate students participated in the summer 2004 program.

The University of Tennessee administered a seven–week Research Experience for Undergraduates (REU) from June 11–August 2, 2004. The REU targeted minority undergraduate students who are interested in careers in Earth Sciences, Biological Sciences, Environmental Sciences, and Engineering. The international host institution is the University of Free State (UFS) in Bloemfontein, South Africa. Of the ten U.S. students, there were three males and seven females. Minorities represented are three African Americans (2 females, 1 male), one Native American (female), one Pacific–Islander, and one Eurasian (female). Faculty Mentors from the U.S. included three long–term mentors (3–8 wks, Pfiffner, Kieft, Gihring) and three short– term mentors (2 wks or less, Phelps, Onstott, DeFlaun). South African mentors: two females (van Heerden, Piater) for long term and two males (Nthangeni, Litthauer) for short term and 4 visiting lecturers. One Ph.D. student and one post–B.S. student from the U.S. participated as student mentors, with graduate students from the UFS assisting as needed.

Public and invited speaking engagements

IPTAI has an active lecture and seminar participation. Presentations were

made by our Principal Investigator, Co−Principal Investigators, and Co−Investigators.

The following list is organized alphabetically: S. Clifford − Lunar and Planetary Institute

Public Outreach − "Water on Mars: Ancient oceans, deep aquifers, and massive ground ice", dinner speaker at annual meeting of the Indiana Water Resources Association, Valparaiso University, Indiana, June 2004.

Public Outreach − "Water on Mars," Houston Museum of Natural Science, Houston, TX, January 2004.

K. Davis − University of Tennessee

Selection of Tennessee candidates for Astrobiology Laboratory Institute for Instructors (ALI'I), University of Hawai'i, Manoa, June 14 −18, 2004. With S. Pfiffner.

Coordination, Carnegie Institution of Washington's Interactive Exhibit on hydrothermal vents at the Southern Appalachian Science and Engineering Fair, University of Tennessee, April 5−8, 2004. With S. Pfiffner.

Co−director, the National Science Foundation sponsored "REU Site: Biogeochemical Educational Experiences − South Africa" 2003−2004. With S. Pfiffner.

D. P. Moser − Pacific Northwest National Laboratories

"Snapshots in the darkness: probing the subsurface biosphere by ship, shovel, and ultradeep mines." University of Guelph, Department of Environmental Biology, Guelph, Ontario Canada − February 2004.

"Deep continental biospheres: new insights from lake sediment and the world's deepest mines." Denver University, Department of Biology, Denver CO − February 2004.

"Three billion years from daylight: exploration of subsurface microbial ecosystems via ship, shovel, and the world's deepest mines." Desert Research Institute, Reno March 11, 2004. Desert Research Institute, Las Vegas March 12, 2004.

T.C. Onstott − Princeton University

Public Outreach : T.C. Onstott and David Klassen, an interview on WHYY Public Radio, Philadelphia, with Marty Moss−Coane − "To the Moon, Mars and Beyond." January 16, 2004. http://www.whyy.org/cgi−bin/RTsearcher.cgi

Public Outreach : "Mars Rovers and the Searching for Life on Mars." Lecture for Princeton Charter School, 6th grade. April 13, 2004.

In Progress: Public Outreach : New York Museum of Natural History, video for exhibit on life in extreme environments. With Lynn Rothschild, Chris McKay and John Baross.

Student work: Jessica Garvin, senior thesis entitled "The Geology of Eagle Crater."

S.M. Pfiffner – Tennessee

"Adventures in South African Gold Mines: A Model to Study Extraterrestrial Life." (PDF) University of Oklahoma, Oct. 24, 2003, East Tennessee State University, Feb. 11, 2004, Florida A&M University, Feb. 20, 2004.

"Biogeochemical Educational Experiences – South Africa (BEE–SA)" (PDF), Research Experience for Undergraduates (REU Site) June 11 – August 2, 2004.

Public Outreach: Request for information on IPTAI from Congressman John J. Duncan, Jr. – March 4, 2004 (PDF).

Public Outreach – Carnegie Institution of Washington's Interactive Exhibit on hydrothermal vents at the Southern Appalachian Science and Engineering Fair, University of Tennessee, April 5–8, 2004.

Education – K–12 teachers: IPTAI funded three high school science teachers (two women and one man, covering east Tennessee, Knoxville and Virginia) to attend the NAI teacher workshop, Astrobiology Institute for Teachers at the University of Hawaii–Manoa, Honolulu, Hawaii. The workshop was held June 14 – 18, 2004 and was led by Mary Kado'oka (EPO lead for the University of Hawaii). In August the teachers will meet with Dr. Pfiffner to discuss the various plans the teachers have for disseminating what they have learned to area schools.

Education : "Biogeochemical Educational Experiences – South Africa (BEE–SA)" Research Experience for Undergraduates (REU Site), June 11 – August 2, 2004.

T.J. Phelps – Oak Ridge National Laboratory

"Life at the Extremes of Temperature and Salinity, Particularly as Related to Astrobiology." Brown University, Oct. 2003.

"Subsurface Biogeochemical Processes and Potential Applications for the 21st Century."

L.M. Pratt – Indiana

Public Outreach: Brownie Math and Science Day, October, 2003.

Public Outreach: "Exploring the Subsurface of Mars" iMars Technology and Space Exploration, School of Informatics, Indiana University Bloomington,

February 23, 2004 (PDF). With D. Bish. website: www.iustv.com (under "video archives" February 26)

Public Outreach: The Friday Zone , Friday Zone Pro: Videotaped meeting with 10 year−old children, challenging them to become Martian scientists. With D. Bish. Program airs every Friday on PBS statiions WTIU and WFYI in Indiana. February 17, 2004. Public Outreach: Indiana University College of Arts and Sciences Advisory Board Presentation, "Indiana−Princeton−Tennessee Astrobiology Initiative Detection of Biosustainable Energy and Nutrient Cycling in the Deep Subsurface of Earth and Mars." February 6, 2004.

Public Outreach: NASA Astrobiology Science Conference panel debate, "Terraforming Mars." NASA Ames Research Center. Sponsored by Astrobiology Magazine. March 30, 2004.

Public Outreach: Phi Beta Kappa Fellows Lectureship, Augustana College, Iowa, "If we encounter life on Mars, will we recognize it as living?" April 19, 2004.

Public Outreach: Phi Beta Kappa Induction Banquet, Indiana University Bloomington, "Detection of Biosustaining Energy and Nutrient Cycles in the Deep Subsurface of Earth and Mars." April 27, 2004.

In progress: Public Outreach: NOVA PBS television interview, May 3, 2004.

Course Development

Princeton University: Geo255−Life in the Universe Are we alone? Discoveries of microbes at great depths on Earth raise the prospect of life beneath the surfaces of Mars and Europa. Increasing numbers of extra−solar planets discovered nearby offer targets for NASA space telescopes searching for life in the next decade. Advances in our understanding of life's origin and evolution on Earth are guiding our search for life elsewhere. This course introduces students to a new field, Astrobiology, where scientists trained in biology, chemistry, astronomy, and geology combine their skills to discover life's origins and to seek extraterrestrial life. Students will experience first−hand the diverse techniques used to study extremophiles in hot springs and on future Mars missions during an excursion to Yellowstone.

Indiana University: Geomicrobiology Graduate Course at Indiana University Spring 2004.

Geomicrobiology provides an introduction to microbiology for graduate students with interests ranging from biogeochemistry, ground−water microbiology, extremophile ecosystems, and astrobiology, to origins of life. The first six weeks focused on textbook readings with supporting lectures on microbial classification, growth, metabolism, and genetics, in order to build a conceptual framework and a technical vocabulary. During the second six weeks, dialogue was incorporated into lecture through discussion of recent journal articles. Three papers were covered each week with assigned articles drawn primarily from Science, Nature, Applied and Environmental Microbiology, and

Geochmica et Cosmochimica Acta. The final two weeks of the semester were reserved for student presentations. There were two mid−term exams (30% each) and a three−page executive summary supported by an annotated bibliography with a minimum of 20 journal references (20%). Each student presented a 30−minute oral summary (20%) of their term paper.

Geomicrobiology was offered for the first time in Spring 2004. There were 13 enrolled graduate students with representation from the School of Public and Environmental Affairs, School of Education, and the Department of Biology, in addition to the Department of Geological Sciences.

Astrobiology: Discovering New Worlds of Life Kiosk (Interactive)

University of Tennessee, Knoxville, held the second public demonstration for the Carnegie Institution in Washington Astrobiology interactive kiosk on the deep−sea vents. This activity was designed to introduce Astrobiology and the new IPTAI to the local and regional community of students, parents, and teachers. The event was held April 6−8, 2004 at the University of Tennessee, Knoxville, during the Southern Appalachian Science and Engineering Fair. Posters and flyers were distributed. NASA educational research guides will be distributed to regional schools that participated in the science fair.

Science Teacher Workshop in Hawaii

IPTAI funded three regional high school science teachers (two females and one male, covering east Tennessee, Knoxville, and Gate City, Virginia) to attend the Astrobiology Laboratory Institute for Instructors (ALI'I) at the University of Hawaii, Manoa. The workshop was held June 14 − 18, 2004 and was lead by Mary Kado'oka. In August the teachers will meet with Dr. Pfiffner to discuss the various plans the teachers have for disseminating what they have learned to area schools. Teachers will be meeting with Dr. Pfiffner to discuss opportunities to disseminate information learned at the workshop to area high schools.

Deep−Life Animation and Documentary Video

On August 20th 2004 we are submitting a trailer for a work in progress. The Deep Life trailer will be accessible on a server at Indiana University via this link: http://video.indiana.edu:8080/ramgen/ip/itvideo/iptai_epo_dvd_demo.rm. The work consists of video footage, animation sequences and stills, original music, and text. Over the coming year, this work will be expanded into an interactive DVD for upper−elementary students and high school science honors students. Individual elements can be re−purposed for use in a wide range of public outreach and education efforts. In particular, the documentary footage can be applied to high−definition broadcast products. Production of the Deep Life trailer was done in collaboration with a graduate student in the Indiana University School of Education, allowing development of a script that adheres to U.S. federal knowledge standards for science education.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: Indiana University

Members: Indiana University

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Team Reports: Jet Propulsion Laboratory

Jet Propulsion Laboratory
Executive Summary
Principal Investigator: Kenneth Nealson

For information about the astrobiology research and activities being done at JPL visit http://www.jpl.nasa.gov/

Project Report: Simulating planets around F, G, K, and M stars_Kasting

Project Investigator:	***James Kasting***

Project Progress

This report describes progress made while on sabbatical at Caltech with Vikki Meadows' NAI group. My Penn State activities are described elsewhere. At Caltech, I worked primarily on two projects: 1) Simulating the atmospheres of possible Earth–like extrasolar planets with my postdoc, Antigona Segura, and 2) Calculating the hydrodynamic escape of hydrogen from the early Earth with Caltech postdoc, Chris Parkinson. Progress on the first project has been good. A paper on planets around F, G, and K stars came out in *Astrobiology* last year (2003). We showed that ozone is visible down to O_2 levels of 10^{-2} PAL or thereabouts. A new paper on planets around M stars is being written. We can show that CH_4 is potentially observable along with O_2 (or O_3). The much lower near–ultraviolet (UV) flux, 200–300 nm, causes tropospheric OH densities to be low; hence, methane is long–lived even in O_2 –rich atmospheres of M–star planets. Progress on the second project has been slow. Despite considerable effort over the last year, we do not have a running, transonic escape model. We did code up a new subsonic escape code. We hope to get the transonic code running, but we don't yet know exactly how to fix it.

Highlights

- Earth–like planets were simulated around F, G, and K stars. Ozone should be an observable biomarker on planets around all three types of stars.
- Earth–like planets circling M stars may have high concentrations of CH_4, in addition to O_2 (or O_3). The simultaneous observation of O_2 and a reduced gas like CH_4 is considered the best remote spectroscopic evidence for life.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This project is directly related to TPF. We are building a library of planetary spectra that can be used to interpret future TPF observations.

Cross Team Collaborations

This work overlaps nicely with my work at Penn State.

Publications: Jet Propulsion Laboratory

Segura, A., Krelove, K., Kasting, J.F., Sommerlatt, D., Meadows, V., Crisp, D., Cohen, M. & Mlawer, E. (2003). Ozone concentrations and ultraviolet fluxes on Earth−like planets around other stars. *Astrobiology*, 3: 689−708.

Segura, A., Krelove, K., Kasting, J.F., Sommerlatt, D., Meadows, V., Crisp, D., Cohen, M. & Mlawer, E. (2003). Surface UV fluxes on Earth−like planets around F, G, and K stars [Abstract]. AbSciCon 2004, NASA Ames Research Center, Moffett Field, CA. International Journal of Astrobiology, Supplement 1 (March): 72−73.

Members: Jet Propulsion Laboratory

Team Members sorted by current team.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Team Reports: Johnson Space Center

Johnson Space Center
Executive Summary
Principal Investigator: David McKay

For information about the astrobiology research and activities going on at Johnson Space Center visit http://www.jsc.nasa.gov/

Team Reports: Marine Biological Laboratory

Marine Biological Laboratory
Executive Summary
Principal Investigator: Mitchell Sogin

From Early Biospheric Metabolisms to the Evolution of Complex Systems

Early life forms:

One central theme in Astrobiology is to investigate how ancient life forms influenced early Earth with reference to the formation of habitats capable of supporting complex biological communities and multi–cellular organisms. Based upon what we know about Earth's 2.2–3.5–billion–year evolutionary history, microbial organisms were its sole inhabitants until the origins of plants and animals, a mere 560—900 million years ago. The general goal of the Astrobiology Program at the Marine Biological Laboratory (MBL) is to investigate early evolving metabolisms and activities that had the potential to reshape planetary environments, and to understand the evolution of genome architecture that led to more complicated life forms. These studies contribute to flight–related missions through the development of life detection technologies and design of models for remote sensing of bio–signatures. Many of our projects focus on the evolution of single–cell organisms and complex microbial communities that live under extreme conditions including anoxic and iron–rich environments. Others use microbial model systems (both free–living and symbionts of metazoans) to understand the evolution of metabolic innovation and mechanisms that govern genome evolution. Our genomic, microbial and metabolic diversity–related investigations take advantage of high–throughput DNA sequencing capacity at the MBL and powerful computational systems for phylogenetic inference.

The importance of microbial–centric studies of astrobiology reflects the key role that these organisms have always played in biogeochemical processes on Earth. Microbes of untold diversity are the primary catalysts of energy transformation, and are responsible for > 98% of the carbon and nitrogen cycling [1]. An estimated 3.6 x 10^{30} microbial cells with cellular carbon of ~3 x 10^{17} grams may account for more than 90 percent of the total biomass [2]. Given the ability of microbes to transform Earth's environment from one that was highly reducing to a habitat that is capable of supporting complex, oxygen breathing, multi–cellular organisms, we hypothesize that life on other planets will also be microbial in form. The general goal is to understand patterns and mechanisms of genome evolution and metabolic variation that allowed diverse

microorganisms to adapt to new environments, generate novel phenotypes, and evolve processes that led to environmental changes on a global scale, some of which can be detected through remote sensing.

Metabolisms in extreme environments:

Our investigations of early metabolic evolution focus upon phylogenetic analysis of functional genes from hydrothermally altered anoxic sediments of Guaymas basin in the Gulf of California, the Deep subsurface from the Peru Margin, the acidic, iron−rich, heavy metal laden Río Tinto of southwestern Spain, and cultured isolates from anoxic marine sediments or the Juan de Fuca ridge.

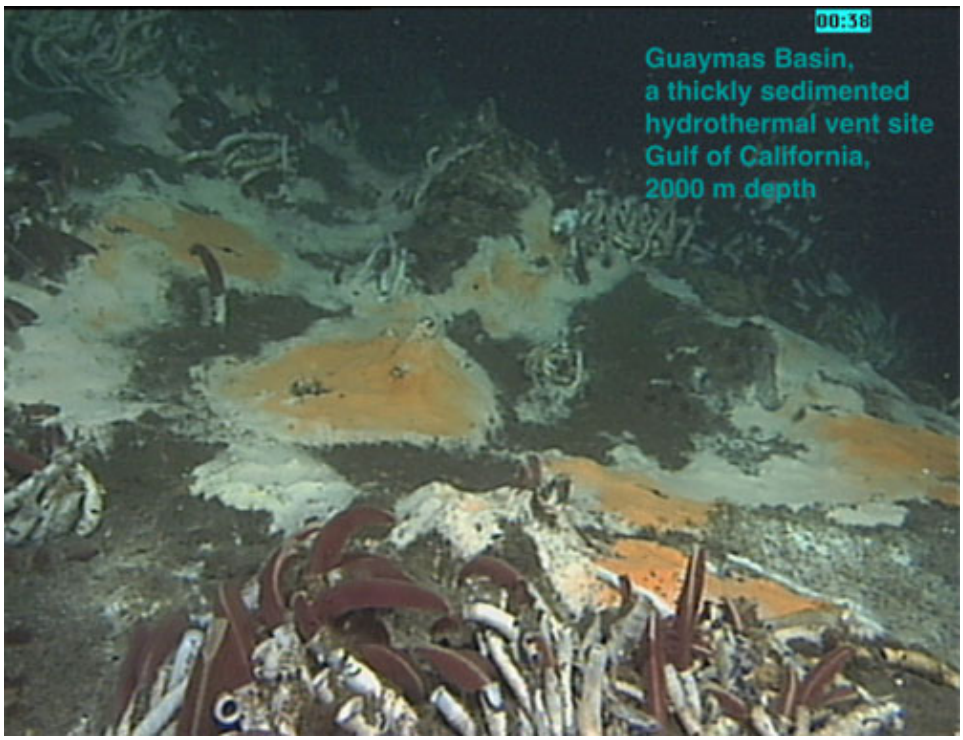

Figure 1. Guaymas Basin Ecosystem. Hydrothermally active sediments in Guaymas Basin and Yellow and Orange Begginton mats grow where sulfidic vent fluid diffuses up from the sediment. Anaerobic CH_4 and S cycling in these sediments is catalyzed by a diverse community of sulfate reducers, methanogen archaea and methanotrophic consortia, including members of novel, deeply branching lineages.

These environments most likely reflect conditions on early Earth or a wetter Mars. Life on early Earth developed within an anaerobic environment and evolved physiologies and metabolisms that were ancestral to modern−day sulfate−reducing, methanogenic, and methane−oxidizing microbes. Our initial surveys of functional genes targeted the anaerobic pathways of sulfate reduction (dissimilatory sulfite reductase (*dsr*)) [3] and methanogenesis (coenzyme M methyl reductase (*cmr*)). We are expanding these investigations to include genes associated with the reductive TCA cycle and iron oxidation. All of these investigations rely upon microbial population structure analyses

(based upon sequence analysis of polymerase chain reaction products for rRNA genes) to link evolutionary studies of functional genes with specific classes of microorganisms (Palacios, Amaral Zettler and Sogin, manuscript in preparation).

Microbial population structures in extreme environments: Based upon full length rRNA sequence analyses we previously reported unexpected eukaryl diversity in both the Guaymas basin and Río Tinto [4, 5].

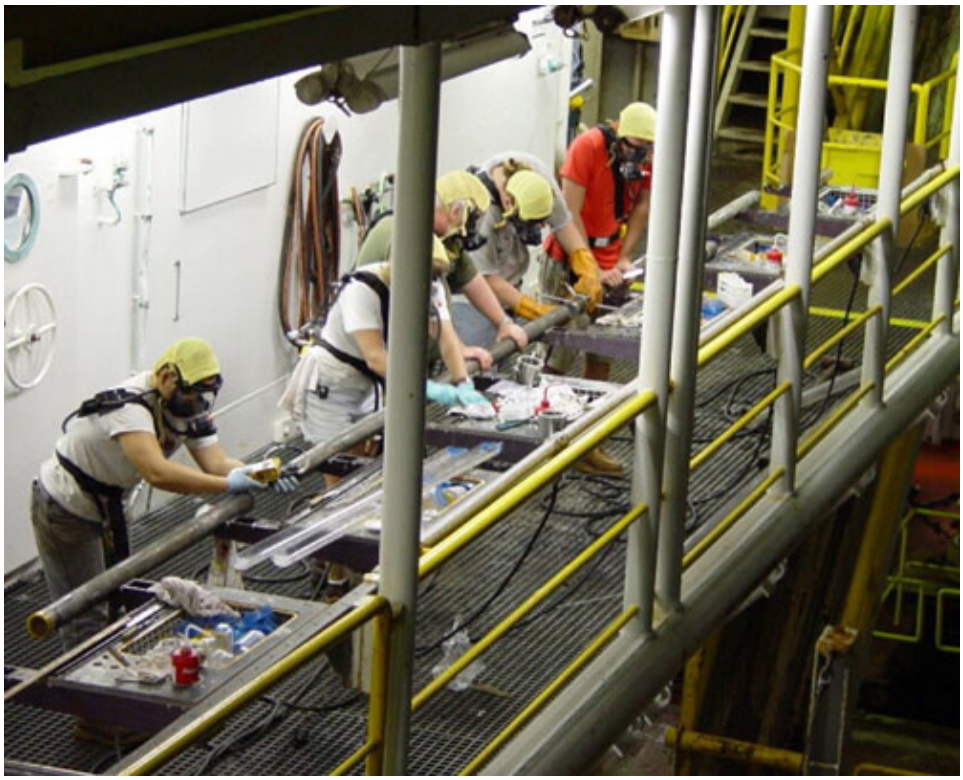

Figure 2. Night sectioning of a freshly retrieved deep sediment core from the Peru Margin. The core is rich in the poisonous gas H2S that is produced by sulfate−reducing bacteria that are active in the deep subsurface; protective masks have to be worn by the shipboard technicians. The subsurface microbiota in these organic−rich cores (sites 1227 to 1230) were investigated with multidisciplinary approaches (molecular biology, dominated by subsurface lineages (Chloroflexi phylum, JS1 phylum; DSAG archaeal lineage) that occur consistently in the subsurface.

In contrast, bacterial diversity is much lower with polymerase chain reaction (PCR) amplicons representing only about 1/3 of the known phyletic diversity of bacteria in Guaymas and only a handful of different kinds of bacteria from the Río Tinto. To expand these descriptions of microbial population structure Kysela, Palacios, and Sogin developed a high throughput technology, serial analysis of ribosomal sequence tags of the V6 (SARST−V6) [6], for characterizing microbial population structures at the DNA sequence level. With this technology we capture sequence information from many more microbial taxa at 1/10th the cost of more traditional sequence analyses of PCR amplicons for full−length rRNA genes.

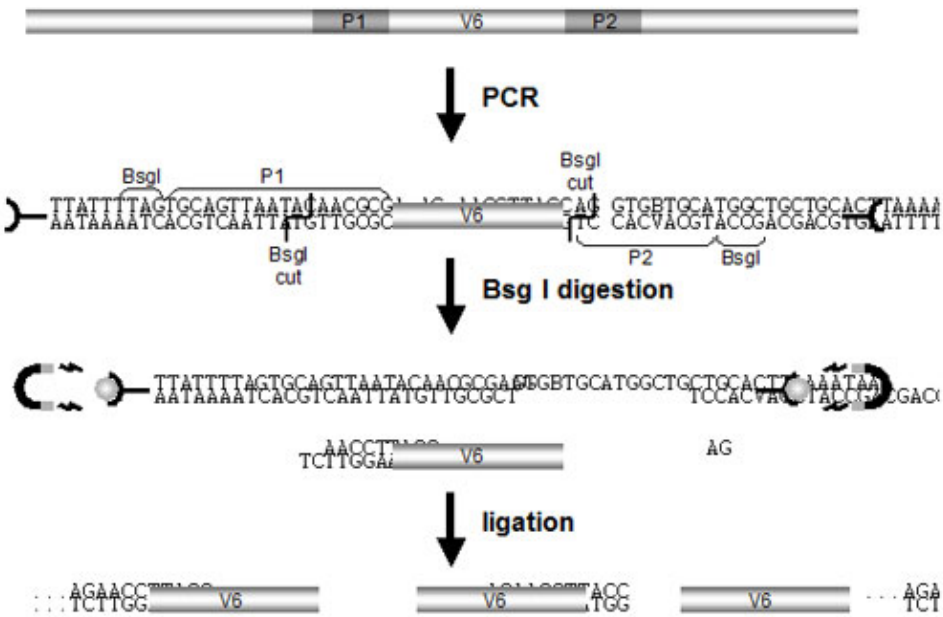

Figure 3. Overview of the serial analysis of V6 ribosomal sequence tags (SARST−V6) method. Biotinylated PCR primers target conserved sites flanking the V6 hypervariable region of the 16S rRNA gene. Primers include a 5 linker sequence containing the recognition sequence for the type IIs restriction enzyme BsgI. Digestion by BsgI results in DNA cleavage 16 bp downstream of the recognition sequence on the sense strand and 14 bp downstream on the antisense strand, leaving a 2 bp overhang at each end of the amplicon. Digested termini are purified away using magnetic streptavidin−coated beads. Ligation of digested amplicons yields concatemers with multiple, serially arranged PCR products. Sequence regions are not to scale.

In brief, SARST−V6 produces sequences of large concatemers of PCR−amplified ribosomal sequence tags (RSTs) from homologous V6 hypervariable regions in rRNA genes. Comparison against a comprehensive rRNA gene database identifies the taxonomic assignment of individual RSTs in the concatemers. SARST−V6 thus evaluates the diversity and relative numbers of different rDNA amplicons from a heterogeneous microbial population. Since SARST−V6 allows for the sampling of 10−20 rRNA genes by sequencing both ends of a single cloned PCR amplicon, we obtain improved statistics for descriptions of different kinds of microbial taxa in environmental DNA samples. There was excellent correspondence between the SARST−V6 analysis and full−length rRNA studies from Guaymas basin cores. In the case of the Río Tinto, SARST−V6 reported all of the microbial taxa described using more traditional microbial ecological methods. It also identified new microbes that were not detected in full−length sequence analyses of PCR amplicons of rRNAs from the Río Tinto including taxa observed in geographically remote acidic environments such as Iron Mountain.

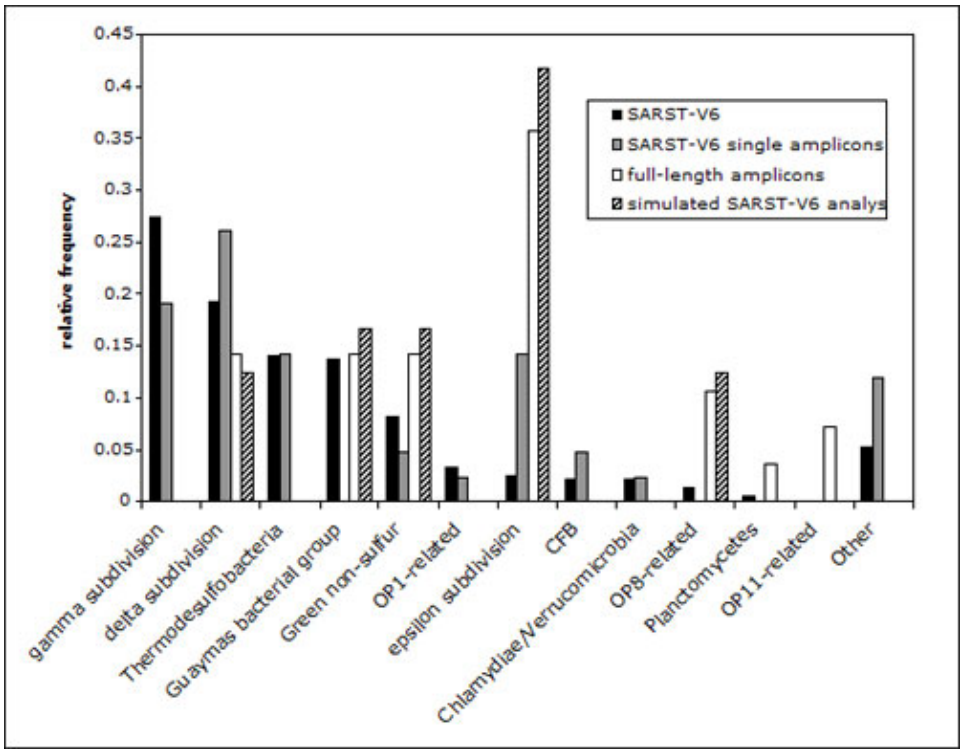

Figure 4. Bacterial phylotype distributions obtained using SARST−V6 and other analysis methods. All data were collected on hydrothermally heated sediments from the Guaymas Basin (Gulf of California). Results of four analyses are shown: SARST−V6 (black; N=364), single amplicon cloning using SARST−V6 primers (gray, N=42), phylogenetic analysis of full−length 16S rRNA gene clone sequences (white, N=28) and a simulated SARST−V6 analysis of full−length sequences (hatched, N=24). Except for phylogenetic analysis of full−length gene sequences, taxonomic assignments were based on results of BLAST searches of the Genbank nt database.

Sulfite Reducatases: We have previously reported on the diversity of the dissimilatory sulfate reduction genes (*dsrAB*) [3] and recently included those sequences in a phylogenetic analysis of conserved active centers from both dissimilatory and assimilatory sulfite reductases [7]. Dhillon and Goswami demonstrated that these activities are phylogenetically linked through an ancestral monomeric reductase. A gene duplication of the reductase generated the assimilatory and dissimilarity forms with the latter undergoing a second gene duplication for form dsrA and dsrB prior to the split between bacteria and archaea. We have now expanded the surveys of functional genes through studies of mcrA, the alpha subunit of methyl−Coenzyme M reductase.

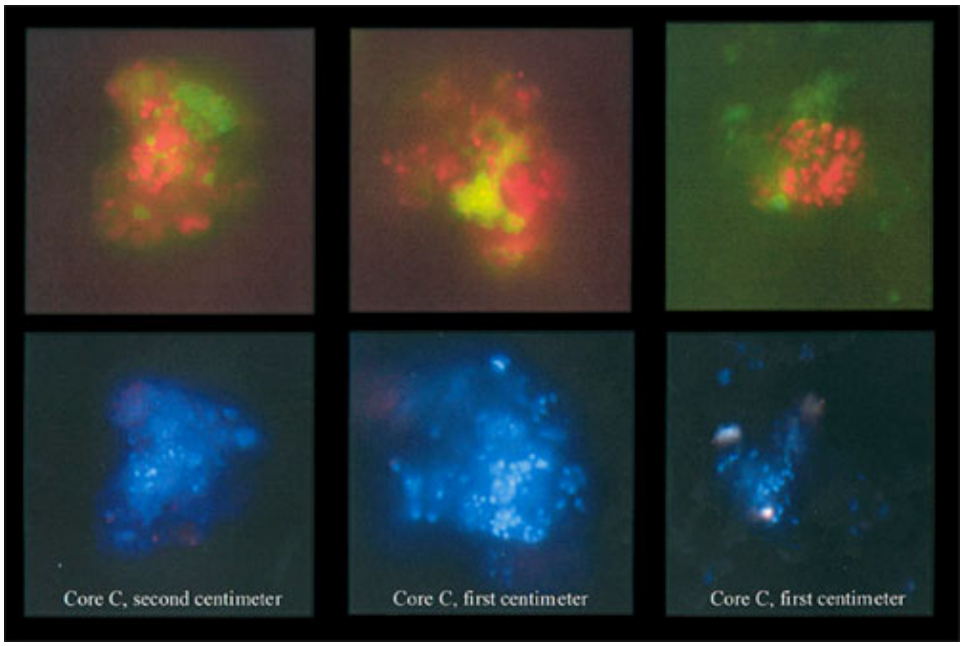

Figure 5. FISH (Fluorescent in–situ hybridization) with 16S rRNA–targeted oligo nucleotides of archael/bacterial consortia in Guaymas Basin. Archaea are stained red, bacteria green, DAPI stained images are blue. These consortia are the likely catalysts of Anaerobic methane oxidation in Guaymas. Photo courtesy of K. Knittel and A. Boetius.

We have identified within environmental DNA samples from Guaymas sediments mcrA genes from the methanogens Methanosarcinales, Methanomicrobiales, and Methanococcales. There appears to be a diversified, partially thermophilic methanogen community in guaymas with several uncultured lineages among the Methanosarcinales and Methanomicrobiales. Within the next year, we anticipate the development of a more comprehensive description of phylogeny and divergence of methanogenic terminal anaerobic degraders based upon evolutionary analyses of several functional genes and rRNA coding regions.

Reductive TCA metabolism: Autotrophic carbon fixation under anaerobic conditions represents yet another putatively ancient pathway for early evolving bacteria. The reductive TCA cycle is essentially the TCA cycle running in reverse, leading to the fixation of 3 molecules of CO_2 and the production of one molecule of triose phosphate. Most of the enzymes between the two pathways are shared, with the exception of two key enzymes that allow the cycle to run in reverse: ATP citrate lyase (ACL) and 2–oxoglutarate:ferredoxin oxidoreductase (OOR). To explore the phylogeny of ACL and OOR, Sievert and Edgcomb selected thirteen thermophillic bacterial and archaeal strains suspected of carrying out reductive for physiological and molecular analyses. Using ten different kinds of media under multiple anaerobic incubation temperatures, they obtained biochemical evidence for the operation of the reductive TCA cycle in two of the e–proteobacteria, and in *Desulfurobacterium autotrophicum* (*Aquificales*). Custom designed primers allowed for the PCR amplification of ACL genes from several cultures and from this limited data set there is congruence between trees inferred from 16S and ACL genes. This suggests that ACL will be a valuable tool for exploring RTCA evolution from

environmental DNA samples isolated from different chemosynthetic environments.

Iron metabolism and iron rich environments: Iron has always played an important role in life's history. Banded iron formations (BIF) date back to the Archean, and proteins with FeS centers are widely distributed in the tree of life. Several of our projects share a common interest in microbial Fe metabolism or growth in Fe−rich environments such as the Río Tinto. The study of environments enriched in iron may provide insights into the biochemistry and metabolisms of the early Earth and ancient Mars. Despite the pivotal role of iron in biological systems, there is only limited knowledge about Fe oxidation as an ancient metabolic pathway. Edwards has isolated several new Fe oxidizing autotrophs from deep−sea cultures.

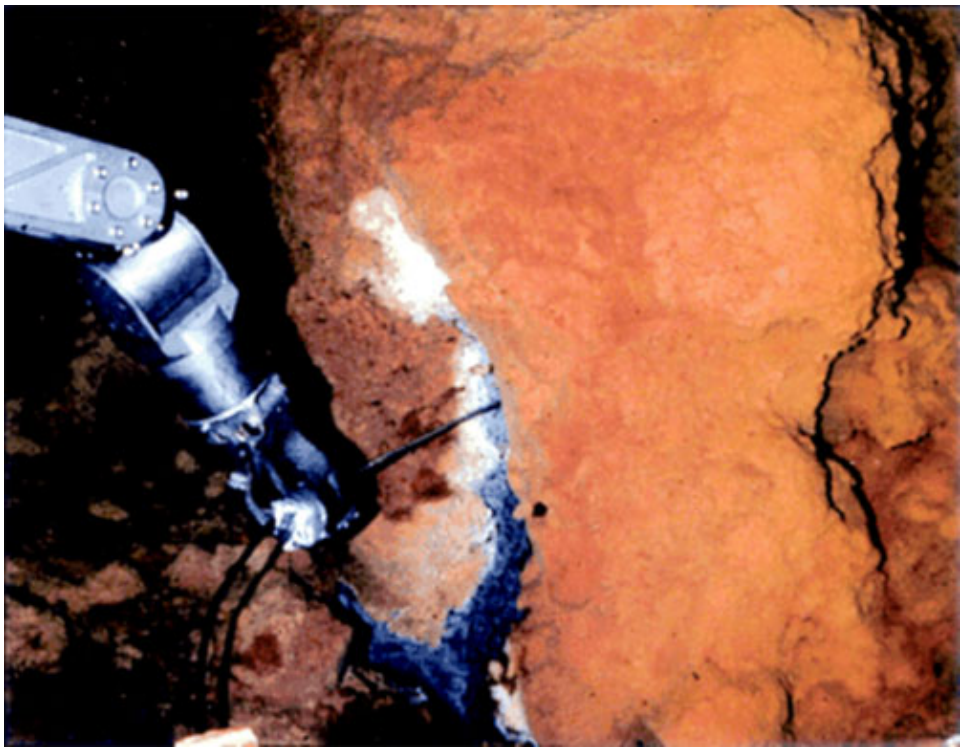

Figure 6. Loihi hydrothermal vent site. A temperature probe is being inserted into the vent orifice; note the extensive deposits of Fe oxides surrounding the vent opening.

These strains will provide an opportunity to explore phylogenetic diversity of neutrophillic Fe metabolism and to establish model systems for molecular metabolic studies. The isolates are facultative autotrophs and/or mixotrophs and most are phylogenetically affiliated with either gamma or epsilon proteobacteria. *Marinobacter aquaeoloi* serves as a model system for exploring Fe metabolism. It has the growth characteristics of a psychrophilic bacterium with a 35 kDa protein that is up regulated with increasing Fe(II) content in medium. Dhillon, Sogin and Edwards have constructed a shot−gun genomic library that will be used for high throughput DNA sequencing. We have submitted a request to the Department of Energy's Joint Genome Institute (JGI) for full genome sequencing of the library. However, if the JGI is unable to sequence the M. aquaeoloi genome within the next few months, we will take

advantage of the low−cost, high−throughput facilities in Woods Hole to ensure the rapid analysis of the *M. aquaeoloi* genome. To identify genes involved in iron metabolism, Edwards has developed a novel plate−based screening assay that relies upon formation of colored colonies for the detection of Fe oxidation. This assay will facilitate the optimization of conditions for transposon mutagenesis and for the cloning of genes involved in Fe oxidation into *E. coli*. Using a 40−kb DNA fosmid insert library from *M. aquaeoloi*, Dhillon has transformed *E. coli* and the observed changes in colony coloration (pinkish−brown colonies) are consistent with development of functional iron oxidation under neutral conditions in the presence of ferric chloride. Dillon and Edwards will use the same assay to identify recombinant clones with iron oxidation activities from large insert libraries of environmental DNAs extracted from Fe−oxidizing mats. In a similar manner, Amaral Zettler and Edwards will isolate eukaryotic genes that play a role in iron oxidiation from the Río Tinto.

The development of this plate−based functional assay for iron metabolism will play an important role in a new project to be carried out by Julie Huber who recently received an NRC/NAI Post Doctoral award. Her project will explore the genomic context of different functional genes in geographically distinct environments that have similar, if not identical, water chemistries. While molecular and culture studies have revealed a phylogenetically and physiologically diverse microbial community indigenous to the subseafloor, very little is known about either its genetic content or its functional and metabolic potential. Genome studies suggest that functional genes can shuttle between microbial lineages. If early life experienced higher levels of lateral gene transfer than contemporary communities, this may have allowed microbes to reassemble or borrow genes, thus facilitating adaptation into diverse anaerobic thermal habitats. Whether similar processes are dominant factors in reshaping adaptation by microbial populations today is unknown. With the development of functional assays that can interrogate large insert libraries prepared from environmental DNA, we predict that it will be possible to define the role of horizontal gene transfer in natural settings. The ability to identify genes responsible for Fe oxidation according to function rather than sequence similarity (as is commonly done for PCR−based studies) will allow us to examine the genomic context of genes that have a clearly defined function.

A Fe−rich Terrestrial Analogue for Early Mars – Río Tinto: Investigations of microbial diversity and population structure in the Río Tinto will link shifts in microbial communities with changes in

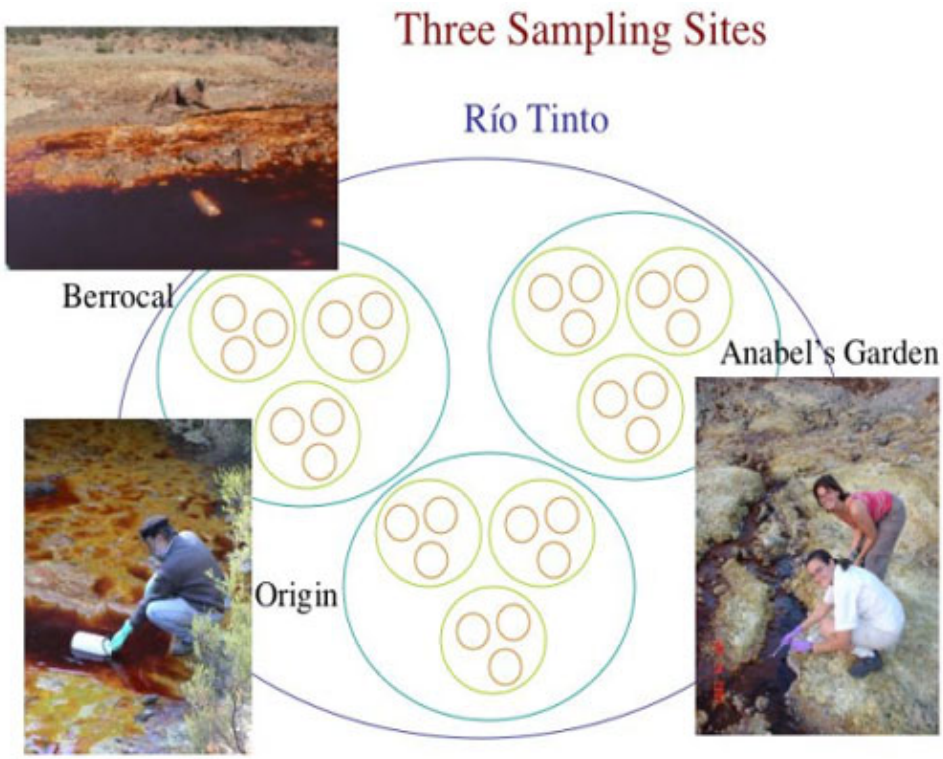

Figure 7. Sampling strategies for microbial population structure studies in the Rio Tinto. The Origin is generally more acidic and has higher iron concentrations (>20 mg/ml) than other locations. Anabel's Garden supports large biofilm communities and elevated levels of ferrous iron. Berrocal has the highest flow rates and is sometime anoxic.

water chemistry. Two sampling trips, the fall of 2003 and January of 2004, correspond to the dry and wet seasons. Using three stations where different oxidiation states of iron are present, Amaral Zettler and Palacios of the MBL and Ricardo Amils of Centro de Astrobiologia (CAB) have sampled DNA, collected physico−chemical parameters consisting of *in situ* (pH, oxygen, redox, temperature and conductivity) and *ex situ* (S, Fe, Zn, Cu, Al, As, Ni, Mg, Ca, K, etc.) measurements, and preserved formalin samples for bacterial and protist enumeration. Using SARST−V6 described above, we are developing in−depth studies of microbial population structure for both eukaryotic and prokaryotic organisms. In addition to collection of 70 full−length rRNA PCR amplicon sequences, Palacios has also recovered more than 4,000 SARST sequenced tags for calculating alpha and beta diversity indices. The SARST diversity data will be combined with the physico−chemical parameters in analyses that will reveal important aspects of the biogeochemistry of this extreme environment. To date, the analysis of the 70 full−length sequences revealed the presence of phylotypes not detected in previous studies including members of the archaeal “alphabet” plasmas, close bacterial relatives to taxa found in other acidic extreme environments and examples of anaerobic amoeboid protists. The SARST−V6 analysis

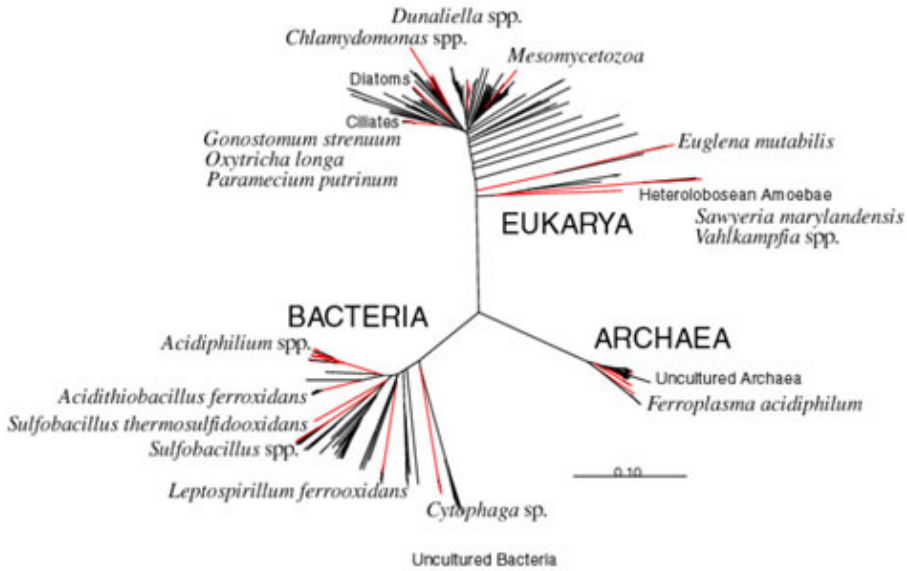

Figure 8. Phylogenetic tree of nearly full–length rRNA genes isolated from the Rio Tinto sampling sites. The red lineages indicate the phylogenetic placement of a limited number of small subunit rRNA environmental clones derived from specific bacterial, archaeal and eukaryotic PCR amplicon clone libraries. The actual phylogenetic affinity of the environmental clones is indicated by labeled lineages. This tree shows the minimal range of phylogenetic diversity of the three domains of life present in the Rio Tinto.

detected the same bacteria in the Río Tinto as reported using other microbial ecology methods, plus candidate novel organisms for extreme environments including free–living bacteria, parasites and endosymbionts. In conjunction with the microbial population structure studies and biogeochemical measurements for the Río Tinto sampling sites, the geologists in our NAI team are developing a strategy for remote sensing of the Río Tinto that will be applicable to Mars. The development of spectral libraries and databases required for interpreting remote sensing data will be completed next year and will be correlated with shifts in microbial populations and biogeochemicals. The goal is to use the Rio Tinto as a development site for interpreting remote sensing data from the Mars Express instruments.

Microbial symbionts and the evolution of genome architecture:
Evolutionary comparisons of genome sequences (phylogenomics) provide compelling evidence that horizontal gene transfer serves a major role in the evolution of genome architecture. Symbioses in which an organism inhabits the cytoplasm of a second organisms has the potential to accelerate horizontal gene flow and to influence genome evolution. The origins of mitochondria and chloroplasts are well–documented examples. These organelles were derived from alpha proteobacterial (mitochondria) or cyanobacterial (plastids) symbionts. The genomes of these organelles experienced major change including shifts in base composition, reductions in genome complexity, and transfer of key coding regions into the host genome. These events occurred over long evolutionary time frames, but we know little about underlying mechanisms. In contrast, studies of contemporary bacterial symbioses in animal hosts offer an opportunity to explore mechanisms that might explain the

remodeling of symbiont and host genome architecture. Wernegreen's and Bordenstein's genome studies of divergent bacterial symbionts in insects have shown there is retention of genes according to the nutritional physiology of specific hosts and they offer hypotheses to explain radical shifts in base composition for endosymbiont genomes [8]. The movement of genes also involves newly discovered bacteriophages of Wolbachia which appear to move laterally between divergent strains, and may shuttle chromosomal genes [9]. Sequence analysis is now complete for the full genome of *Blochmannia* associated with *Camponotus pennsylvanicus* (i.e., *B. pennsylvanicus)*, totaling 19,480 reads (15.4 Mb total) from a short−insert genomic library to obtain 12−fold coverage of this 792 kb chromosome and efforts to annotate this closed genome are underway with Dr. Monica Riley's group.

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Project Report: Recognition of Theoretical Environments on Mars

Project Investigators:	***James Head , John Mustard***

Project Progress

This is the first year of our effort in the Marine Biological Laboratory (MBL) NAI. Our accomplishments have largely been in developing foundations for future research efforts from our ongoing research on the effects of changes in the climate of Mars on surface deposits and implications for the presence and state of water on the surface. Our preparatory work has included developing spectral libraries and databases necessary for the interpretation of remotely−sensed data of Mars and the Rio Tinto site, and developing linkages necessary to complete the first phase of research which we plan to begin more fully in the second year of the investigation. We have identified a graduate student to begin work on this project beginning in the fall of 2004, and have also helped Aline Gendrin attain a NRC post doctoral to work on the project. She will begin in the fall of 2004 as well. One primary objective of our research is to methodologies and understanding from the Rio Tinto site that could be used as exploration tools for Mars. Over the last 6 months we have been working with the data from Mars Express instruments HRSC (High Resolution Stereo Camera) and OMEGA. Both have returned spectacular data that will be integrated into the analyses planned for data collected during the field and laboratory phases of the Rio Tinto work beginning this fall.

Highlights

- A foundation has been established to fulfill the primary research objectives of our project through the development of spectral library databases and calibration of HRSC and OMEGA data for analysis in the context of the Rio Tinto results.
- Using data from the recent Mars missions (MGS and Odyssey), we showed multiple lines of evidence for surface deposits formed as a result of quasi−periodic climate change on Mars. The observations span a large number of scales (meters−kilometers−100s of kilometers), are of diverse nature (morphology, topography, and chemistry), and are remarkably consistent with models of current and past ground−ice stability. These results all point to the presence of a meters−thick, latitude−dependent surface deposit that is young, ice−rich when formed, and whose deposition is driven by orbitally induced climate

change.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Reconnaissance Orbiter	Co−Investigator
1	Mars Express	Co−Investigator
2	Mars Science Laboratory	Other
3	Astrobiology Field Laboratory	Planning Support

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

We are developing strategies to relate the observations of Rio Tinto and its unique environment to remotely sensed signatures of relevance to existing (Mars Express OMEGA/HRSC) and future (Mars Reconnaissance Orbiter CRISM; MSL) Mars missions.

Project Report: Microbial symbionts: Agents for reorganizing genome architectures.

Project Investigator:	***Jennifer Wernegreen***

Project Progress

Bacterial endosymbionts, intracellular microbes that replicate within the domain of the host cell, have catalyzed the origin of the eukaryotic cell, the evolution of multicellular complexity, and diversification of numerous eukaryotic lineages. Mitochondria and chloroplasts, for example, result from endosymbiotic events of lasting significance that fundamentally changed cellular structure, species diversity, and the range of acceptable habitats of Life. Today, endosymbionts include several important human pathogens as well as diverse mutualistic lineages that are critical to the reproduction and success of their eukaryotic hosts. This project targets associations between bacteria and insects as model systems to study the drivers and consequences of genome remodeling.

During the reporting period, we made significant progress toward understanding the impact of long−term, stable genome interactions on molecular evolution and genome architecture. Our extensive molecular evolutionary analysis of *Blochmannia* and its ant hosts demonstrated strict host−symbiont cospeciation, and revealed extremely rapid evolutionary rates indicating unprecedented mutation rates in this ant mutualist (Degnan et al. 2004). As an extension of this work, we have also completed a phylogenetic analysis of endosymbiotic and free−living bacteria that explicitly accounts for their wide variation in GC content and shows independent origins of primary endosymbionts (Herbeck et al., submitted). We have published two population genetic studies showing exceptionally strong effects of mutational pressure and genetic drift in endosymbionts (Herbeck et al. 2003a; Wernegreen and Funk, in press). In addition, we published a genome−wide analysis of codon and amino acid usage in Wigglesworthia, the long−term obligate bacterial endosymbiont of the tsetse fly (Herbeck et al. 2003b). We used multivariate statistical analyses to test the hypothesis that mutational bias and genetic drift shape synonymous codon usage and amino acid usage in this severely reduced, 697−kb genome. Our results showed that codon and amino acid usage in Wigglesworthia reflect a strong AT mutational bias and elevated levels of genetic drift, consistent with expected effects of an endosymbiotic lifestyle and repeated population bottlenecks. However, these impacts of mutation and drift are apparently attenuated by selection on amino acid composition at functionally conserved, high−expression genes.

Our research on *Wolbachia* , a reproductive parasite, explores the evolution of a dynamic genome–genome interaction. We demonstrated significant genome size variability among parasitic Wolbachia strains (Bordenstein and Wernegreen, in prep). This result sets the stage for comparative genomic analyses to identify changes in gene content that trigger new host associations and symbiont phenotypes. We also documented recombination of an active bacteriophage in Wolbachia strains, and developed a novel hypothesis on the exchange of genetic information between intracellular microbial communities (Bordenstein and Wernegreen, in press). This research is part of the NAI/NRC Fellowship of Dr. Seth Bordenstein, and is described in more detail in his separate report.

Highlights

- Bacterial endosymbionts of diverse insects show similar patterns of genome reduction, strong AT mutational bias, and effects of genetic drift on protein evolution. However, certain distinct features of these endosymbiont genomes (e.g., the specific biosynthetic genes they retain) can be linked to the nutritional physiology of their specific hosts.
- Parasitic Wolbachia strains show considerable genome size variation that may underlie their distinct host ranges and symbiont phenotypes.
- Bacteriophages of Wolbachia play a significant role in the genome flux of this endosymbiont. These mobile elements are widespread among Wolbachia, transfer laterally between divergent strains, and may shuttle chromosomal genes.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Project Report: Microbial diversity and population structure studies in the Rio Tinto

Project Investigators:	***Linda Amaral Zettler , Mitchell Sogin***

Project Progress

As part of our *Microbial diversity and population structure studies in the Río Tinto* , we have carried out two full sampling efforts, in the fall of 2003 and in January of 2004, corresponding to the dry and wet season extremes. We have chosen our stations based on varying concentrations and oxidation state of iron present (see http://astrobiology.mbl.edu/riotinto/ for more detailed information and photographs of the study locations). For each station we have sampled three different sites, with three−fold replication. For each sample, we filtered 2 L of water for DNA extraction and concomitantly collected physico−chemical parameters consisting of *in situ* (pH, oxygen, redox, temperature and conductivity) and *ex situ* (S, Fe, Zn, Cu, Al, As, Ni, Mg, Ca, K, etc.) measurements, and preserved formalin samples for bacterial and protist enumeration. To date, all DNA has been extracted and physico−chemical measurements completed. We plan to use these DNA samples to both build rDNA clone libraries and conduct a three−domain serial analysis of ribosomal sequence tags (3D−SARST) analysis for the three domains of life.

We are currently analyzing the results of both clone library sequences and serial analysis of V6 ribosomal sequence tags (SARST−V6) hypervariable region− a region spanning from 52−152 base pairs in length in known bacteria) experiments on samples collected during a pilot project conducted in October of 2002. We have built bacterial, archaeal and eukaryal clone libraries for one sample from each station. Over seventy unique clones were fully sequenced and used in a three−domain phylogenetic analysis consisting of 300 total taxa. Over 4,000 SARST sequenced tags have also been recovered and used in calculating alpha and beta diversity indices. The SARST diversity data will be combined with the physico−chemical parameters in analyses that will reveal important aspects of the biogeochemistry of this extreme environment. We will summarize these data in a review paper of the diversity in the river and other publications focusing on the microbial ecology to be submitted later this year.

Highlights

- Phylogenetic analyses of full−length sequences revealed additional phylotypes not detected in previous studies including members of the

archaeal “alphabet” plasmas, bacterial sequences related to environmental sequences from other acidic extreme environments, and sequences derived from relatives of anaerobic amoeboid protists.
- SARST−V6 found many of the same bacteria in the Río Tinto as reported using other microbial ecology methods, however, also identified organisms never detected in this extreme environment before such as free−living bacteria, parasites, and endosymbionts.
- Some of the most abundant SARST−V6 sequences matched 100% several other uncultured bacterial organisms not reported in the Río Tinto before but observed in other acidic environments like Iron Mountain.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

Field Expeditions

Field Trip Name: Rio Tinto Sampling	
Start Date: 25 Sept 03	***End Date:*** 27 Sept 03
Continent: Europe	***Country:*** Spain
State/Province: Andalucia	***Nearest City/Town:*** Nerva
Latitude: N 37degrees 43.316 minutes	***Longitude:*** W 06 degrees 33.067 minutes
Name of site(cave, mine, e.g.): Origin, Anabel's Garden, Berrocal	***Keywords:***
Description of Work: Collected water samples for DNA and RNA extraction; measured in situ pH, oxygen, conductivity, redox and temperature; also ex situ geochemical analsyes of major metals using TXRF and ICP methods; collected samples for formalin preservation;	
Members Involved:	

Field Trip Name: Rio Tinto Sampling	
Start Date: 03 Jan 04	***End Date:*** 07 Jan 04
Continent: Europe	***Country:*** Spain
State/Province: Anadulcia	***Nearest City/Town:*** Nerva
Latitude: N 37degrees 43.316 minutes	***Longitude:*** W 06 degrees 33.067 minutes
Name of site(cave, mine, e.g.): Origin, Anabel's Garden, Berrocal	***Keywords:***

Description of Work: Collected water samples for DNA and RNA extraction; measured in situ pH, oxygen, conductivity, redox and temperature; also ex situ geochemical analsyes of major metals using TXRF and ICP methods; collected samples for formalin preservation;

Members Involved:

Cross Team Collaborations

CAB member Ricardo Amils on field related work described above. A review paper is in progress, as well as the first manuscript from the SARST work.

Project Report: Iron Oxidation – Shaping the Past and Present Environments

Project Investigator:	***Katrina Edwards***

Project Progress

The principal objective of our project is to develop a better understanding of the fundamental biology of microbial iron (Fe) oxidation at neutral pH. Though the capacity for Fe oxidation is likely an ancient metabolic pathway, it is to date the least well understood among the major microbial metabolisms. We secondarily wish to explore the potential for Fe oxidation among eukaryotes, using the acid mine drainage system “Rio Tinto” and the eukaryotic culture collection as a model system.

Toward our first objective, we have identified an ideal model bacterium that we have focused most of our efforts on in the past year. Our deep–sea Fe–oxidizing culture collection consists entirely of obligate Fe–oxidizing autotrophs. Many of these are gamma Proteobacteria that are closely related to the common marine heterotrophs *Marinobacter* and *Halomonas* . In testing available cultures of these bacteria, we found that many of them are facultative autotrophs and/or mixotrophs that are capable of oxidizing Fe. We have developed one of them, *Marinobacter aquaeoloi* , as a model bacterium for studying Fe oxidation, because of its advantageous growth characteristics. Using SDS–PAGE gel electrophoresis of cell extracts we have determined that a 35 kDa protein is up regulated with increasing Fe(II) content in medium. We have also developed a plate–based screening assay for the detection of Fe oxidation. This plate–based method is being used to develop a genetic system in *M. aquaeoloi,* which we have determined to be competent, and are in the process of optimizing conditions for transposon mutagenesis. This plate screen will also be used for our second objective with eukarya. Finally, we are working towards genome sequencing of *M. Aquaeoloi* and toward this end have extracted high–molecular–weight DNA and sized the genome, which is 2.555 –2.595 kb. Large insert libraries have also been made (Fosmid).

Highlights

- Identified “model” Fe–oxidizing bacterium: *M. aquaeoloi*.
- Developed a plate–based screening method for *M. aquaeoloi*.
- Determined that Fe oxidation is upregulated in *M. aquaeoloi* in the presence of Fe(II) and a 35 kDa protein can be detected.

- *M. aquaeoloi* is competent and a genetic system is being developed.
- A fosmid library has been constructed with *M. aquaeoloi* DNA.
- The genome of M. aquaeoloi has been sized at 2.555–2.595 kb.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere

Cross Team Collaborations

I collaborate extensively with Dave Emerson on the topic of neutraphilic iron oxidizing bacteria. We have a collaborative field project at Loihi seamount. The methods that we are developing using cultures, specifically the development large insert libraries and application of our plate screening mehod will be used in the collaborative project with Emerson with environmental template material.

Project Report: Genome–Genome Integration: Symbiosis, genetic assimilation, and evolutionary innovation

Project Investigator:	***Jennifer Wernegreen***

Project Progress

Our broader goal is to elucidate changes in gene content and expression patterns that catalyze the establishment and diversification of genome–genome interactions. Using insect–associated bacteria as model systems, we are examining the molecular andevolutionary forces that shape endosymbiotic associations. Our studies target Proteobacterial species that represent both long–term, stable mutualisms and transient parasitic interactions. This research extends our previous project, "Microbial symbionts: Agents for reorganizing genome architectures," under NASA grant NCC2–1054.

Obligate mutualists are ideal models to study extremes of bacterial evolution, as they represent the most radical retooling of genome size and structure known in the prokaryotic world, and include the smallest known prokaryotic genomes (as small as 450 kb, and typically < 1 Mb). Yet, their close phylogenetic relationship to well–characterized free–living bacteria such as *Escherichia coli* enables direct comparisons across species with distinct lifestyles. Our results to date elucidate how genome interactions affect molecular evolution and genome architecture in these long–term, stable mutualisms (Fry and Wernegreen, submitted). We published two population genetic studies showing exceptionally strong effects of mutational pressure and genetic drift in obligate endosymbionts (Herbeck et al. 2003, Wernegreen and Funk, in press). In addition, we completed a collaborative, multivariate analysis of codon and amino acid usage of the five published mutualist genomes (Schaber et al. submitted). This study extends our *Wigglesworthia* genome analysis published last year, and shows variable evolutionary rates and amino acid usage among functional categories.

In the past year, we successfully completed and closed the full genome sequence of *Blochmannia* associated with *Camponotus pennsylvanicus* (i.e., *B. pennsylvanicus)* , totaling 19,480 reads (15.4 Mb total) f rom a short–insert genomic library to obtain 12–fold coverage of this 792–kb chromosome. With consultation of Dr. Monica Riley's group at the Marine Biological Laboratory (MBL), we are using extensive genetic, biochemical and metabolic information available for *E. coli* to refine automatic annotation and metabolic pathway

predictions in this and other endosymbiont genomes. Comparison with the published *B. floridanus* genome shows several differences in gene content; however the two genomes otherwise show complete synteny indicating exceptional genome stability throughout the ~20 MY since they diverged. Building on this genome data, we have identified several candidate "key symbiotic genes" that may mediate bacteria–eukaryotic associations. We have successfully applied reverse transcriptase, quantitative PCR to measure the relative expression of certain loci, including biosynthetic and housekeeping loci of *Blochmannia* .

Standard methods of phylogenetic reconstruction are based on models that assume homogeneity of nucleotide composition among taxa. However, this assumption is often violated in actual datasets. We are examining possible effects of nucleotide heterogeneity among lineages on phylogenetic reconstruction, and aim to develop computationally feasible and rigorous approaches to account for variable %GC content in systematics (Herbeck et al. submitted) . Our initial focus has been intracellular and free–living species in the gamma–Proteobacteria, but the approaches developed should prove useful for studying any group with variable modes and patterns of sequence evolution.

Our research on *Wolbachia* explores genome dynamics in this reproductive parasite that represents a dynamic genome–genome interaction. Our synthetic review article of the recently–published Wolbachia genome notes its distinctly higher plasticity compared to stable mutualist genomes (Wernegreen, 2004). By understanding mechanisms of this plasticity, we hope to elucidate processes that drive this endosymbiont's exceptionally wide host range and diverse biological roles. Using molecular phylogenetic approaches, we have documented lateral transfer and recombination of an active bacteriophage among Wolbachia strains, and developed a novel hypothesis on the exchange of genetic information between intracellular microbial communities (Bordenstein and Wernegreen, in press). Using quantitative PCR, we have successfully measured the relative densities of phage, Wolbachia, and host genomes across several insects showing different degrees of Wolbachia–induced reproductive alterations. These quantitative studies suggest a direct role of phage in symbiont phenotypes. These and other *Wolbachia* projects largely extend upon the NAI/NRC Fellowship of Dr. Seth Bordenstein, and are described in more detail in his separate report.

Highlights

- Genome comparisons within clades of stable mutualists show complete synteny, indicating a lack of inversions, transpositions, or gene acquisition by lateral transfer. This striking genome stability contrasts sharply with labile genomes of free–living or parasitic bacteria.
- Although AT mutational bias and genetic drift affect all loci in endosymbiont genomes, the distinct effects of natural selection at functionally significant genes offers a valuable computational tool to identify pathways that are critical to the bacteria and/or its host.
- Bacteriophages of Wolbachia play a significant role in the genome flux of this endosymbiont. These mobile elements are widespread among Wolbachia, transfer laterally between divergent Wolbachia strains, and

may shuttle chromosomal genes. Preliminary quantitative analysis of phage and Wolbachia dynamics suggests that phage may play role in Wolbachia−induced alterations of insect reproduction.
- Due to extreme heterogeneity in base composition among free−living and endosymbiotic bacteria, the use of nonhomogenous models of sequence evolution that acount for variable GC content provides significant improvement in estimating their phylogentic relationships.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Project Report: Genes that Regulate Photosymbiotic Interactions

Project Investigator:	***Rebecca Gast***

Project Progress

This project focused on recovering and identifying genes expressed in photosymbiotic relationships of planktonic sarcodines. Genes involved with symbiont identification, acquisition, and symbiosis maintenance were of particular interest. Initial experiments concentrated on comparing cDNA populations from the symbiotic and free−living states of a single dinoflagellate symbiont *Scrippsiella nutricula* but were expanded to include comparisons of a known foraminifera symbiont (*Gymnodinium beii*) with a closely related but strictly free−living dinoflagellate, *Gymnodinium simplex* . In all cases, a technique called cDNA Suppression Subtractive Hybridization followed by cloning and DNA sequencing was the method used.

As reported previously, we were successful in isolating and cloning a number of partial gene fragments whose expression was up regulated in the symbiotic state. All of these gene fragments appeared to originate from previously unknown genes. Clone−specific primers were designed for several different clones (E7, B8, and C4 to name a few) and Rapid Amplification of cDNA ends (RACE) used to isolate the full−length genes. Unfortunately, typical RACE amplifications resulted in fragments of only 200−400 nucleotides in length with a short overlapping region of close similarity to the target clone. Because of the large number of separate amplifications needed to generate full−length sequences and extremely limited starting material we were unable to recover full−length genes.

Thanks to additional funding through the Astrobiology supplement we were able to collect a significant number of symbionts from the west coast in April of 2003. The RNA extracted from these samples was used directly in continued RACE experiments and also in an attempt to establish traditional cDNA libraries. We hoped that a cDNA library would facilitate full−length gene recovery and permit better evaluation of their potential identity and function.

1. *Scripsiella* symbiont vs. free−living state comparison results:

   Three clones were identified as potential RACE targets based on their apparent increased expression in the symbiont state. One of these

clones, B8, harbored a long poly−A tail and permitted RACE amplifications in only 1 direction. Amplifications of the other clones were attempted in both directions and were repeated until the longest open reading frame (ORF) was found. Single RACE amplifications of clones B8 and C4 resulted in ORFs of 295 bp and 189 bp respectively. BLAST results showed no strong homology to anything in the GenBank database. Clone E7 was successfully extended by 2 rounds of RACE in the 5' direction (see Figure 1). No stop codons were detected throughout the entire fragment length. The last 225−bp fragment amplified was largely comprised of a repeat sequence. This repeat showed high identity to a fragment of the Cyplasin S gene from the gastropod *Aplysia punctata* . Because of the presence of this repeat, we were limited in our ability to design suitable primers for continued RACE amplifications and were unsuccessful in further extending this fragment.

2. *Gymnodinium simplex/Gymnodinium beii* comparison results:

   Nine clones were identified as potential differentially expressed gene fragments that were up regulated in *G. beii* . Based on apparent expression levels, clone−specific primers targeting clones G8 and F12 were initially designed. A short ~100 bp fragment was recovered from G8 RACE experiments. This fragment included a long poly−A repeat and resulted in a 1020bp ORF. BLAST results of the G8 clone showed high homology to the psaA_psaB photosystem 1 psaA/psaB protein. The clone F12 RACE experiments were all unsuccessful.

3. cDNA library construction results:

   Our goal was to generate a cDNA library of full−length cDNAs. This library was then to be used to screen for differentially expressed genes thus eliminating the need for multiple RACE experiments. A small library of cDNAs from the *Scrippsiella* symbiont of the oceanic chondrophore *Velella velella* was established. These symbionts are known to be identical to the radiolarian symbiont used to generate our clones. Isolation of full−length cDNAs proved difficult, and the titer on the library was low (a common problem for dinoflagellate cDNA libraries). The size range of our library was 250bp−1kb with the average size being roughly 500bp. The number of clones in our library is estimated at 5000. Despite repeated attempts, we were unable to generate clones containing inserts greater than 1kb.

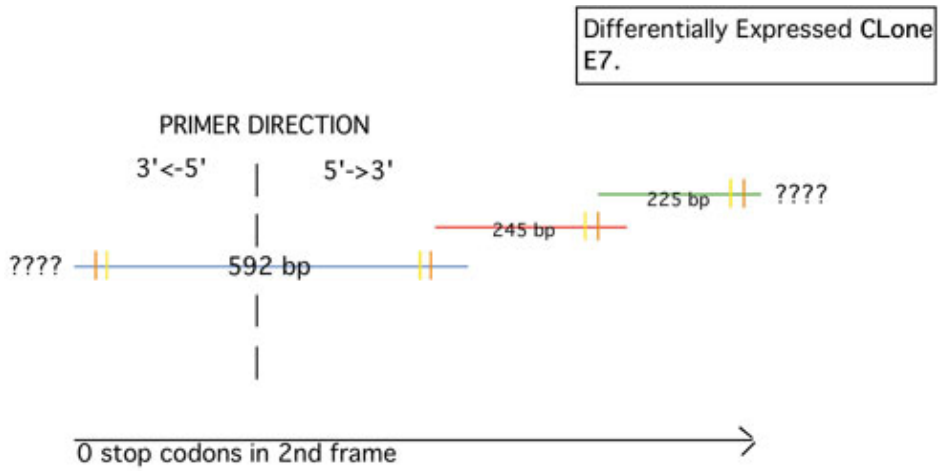


FIGURE 1.

Schematic of clone E7 RACE amplifications. The original clone is shown in blue. Subsequent fragments amplified by RACE are shown in red (fragment 1) and green (fragment 2). Primary and nested primers sites are indicated by orange and yellow respectively.

Highlights

- Three fragments were recovered from subtraction analyses that represent genes upregulated in the symbiotic state of the dinoflagellate *Scripsiella nutricula*. Although still unidentified/novel gene sequences, they represent very promising targets for future symbiosis research.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co–evolution of microbial communities

Field Expeditions

Field Trip Name:	
Start Date: April 7, 2003	***End Date:*** April 10, 2003
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Los Angeles
Latitude:	***Longitude:***
	Keywords:

Name of site(cave, mine, e.g.): San Pedro Chanel	

Description of Work: A small boat was chartered through contacts at the University of Southern California to take the PI out into the San Pedro Chanel area to collect symbiont containing planktonic sarcodines and Velella velella.

Members Involved:

Project Report: Evolution of Proteins

Project Investigator:	***Monica Riley***

Project Progress

To gain insight on the process of speciation of bacteria from earlier ancestors, we have prepared groups of paralogous proteins from different bacterial species and have compared them. Paralogous groups of genes are sets of genes that are related by sequence and seem likely to have descended from a common ancestor. We found that closely related bacteria such as *Escherichia coli* and *Salmonella enterica serovar Typhimurium* have paralogous groups that are almost identical. More distant species such as *Bacillus subtilis* and *Pseudomonas aeruginosa* have related paralogous groups with pronounced differences. We are analyzing the differences between the species in terms of the functions of the genes that are present in one and not the other species. We are able to see in some cases how genes present in one are genes that are appropriate to the environment of that bacterium. Thus we can see how duplication and divergence from the same original ancestral gene took slightly different paths to create bacterial species with different properties, suited to living in different environments.

Highlights

- The course of evolution of biological macromolecules and species of unicellular organisms can be studied by focusing on the events of ancestral gene duplication and divergence in more than one species.
- Common ancestor proteins have given rise by duplication and divergence to families of proteins of similar sequence but expanded functions.
- Not all members of a protein family are the same in different organisms.
- The process of divergence of gene sequences gave rise to proteins appropriate to the life style of each species.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms

Project Report: The evolution and diversity of ancient CO_2–fixation pathways in anaerobic and extremophilic microorganisms: Clues to the early evolution of life on Earth

Project Investigator:	***Stefan Sievert***

Project Progress

This project report reports on the accomplishments of the project "The evolution and diversity of ancient CO_2 –fixation pathways in anaerobic and extremophilic microorganisms: Clues to the early evolution of life on Earth" as part of NNA04CC04A "From Early Biospheric Metabolisms to the Evolution of Complex Systems" (Stefan Sievert – Co–PI, Woods Hole Oceanographic Institution (WHOI)).

We have selected a total of 13 bacteria or archaea on the basis of having, or being suspected of having, enzymes of the reductive tricarboxylic acid cycle (RTCA). Most of the microorganisms were obtained from the German Collection of Microorganisms and Cell Cultures (DSMZ) as active or freeze–dried cultures. Except for two organisms, all are thermophiles that have optimum growth temperatures from 60–100 °C. Incubations at 8 different temperatures within this range were required. Ten different growth media were prepared in serum bottles to re–establish growing cultures from the purchased ones. Since enzymes involved in autotrophic CO_2 fixation can be oxygen sensitive, a procedure to harvest and store cells under anoxic conditions was developed and employed. Cells for nucleic acid extraction were also concentrated and stored by the same method. So far, nucleic acids have been extracted from eight cultures. We have also received deoxyribonucleic acid (DNA) from Constantino Vetriani (Rutgers University) and Ken Takai (JAMSTEC, Japan), with whom we are collaborating on these questions. All these organisms either belong to the ε–proteobacteria or the *Aquificales* . Using a PCR protocol established in our laboratory we have so far successfully amplified ACL genes from eight cultures. In addition, we are also in the process of obtaining ACL sequences from deep–branching eukaryotes to reconstruct the evolutionary history of this enzyme. So far we have amplified ACL from representatives from seven groups.

We now have biochemical and genetic evidence for the operation of the RTCA in two members of the ε–proteobacteria , and in *Desulfurobacterium autotrophicum* (*Aquificales*). Bacteria of the ε–proteobacteria have been identified as very important members of the microbial community at

deep−sea hydrothermal vents. However, no information exists as to what CO_2 −fixation pathway might be used by ε−proteobacteria or *Desulfurobacterium* . This work is presently being prepared for submission to the *Journal of Bacteriology* .

Highlights

- ε −proteobacteria use the reductive TCA cycle for autotrophic fixation of CO_2 .
    - In recent years, the ε −subdivision of the proteobacteria has received increased attention as small subunit ribosomal RNA genes (ssrRNA) phylogenetically associated with ε −proteobacteria have been frequently obtained from a variety of environments, including hydrothermal vents, the oxic−sulfidic interfaces of Cariaco Basin and the Black Sea, and oilfields indicating their importance in these systems. Recently, several chemolithoautotrophic ε − proteobacteria have been isolated. However, no direct information, i.e., biochemical and genetic, existed prior to our work that autotrophic carbon fixation might be used by these bacteria.
- Autotrophic fixation of CO_2 through the reductive TCA cycle might be more significant and widespread than previously thought.
    - ε −proteobacteria have been identified as a major, if not dominant, component of microbial communities in a variety of extreme habitats (see above). There is data that suggest that many of these organisms could potentially be autotrophs, obtaining energy by oxidation of reduced sulfur compounds and hydrogen with dissolved free oxygen or nitrate , which makes it likely that these organisms contribute significantly to primary production in these systems.
- ACL will prove useful as a functional gene marker to assess the diversity and abundance of organisms utilizing this pathway for autotrophic carbon fixation in the environment.
    - The results obtained so far show that the phylogeny obtained based on ACL sequences is largely congruent with phylogenetic trees based on16S rRNA or 18S RNA. However, clearly more sequence data is needed to further confirm this result.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.1:*** Earth's early biosphere

Project Report: Searching for ancestral sequences

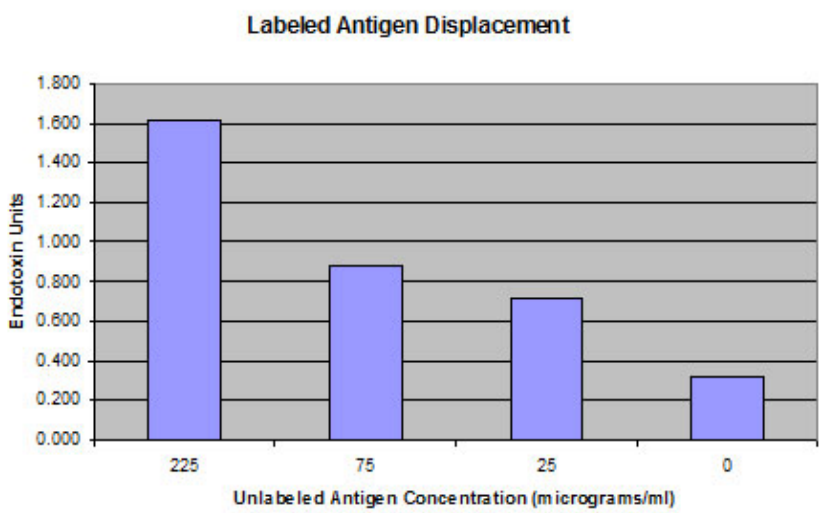
Project Investigators: ***Rebecca Gast , Norman Wainwright***

Project Progress

A major objective of Astrobiology is to search for signs of life in the Solar System and beyond. While remote sensing of biological signatures is a major target for identifying promising sites for future missions, direct analysis of samples for the presence of biomarkers of interest will continue to be an important area for technology development.

This project's main goal is to link the amplification of the Limulus Amebocyte Lysate (LAL) enzyme cascade to biomarkers associated with microbial life, enabling rapid and sensitive detection of life *in situ* . A major sub–goal is to "Use the existing prototype instrument design to collect kinetic spectrophotometric data from competitive labeled antibody assays."

We have demonstrated feasibility of linking lipopolysaccharide (LPS) to an antigen, as the first step toward accomplishing this goal. Fluorescein coupled LPS was captured by anti–fluorescein antibody immobilized on a polystyrene plastic surface. Exposure of the captured label to unlabeled fluorescein resulted in a proportion LAL signal, shown in Figure 1.



Proportional displacement of LPS coupled fluorescein is able to be measured

in Endotoxin Units by LAL after exposure to increasing unlabelled antigen. Assay sensitivity in this example in the microgram range. This relatively low sensitivity is likely due to the low specific activity of the LPS coupled antigen. Future work will improve ratio of LPS label per molecule. We will use a periodate oxidation of the LPS molecule to covalently couple to protein and peptide target sequences. This chemistry will also be attempted with nucleic acid probes.

We have also established a collaboration with Andrew Steele, Carnegie Institution of Washington (CIW) Astrobiology Center . Part of that collaboration was a study of the performance of immunoassays in microgravity (KC−135 flights) that will have direct bearing on our project (Maule, et al., J. Gravitational Physiology, in press 2004). Contrary to our initial concern, antigen/antibody binding was unaffected and in some tests, enhanced in microgravity. We hypothesize that greater liquid mixing may be occurring in microgravity. Collaboration with CIW will link development of our enhanced LAL−coupled immunoassay to CIW's "Lab on a Chip" technology development.

Highlights

- Feasibility of linking LPS to a specific antigen for amplified detection by LAL was demonstrated.
- A collaboration with Andrew Steele at the Carnegie Institution of Washington was established, linking our project to the MASSE “Lab on a Chip” project.

Roadmap Objectives

- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Cross Team Collaborations

Andrew Steele, Carnegie Institution, Washington DC Identified as a collaborator to incorporate this project with MASSE project "Lab on a Chip"

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: Marine Biological Laboratory

Project Report: SARST−V 6 Development

Project Investigator:	***Mitchell Sogin***

Project Progress

During this period of the NAI grant we have completed the development of serial analysis of V6 ribosomal sequence tags (SARST−V6) and its publication. Serial analysis of ribosomal sequence tags (SARST) is a novel technique for characterizing microbial community composition that captures sequence information from concatemers of short 16S rDNA PCR amplicons from complex populations of DNA. We have developed this method for the V6 hypervariable region of bacterial 16S rRNA genes and applied it for analyses of bacterial community composition in hydrothermal marine sediments from Guaymas Basin. Our results resembled those of cloning and sequencing of single, full−length PCR products from RNA genes of the same microbial community. With this work we have demonstrated that SARST−V6 is an ideal methodology for analysis of microbial community composition analysis because of its high−throughput but yet taxonomic information recovery from the microbes present in an environmental sample.

Highlights

- Consolidation of SARST−V6 as an ideal method to study microbial community composition in natural environments because of its high and informative throughput.
- Publication of this methodology developed under the scope of the NAI in a journal widely distributed and read by microbiologists.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities

Project Report: Diversity and physiology of prokaryotes in selected thermophilic and mesophilic environments in selected hydrothermal vents and subsurface environments

Project Investigators:	***Mitchell Sogin , Andreas Teske***

Project Progress

Guaymas Project: The novel, deeply branching dsrAB genes found earlier during the Guaymas project were included in a phylogenetic analysis of dissimilatory and assimilatory sulfite reductases, based on a comprehensive dataset of both enzymes. The phylogeny was based on the highly conserved active centers only, to avoid problems with insufficient full–length homology of these diversified enzymes. Assimilatory and dissimilatory enzymes diverged into two major phylogenetic domains that corresponded to assimilatory and dissimilatory function. Within the assimilatory domain, the phylogeny supports the hypothesis that a small, monomeric reductase was the ancestral form which underwent gene duplication and modification of subunits. Within the dissimilatory domain, the ancestral gene duplication into dsrA and dsrB genes appears to have predated the bacteria/archaea divergence; as a corollary, the split into assimilatory and dissimilatory sulfite reductases must have predated this divergence (Dhillon, Goswami, Riley, Teske, and Sogin, 2004).

We have continued the Guaymas key gene survey with a key gene for methanogenesis, mcrA, which codes for the alpha subunit of methyl–Coenzyme M reductase, the last enzyme in diverse methanogenic pathways. So far, we have identified mcrA genes of major methanogenic families (Methanosarcinales, Methanomicrobiales, Methanococcales) in the Guaymas sediments. The results in detail indicate a diversified, partially thermophilic methanogen community, with several uncultured lineages among the Methanosarcinales and Methanomicrobiales. Analogous to the previous dissimilatory sulfite reductase survey, we are working towards a more comprehensive view of the phylogenetic depth and divergence pattern of methanogenic terminal anaerobic degraders (Dhillon, Lever, Lloyd, Sogin, and Teske, 2004).

Deep Subsurface Project: In collaboration with the University of Rhode Island (URI) "Subsurface Biosphere" NAI group, the phylogenetic analysis of deep marine subsurface sediments is continued with emphasis on organic–poor, low activity sites (Ocean Drilling Program (ODP) site 1225, 1231 in the Equatorial Pacific and Peru Basin). Here, microbial communities persist in low–activity

sediments that show very little geochemical evidence of the predominant marine anaerobic remineralization pathways, sulfate reduction and methanogenesis. So far, the archaeal community in these subsurface sites overlaps with major archaeal lineages found in marine sediments (Benthic marine crenarchaeotal Groups A and B) and with archaea dominant in the deep−sea water column (Pelagic Group I). Several newly found euryarchaeotal and crenarchaeotal lineages at Site 1231 have their closest relatives in hydrothermal vent sites, indicating shared populations between the hydrothermal and the non−hydrothermal subsurface (Sørensen, Lauer, and Teske, 2004).

As a collaborative project with ODP Leg 201 participants, organic−rich sediments of the Peruvian continental shelf (site 1227) and the Peru Trench (site 1230) are surveyed; interestingly, one of the dominant archaeal groups is the Benthic marine crenarchaeotal group B (synonymous with DSAG, Deep Sea Archaeal Group) (Inagaki et al. 2004). This ongoing project attempts a comprehensive inventory of deep−surface microbial lineages, and their occurrence range in the marine subsurface and other habitats.

Highlights

- The phylogeny of highly conserved active centers of sulfite reductase enzymes supports a deep diversification of assimilatory and dissimilatory sulfate−reducing pathways, possibly originating before the bacterial/archaeal divergence.
- Novel diversity of mcrA genes has been found in the Guaymas Basin, with several new methanogen lineages (on family and genus level) within the Methanosarcinales and the Methanomicrobiales.
- 16S rRNA surveys reveal that the deep marine subsurface has its own microbial community footprint that is distinct from the water column or other marine habitats. Specific archaeal phylum−level lineages show a cosmopolitan distribution pattern in the deep marine subsurface.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
3	Concept	Co−Investigator

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:

1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Identification of subsurface microbial life, its phylogenetic diversity, and distribution pattern in response to geochemical controls, such as in–situ chemical and physical regimes.

Field Expeditions

Field Trip Name: JOIDES Resolution cruise to the Juan de Fuca	
Start Date: 6/26/04	***End Date:*** 8/24/04
Continent: North America	***Country:*** US and Canada
State/Province: Washington	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Eastern Ridge Flank of Juan de Fuca	***Keywords:*** Juan de Fuca
Description of Work: My graduate Student Mark Lever (UNC Chapel Hill) is retrieving deep sediment samples from the sediment cover of the hydrothermally active ridge flank at Juan de Fuca, for analysis of microbial populations using functional genes (in particular methyl coenzyme M reductase, the key gene for Methanogenesis).	
Members Involved:	

Cross Team Collaborations

Collaborations with the "Subsurface Biospheres" NAI team at URI, for cruises and retrieval of deep marine subsurface samples, in most cases with JOIDES Resolution within the ODP and IODP program. So far, deep marine subsurface sediment samples were obtained from the Nankai Trough (2000), the Eastern Equatorial Pacific and the Peru Margin (2002; ODP leg 201), from the Hydrate Rudge offshore Oregon (2002, ODP leg 204), the Desmarara Rise offshore French Guyana (2003; ODP leg 207), and hydrothermal water samples from subsurface formation fluid within the sealed ODP borehole 896A on the Cocos Rift offshore Costa Rica (2003) were obtained, for molecular analysis of deep subsurface communities.

Individiuals involved: Steve D'Hondt, David Smith, Arthur Spivack (URI); Kai Hinrichs (WHOI and Bremen University, Germany), Helen Sturt (WHOI).

Current outcomes of the ODP leg 201 are two publications (Inagaki et al. 2004; Soerensen et al. 2004; see list). A ribosomal RNA and Rubisco sequencing survey of the microbiota in the hydrothermal formation fluid from the Cocos Ridge (ODP Borehole 896A) is in progress in the Teske lab (Kate Harris, UNC) and will get into the publication stage next year.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Fellowships: Marine Biological Laboratory

The NAI–NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Seth Bordenstein
Project Title: Genomic determinants of parasitism and mutualism in bacterial endosymbioses
Advisor: Jennifer Wernegreen, Co–Investigator
NAI Lead Team: Marine Biological Laboratory
Fellowship Began In:

Project Report: Genomic determinants of parasitism and mutualism in bacterial endosymbioses

NAI–NRC Postdoctoral Fellow : ***Seth Bordenstein***

Project Progress

We are studying the genetic assimilation events that fashion different prokaryotic–eukaryotic endosymbioses, i.e., mutualism and reproductive parasitism, using the most abundant bacterial endosymbiont on the planet, *Wolbachia* . Our findings have important Astrobiology implications, including insights into small life (bacteriophages and the highly–reduced bacterial genomes of endosymbionts), genome integration, organismal complexity, the evolution of interkingdom associations, and the adaptations of prokaryotic life in a confined environment – the eukaryotic cytoplasm. In this past year, we have taken our original research objectives farther than expected. We generated new genomic data described in imminent publications on lateral transfer and recombination of an active bacteriophage in the parasitic *Wolbachia* . From this work, we developed a novel hypothesis on the exchange of genetic information between intracellular microbial communities, termed the intracellular arena hypothesis; and we showed that bacteriophage elements not only transfer themselves between *Wolbachia* parasites, but they also transfer mobile genetic elements onto the host bacterial chromosome. We completed a comprehensive phylogenetic analysis on the origin of endosymbiotic parasitism and mutualism in *Wolbachia* and are now writing up this work. Ongoing work focuses on understanding the genome size and content differences that underlie endosymbiont lifestyles. We are using microarrays to identify the gene loss and acquisition events that occurred during the radiation of this endosymbiosis. We will map these genome changes onto the *Wolbachia* phylogeny to determine when these events occurred and how they associate with lifestyle. Our research is drawing general conlusions about the early genome interactions that shape endosymbioses and genomic integration.

Highlights

- Bacteriophages can be widespread in endosymbionts that show labile transmission patterns and parasitism.
- Bacteriophages are a major source of genetic flux (i.e., recombination, lateral transfer) in some endosymbiont genomes.
- Bacteriophages can shuttle selfish mobile elements, e.g., transposons, onto the host bacterial chromosome of some labile intracellular bacteria.

- Genome sizes of the parasitic *Wolbachia* are variable.

Roadmap Objectives

- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co–evolution of microbial communities

EPO: Marine Biological Laboratory

These are the Education and Public Outreach activities for the Marine Biological Laboratory.

Falmouth Academy Science Fair

Lorraine Olendzenski interacted with students while judging high school projects related to microbiology at the Falmouth Academy Science Fair.

Science Journalism Program

Team member Linda Amaral Zettler gave a presentation entitled "Microbial Life in Extreme Environments" to students in the Science Journalism Program at the Marine Biological Laboratory (MBL). The Science Journalism Program offers print and broadcast journalists and editors an opportunity to "step into the shoes of the scientists they cover" by awarding them fellowships to study basic biomedical and environmental science at the Woods Hole, MA, laboratory. During their residencies at the MBL, fellows learn what science is like from the inside out as students and researchers in MBL summer courses and laboratories.

Interview with Eric Mellgren

Science writer Erik Mellgren, from Sweden, is researching a book on Astrobiology. Mellgren interviewed team member Linda Amaral Zettler as part of his research on the topic.

MA Audubon Cape Cod Natural History Conference

Team member Linda Amaral Zettler was a co–author of a lecture entitled "Life (almost) everywhere!" at the ninth annual Mass. Audobon Cape Cod Natural History Conference. The talk described the biodiversity found in extreme environments on earth.

Computational Biological Applications to Microbial Diversity and Molecular Ecology, Costa Rica

Team member Linda Amaral Zettler was director and principal instructor for a training course in "Computational Biological Applications to Microbial Diversity" offered at the University of Costa Rica. The primary goals were to provide a hands–on introduction and logical framework to enable students to solve

biological problems in molecular phylogenetics and evolution using computational methods. Students learned about the basic tools of Astrobiology needed to go from environmental sequence data to a phylogenetic tree. The course emphasized software that is freely available or low–priced and that can run on PC or Linux platforms. The workshop covered the use of NCBI's BLAST, Bioedit, Readseq, ClustalX, ARB, ModelTest, PAUP*, Mr. Bayes and TreeView Programs. The course also made use of an extensive list of scientific references distributed in print and PDF formats. The course contained students from diverse backgrounds including the areas of Biological Sciences, as well as Computer Science and Informatics. Lectures included topics ranging from the Origin and the Tree of Life, to tools for solving Microbial Ecology problems, and practical issues in Linux and Windows environments. Problems and results from our Microbial Observatory, which aims to characterize the microbial diversity (Archaea, Bacteria, fungi, protists) of caterpillar guts in a tropical forest of Costa Rica, were used as examples during the course. The course was the first of its kind at the University of Costa Rica. The varied backgrounds of the students fostered natural exchange during the computer laboratory sessions allowing students to share their respective biological and computer expertise. A Certificate of Participation was extended to the students at the end of the course.

Chronicle of Higher Education

CoI Linda Amaral Zettler provided scientific expertise and background information for the article: "Goodbye, Little Green Men. Hello, Astrobiology" by Rich Monastersky. The article addressed the emergence of astrobiology as an interdisciplinary field and was published in the Chronicle of Higher Education on April 2, 2004.

NY Hall of Science

The New York Hall of Science is New York City's only hands–on science and technology center. The Hall features more than 225 hands–on exhibits about biology, chemistry and physics. Martin Weiss, Science Director, is developing a new interactive exhibit entitled "The Search for Life Beyond Our Planet ." The exhibit will include a section on the extreme environment of the acidic Rio Tinto in Spain. Linda Amaral Zettler is providing scientific expertise, images, and culture material for the exhibit.

Living in the Microbial World

Living in the Microbial World is a one–week intensive hands–on workshop for middle and high school teachers, grades 6–12. Our objective is to prepare middle and high school teachers to teach students and other teachers about the importance of the microbial world by incorporating hands–on microbiology activities into existing curricula. During the workshop, resident and visiting scientists from within the Woods Hole community present teachers with background information and current research developments on topics related to the importance of diversity of microbes in natural environments and microbial processes in the biosphere. In addition to presentations, teachers spend most of the time in a teaching laboratory, engaging in easy and inexpensive

hands−on activities that exemplify basic principles of microbiology. During the workshop, teachers hear six lectures from research scientists highlighting the role of microbes in maintaining the biosphere, the origin of ecosystems, biomineralization and chemolithoautotrophy, extremophiles, protist diversity and fungal biology, and symbiosis. Teachers took field trips to the MBL's Marine Resources Center and the Great Sippiwissett Marsh in Falmouth to see microbial mats. Days were structured to include one lecture per day, and the balance of the time was spent doing hands−on activities in the lab. Evening sessions highlighting available Internet and video resources and a tour of the Josephine Bay Paul DNA sequencing facility also took place. Activities included: an investigation of fungal biology using an inquiry approach; culturing of basidiomycetes using sawdust culture techniques; making simple agar media; soil sample dilutions; measuring oxygen profiles in microbial mats, making Winogradsky columns; construction of plankton nets, Uhlig extractors, and coverslip traps for collecting microorganisms; observation of termite hindgut microbes; and demonstration of the effects of naturally produced antibiotics on microbial growth. Three lab options involving culture of bacteria and slime molds were offered simultaneously: culture and isolation of luminescent bacteria, culture and isolation of lactic acid bacteria, and investigation of slime mold behavior. Culture and isolation of antibiotic−resistant bacteria from alfalfa sprouts was also demonstrated. Astrobiology teaching materials were highlighted in a one−hour demonstration of the Website microscope and in an exploration of other Astrobiology websites. This workshop is offered yearly. This year University of Hawaii and MBL are sponsoring three teachers from Yap, Micronesia to attend the workshop.

Falmouth Academy Biology

Team member Virginia Edgcomb taught a two− week Astrobiology curriculum to three seventh−grade classes (twelve students each) at Falmouth Academy. The students viewed "The Story of Astrobiology" powerpoint presentation and participated in activities from the Educator Resource Guide, including "What is Life?" and "Habitable Planets."

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micro*scope website

The Microscope Website is an innovative biodiversity bioinformatics website that greatly improves access to information about microbes; it is the single best resource for high−quality, downloadable, digital light micrographs of microbes. Presently, the site contains software to manage names and classification; a classification of protists and bacteria; dynamic outlinks for internet searching; original data about microbes; a comprehensive classification of all protist genera and prokaryotes, including 5500 images of microbes with explanatory text; and a variety of educational resources, including Lucid taxonomic guides. Information in the site can be accessed by habitat, cell shape, alphabetic list of genus name, and formal classification. The micro*scope structure proved to be a very effective means of organizing and accessing information about microbes. The generic features are being converted into a template that will be freely available for use as a foundation of other biodiversity−oriented websites. Several such sites are already in development. We are continuing to expand

and improve the site for larger public promotion by ensuring that all aspects work properly. We are adding educational material, including hands−on classroom activities already developed by NAI at MBL, glossary terms, and a tutorial for using Lucid guides. We will be adding a database of available K−12 hands−on activities in microbiology that details which aspects of the National Science Standards are met by each activity.

Lawrence School science projects

Team members Lorraine Olendzenski and Michele Bahr met with middle school students at the Lawrence School, Falmouth, MA, and helped them design individual investigations and projects on space science and astrobiology topics.

UNC: Extremophilic Microbiology and Microbial Evolution

Andreas Teske taught an undergraduate non−majors seminar to freshman entitled "Extremophilic Microbiology and Microbial Evolution" at the University of North Carolina at Chapel Hill (3 credit hours). The course introduced students with no prior exposure to microbiology to a wide range of Astrobiology−related topics including physiology and diversity of extremophilic archaea, molecular phylogeny based on ribosomal RNA with reading of seminal papers by Carl Woese, hydrothermal vents enhanced with original samples of vent invertebrates, and viewing of original video tapes from ALVIN dives, and the early biosphere evolution, based on Andrew Knoll's book "Life on a Young Planet: The first three billion years of evolution on Earth," Princeton University Press, 2003.

Woods Hole Oceanographic Institution − Massachusetts Institute of Technology Joint Program Geomicrobiology students

The Woods Hole Oceanographic Institution (WHOI) Geomicrobiology Group works toward deciphering the co−evolution of earth and life. Co−I Katrina Edwards' research focuses on the role of microorganisms in mediating the rates and mechanisms rock, mineral, and organic matter transformations. Edwards advises graduate student Sheri Simmonson on community structure, biogeochemistry, phylogeny and genomics of marine magnetotactic bacteria and their role in Fe and S cycling, and Peter Canovas and Cara Santelli on microbial Fe and sulfide mineral oxidation at seafloor hydrothermal vents. Erin Banning has recently joined the geomicrobiology Group and hasn't yet chosen her research focus. Team members Andreas Teske and Stefan Sievert, with Edwards, were members of the committee advising graduate student Vanja Klepac−Ceraj. Klepac−Ceraj looked at the diversity and phylogenetic structure of two complex marine microbial communities. She took into account new developments in understanding PCR artifacts and used new statistical approaches toward estimating sampling coverage. Her results reveal an unexpected amount of microdiversity, and contribute to understanding what level of genetic differentiation leads to ecological differentiation. This differentiatrion is a key factor in the evolution of life on a planet with diverse ecosystems.

MBL Microbial Diversity course

Team members Mitch Sogin, Katrina Edwards Stefan Sievert and Andreas Teske presented lectures on their research in the summer Microbial Diversity Course at the MBL. The course is designed primarily for scientists with a substantial background in microbiology who want to isolate, cultivate, and initiate research programs with a diverse range of microbes. The emphasis of the course is on the variety of metabolic pathways and the range of environmental habitats occupied by microbes, similar to the questions posed by NAI. Sievert and Teske spoke on sulfur–oxidizing bacteria, with Teske also lecturing on the microbiology of the extreme environment of hydrothermal vents. Edwards spoke on "Iron Bacteria in the Oceans beyond 16S rDNA Phylogeny: Bioeographical Structure of Archaeal Populations Revealed by Multilocus Screening." Sogin participated in a symposium on Comparative Microbial Genomics.

Life and Living in Space

This three day workshop for teachers focused on various current topics in planetary protection and space life sciences, including microbe detection on equipment destined for spaceflight, growing plants in space, the gravitropic response in plants, and effects of spaceflight and microgravity on the human body. Norm Wainwright (Marine Biological Lab and Johnson Space Center) described his work on developing a rapid detection system for bacteria using the enzyme cascades found in the blood of the horseshoe crab Limulus and the rock crab. He also demonstrated extracting blood from Limulus and showed the clotting response of the blood in the presence of bacterial lipopolysaccharide. Robert Phillips (Colorado State University and NASA Life Sciences Outreach) gave a lecture on trends in food and nutrition in space and the effect of spaceflight on the physiology, anatomy, and life cycles of a variety of organisms. Mary Musgrave (University of Massachusetts Amherst) presented an overview of her research into the problems of growing multiple generations of plants in space, in particular the fertilization of plants and production of viable seeds. Lab activities included testing the effectiveness of different cleaning methods on equipment surfaces and assessing the results using enzyme cascade reactions. We also explored the effect of induced gravitational effect on plant growth (Which Way to Grow? activity), and observed the response of the human vestibular system to spinning motion.

Planetary Protection: Policies and Practices

Lorraine Olendzenski and Michele Bahr presented an introductory lecture to the microbial world and laboratory exercises on basic microbiology principles for the course "Planetary Protection: Policies and Practices." The course is designed to familiarize current and future planetary protection practitioners with NASA and Committee on Space Research (COSPAR) Planetary Protection policies, and with the practices and procedures necessary to implement Planetary Protection procedures during the conceptualization, design, fabrication, assembly, launch, operation, and recovery of solar system exploration missions. The course combines presentations with a laboratory

component emphasizing general microbiology and current planetary protection protocol. Presentation topics by other faculty included communicating policy to the public, current and upcoming interplanetary missions, policy and guidelines for hardware designers, and lessons learned in implementing planetary protection. Two sessions of this course were offered in the United States during 2003–2004.

Earth's Earliest Ecosystems

In this one and one half–day workshop, microbial ecologist Dr. Brad Bebout of NASA Ames Research Center, presented his internet resource for using microbial mat communities as models for basic microbial ecology concepts. The web–based educational module under development features living mats maintained in a remote "Web Lab." In this system, students will be able to propose experiments and observe responses of the mat community in response to a variety of environmental parameters (e.g., light, pH, flow, and temperature). An automated set of microsensors will allow measurements of various physical and chemical parameters in the microbial mat. Data will be posted in real time and we will work towards developing a format in which students are able to collect data, analyze it, and post the results back to the web page, in a true representation of the scientific inquiry process. In our workshop, teachers learned about the importance of microbial mats for astrobiology and ecology, and worked with real microelectrode and other data gathered from the mats. Teachers also provided useful feedback to Dr. Bebout on the design of his web–based project. Other activities included a presentation on mat microbe physiology and as well as a tour or the Bay Paul Center microarray facility.

SEA Teachers' Tour

The Sea Education Association (SEA) offers a 6 week summer program for 15 middle and high school teachers. The teachers were interested in environmental science and genomics, and visited MBL. They viewed a powerpoint presentation about microbes, microbial ecology and evolution, looked at posters, including six posters on Astrobiology research by the MBL team, toured the DNA sequencing facility and spoke with scientists in two laboratories where Astrobiology–related research is conducted.

WHOI–MIT Joint Program course: Symbiosis

Biocomplexity has evolved in numerous ways over time, and the study of this development is of key interest to Astrobiologists. CoI Rebecca Gast taught a 6 credit course entitled Topics in Marine Ecology: Symbiosis. Complex symbiotic relationships have evolved through the adaptation of individual organisms. This course presented different types of symbiotic associations found in diverse terrestrial, freshwater and marine environments. The examples presented ranged from epibiotic to obligate intracellular interactions and explored the various definitions of symbiotic relationships. Students heard lectures on symbionts and methods used to study them, discussed symbiosis, and presented a critical summary on some aspect of symbiosis research. 3 Feb– 13 May 2004

Advances in Genome Technology and Bioinformatics

Genome sequencing, genome analysis, and high throughput gene expression systems have provided major breakthroughs and insights for Astrobiologists and researchers in all fields of biology. PI Mitchell Sogin was the co−director of a comprehensive, four−week course that integrated bioinformatics with the latest laboratory techniques. The course combined a series of lectures with laboratory exercises both at the computer and in a high technology, high throughput facility. The major instructional modules were Genome Sequencing, Bioinformatics and Functional Genomics. Symposia offered included: Advances in genome assembly; Genomes and development; Genome science and environmental biology; Genome evolution; and Impact of genome science on Drug design. The breadth of topics in genome science and the advanced training based upon advanced laboratory technology distinguish this course from all other offerings. In addition to attending the symposia, students had daily hands−on experience with genome sequencing and analysis.

WHOI REU: Quahog Parasite Unkown

Team member Rebecca Gast provided a summer research experience for an undergraduate student, Elizabeth Cushman. Gast's research focuses on symbiotic relationships among organisms. Cushman is working on a project looking for "Quahog Parasite Unknown" in the environment. She is determining the distribution and persistence of the organism in the environment, and looking for alternative reservoirs of the parasite.

Eukaryotes at pH Extremes

Team member Linda Amaral Zettler presented a webcast, "Eukayotes at pH Extremes," as part of the NAI Director's Series. One of the goals of the Astrobiology Roadmap is to explore the limits of life on Earth as analogs for environments on Mars, Europa, and other planets that might support life. Amaral Zettler and colleagues have been exploring the genetic and physiological diversity of organisms living at both acidic (pH < 3) and alkaline (pH >10) pH extremes. She presented an overview of some of these environments that range from the warm (45C), acidic (pH 2.7) Nymph Creek in Yellowstone National Park to temperate alkaline lakes in the Sandhills region of western Nebraska, but focusing on the acidic, heavy metal rich Rio Tinto ("Red River") in Southwestern Spain. Protists in the river thrive and often dominate this environment. They hypothesize that the transition from neutral to acidic environments occurs rapidly over geological time scales, and are currently trying to understand how these organisms have adapted to such environments by exploring the alterations in physiological mechanisms that might allow for growth of eukaryotic microbes at acid extremes.

Woods Hole Science and Technology Education Partnership (WHSTEP)

WHSTEP is a partnership of schools, scientific institutions, businesses, and community resources serving the communities of Falmouth, Bourne, and

Mashpee since 1989. Its purpose is to support, promote, and expand science and technology education and science literacy in the participating communities. Jennifer Wernegreen, an MBL Astrobiology co−Investigator, is the MBL liaison for WHSTEP. As liaison, she has circulated a new web−based registry for science outreach volunteers among the MBL community, in order to help local teachers and students connect with people to share scientific knowledge.

General Education Development (GED) Teachers Microbiology Workshop

Team member Michele Bahr made a two hour presentation to Cape Cod GED teachers attending their annual in−service training. The teachers watched a powerpoint presentation about microbes and their importance in the environment, went online to view web resources available, and experienced a contemporary microbiology technique by extracting DNA. The teachers will be able to incorporate this information in their classes, which are aimed at understanding basic scientific concepts and methods.

Elder Hostel: Life and Living in Space

Lorraine Olendzenski and Diana Jennings (Center for Advanced Study of Space Life Sciences) offered a "Life and Living in Space" module to the Elder Hostel group in residence for a week at the MBL. The module consisted of five presentations including: "The Study of Astrobiology;" "Life in the Space Flight Environment;" "What's it like up there − Human Space Flight;" and "The Solar System and Beyond − Current and Future NASA explorations." Presentations on "Psychrophiles − Life at Low Temperatures" and "Looking for Life in all the Right Places − A Novel Method for Life Detection" were given by Rebecca Gast. Participants also did the "What is Life?" activity from the Educator's Resouce Guide and used the planet cards during the lecture on solar system exploration.

Science for Enabling Human Space Exploration

CoI Norm Wainwright was the laboratory host and one of the presenters at this 3−week workshop for astronauts. The workshop goal is to increase scientific autonomy on space station, the Moon, and eventually Mars by training future science officers in scientific analysis and methodologies within the context of a scientific community. During the course, they attended lectures and performed experiments with equipment they may be exposed to as science officers on future International Space Station and shuttle missions. Through igniting excitement about science, crewmembers will continue to interact with principal investigators and take an active role in scientific aspects of mission planning.

HS student project "Microbial Diversity"

High school student Janina Kanin was mentored by CoI Linda Amaral Zettler for her science project "Microbial Diversity in Extreme Environments." Kanin used RFLP (Restriction Fragment Length Polymorphisms) data to compare and contrast eukaryotic and bacterial diversity in two Atlantic White Cedar swamp sites. Atlantic White Cedar Swamps are considered extreme environments

because they have a low pH, generally around 4 or less. Kanin received an honorable mention at the Falmouth Academy Science Fair, and placed first in the regional, and second in the state competitions.

Brown course: Mars, Moon and Earth

Team member James Head teaches an introductory planetary geology science course "Mars, Moon and the Earth." The goals of the course are for students to understand the approach taken to scientific study and analysis, how the earth works, where the earth fits in context of the solar system, and the basic themes in the formation and evolution of the planets. The planets and their histories are compared to gain insight and a new perspective on the planet Earth. Students attended three hours of lecture per week plus a laboratory. Laboratory exercises were based on real data from space missions such as the very high resolution images by the Mars Orbiter Camera (MOC) on board the Mars Global Surveyor spacecraft.

Seen and Unseen: Discovering the Microbes of Yellowstone

Team member David Patterson is a co–author of this book about the microbial ecology of Yellowstone National Park. The thermal hot springs of Yellowstone are an extreme environment in which complex microbial communities have evolved. The book combines landscape photography of springs, pools, streams and wildlife with photomicrography of their diverse microbial inhabitants. The aim of the book is to use habitats as a starting point for introducing the general public to species found and relationships within microbial communities.

Brown course: Exploration of Mars

Team member James Head teaches an introductory planetary geosciences course "Exploration of Mars." The course is designed to enable freshmen to learn of the rich intellectual and scientific history of the exploration of Mars, starting with the early fascination of the 'red planet' in the sky, through Lowell's canals and civilizations, to the dawn of the modern era with spacecraft exploration. NASA Spirit and Opportunity landers and rovers brought new findings to the students every single day of the semester. Personal experience with 30 years of involvement in NASA's planetary exploration of Mars and other planets was included, as well as field work from the Mars–like Dry Valleys of Antarctica. Students were able to use the Immersive Virtual Reality facility to explore the surface of Mars, met with an Apollo astronaut, and participated in telecons with Brown graduates and others currently involved in the exploration of Mars and planning the future of Mars exploration.

Brown course: Global Environmental Change

Team member John Mustard led this freshman seminar course which examined the relationship between human habitation and planetary processes. Mustard sought to frame some of the compelling environmental questions of our day and examine them from a systems–process point of view. Students examined the evidence that supports or refutes various perspectives on the

problems, but also delve deeper into the scientific principles that govern the fundamental processes at work. Their first goal was to determine what we know, how we know it, and the quality of the data informing this position. Their second goal was to determine what we don't know, what we need to know, and strategies to increase our knowledge to solve current and future problems. Students read classic and contemporary readings in advance of each seminar period and prepared lists of questions or concepts intended to provoke discussion among their peers.

Brown course: Global Environmental Sensing

Our understanding of planetary science includes recognizing a set of interconnected global systems here on Earth, the hydrosphere, geosphere, cryosphere, and biosphere. Team member John Mustard led a seminar examining the nature of these global systems, their inter–relationships, and the scope, origin, and resolution of global environmental problems. Our ability to understand these systems and their connections will require expert use of remote sensing, the only tool that allows global analysis of the Earth on a regular basis. This course provided a detailed understanding of remote sensing techniques and an assessment of the types of global environmental processes that can be analyzed quantitatively using global remote sensing systems. The principles of remote sensing were examined in detail, with emphasis on optical, thermal, and microwave remote sensing. Students examined commonly used remote sensing systems and developed techniques for quantifying key environmental variables from these systems through the use of laboratory assignment, homework problems, and independent research projects.

AbSciCon Meeting

Team member Linda Amaral Zettler acted as a judge for the student poster session at the 2004 AbSciCon Meeting.

Society of Protozoology Meeting

Team member Linda Amaral Zettler acted as judge for the student poster session at the 2004 annual meeting of the Society of Protozoology.

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NASA ASTROBIOLOGY INSTITUTE
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Michigan State University
Executive Summary
Principal Investigator: Michael Thomashow

Low temperature is a predominant environmental characteristic of interstellar space, asteroids, comets, and of course, our solar system, including most of the planets and their satellites. An understanding of the impacts that low temperature has on the responses and evolution of biological organisms is, therefore, integral to our knowledge of Astrobiology. Toward this end, we are exploring multiple aspects of microbial adaptation to low temperature. The basic objectives of one line of investigation—Genomic and Proteomic Analysis of Permafrost Bacteria—include identifying genes and proteins that enable Arctic and Antarctic permafrost bacteria to inhabit subfreezing environments and determining how gene expression in the permafrost bacteria is affected by low temperature and other environmental conditions associated with the permafrost. We are also interested in conditions that “hitchhiker” bacteria might encounter during travel through space on natural objects or spacecraft. In a second line of investigation—Bacterial Adaptation to Low Temperature—we are directly examining, through “test−tube evolution” experiments, how bacteria genetically adapt to low temperatures. The fundamental objective here is to better understand how an organism, with a given complement of genes, can cross niche barriers defined by decreasing temperatures. Finally, in a series of “Field Truth” investigations—Indigenous Bacteria of Arctic and Antarctic Permafrost—we are exploring the microbial ecology of the permafrost environment and the physiological state of the resident microbial community. This is being accomplished by determining the phylogenetic diversity of the bacterial permafrost population and the metabolic activities present in permafrost soils.

Our investigation on Genomic and Proteomic Analysis of Permafrost Bacteria now includes four interrelated research projects: Genomes, Transcriptomes, Proteomes, and Genetics. Over the past year, significant advances have been made in each area. The goal of the "Genomes" project is to determine the repertoire of genes encoded by representative permafrost bacteria with the long−range goal of identifying key genes necessary for bacteria to live in the permafrost environment. An initial objective is to determine, in collaboration with the Joint Genome Institute and the Lawrence Livermore National Laboratory, the complete genome sequences of two bacteria that we have isolated from Siberian permafrost: *Psychrobacter* strain 273−4 and *Exiguobacterium* strain 255−15, psychroactive bacteria isolated from

permafrost soils thought to have been constantly frozen for some 40,000 and 3 million years, respectively. Sequencing of the *Psychrobacter* genome has been completed and now includes a complete “manual curation” of each open reading frame (ORF) yielding the first completely annotated genome of a psychroactive microorganism. Significant progress has also been made in sequencing the *Exiguobacterium* 255−15 genome, which is currently assembled into 70 DNA “contigs.” Results indicate that the *Psychrobacter* 273−4 genome is comprised of 2.64 Mb containing 2,147 ORFs while the *Exiguobacterium* 255−15 genome is approximately 2.9 Mb in size and includes 2,977 ORFs. About 75% of the *Exiguobacterium* 255−15 ORFs encode proteins that are putative homologs of *Psychrobacter* 273−4 proteins. Both genomes encode apparent homologs of stress−related proteins in other bacteria and encode many novel proteins that may have unique roles in adaptation to the permafrost environment. Two particularly striking features of the *Psychrobacter* 273−4 genome are a 20,145 base pair (bp) tandem repeat that encodes an extremely large novel hypothetical protein of 6,715 amino acids and a novel 139 bp sequence present 294 times in the genome that may have roles in cold−regulated gene expression.

Comparative genomic analysis has the potential to generate hypotheses regarding the importance of specific genes and molecular characteristics for life in the permafrost environment. Such analysis is aided by comparisons of closely related isolates originating from habitats with features that differ from those of the permafrost. In this regard, we are excited to have isolated at least three different *Psychrobacter* strains from fish in warm Puerto Rican marine waters (one isolate can grow up to 42°C). In addition, real−time polymerase chain reaction (PCR) analysis has established that *Psychrobacter* is present in warm Puerto Rican mangrove sediments. A comparison of these *Psychrobacter* strains at the genome level with those from the permafrost has the potential to reveal genes important to cryo−adaptation. In a related study, we are conducting physiological, biochemical, 16S rRNA gene and *gyr* B gene comparisons to resolve the taxonomy and phylogeny of 14 *Psychrobacter* strains that we have found have different temperature growth ranges. In addition, we have initiated polyphasic analysis of several *Exiguobacterium* strains including strain 255−15 and 7−3 (isolated from the permafrost) and four reference strains, *E. acetylicum* , *E. aurantiacum, E. antarcticum* and *E. undae* . 16S rDNA sequences, DNA−DNA similarities and BOX−PCR patterns demonstrated that the strains 255−15 and 7−3 are closely related and are related to *E. antarcticum* and *E. undae* . DNA−DNA hybridization and the 16S rDNA sequence data show that the strain 190−11 is probably the same species as *E. undae* , which is a strain isolated in a warmer environment (garden pond in Germany), and represents a strain for genomic comparison.

Another approach that can be used to identify candidate genes with roles in stress tolerance is the identification of genes responsive to stressful conditions. Thus, in the "Transcriptome and Proteome" projects, we are monitoring changes in the levels of transcripts and proteins, respectively, that occur in response to low temperature and low−water activity, two conditions that characterize the permafrost environment. Taking advantage of the results from our Genome project, we have developed a 70mer oligonucleotide array that probes expression of 1990 of the ~2100 genes encoded by *Psychrobacter*

273–4. Using the arrays, we have compared the transcriptomes of *Psychrobacter* 273–4 growing at 22 and 4ºC and at high and low water activities. In both cases, we have detected changes in gene expression. For instance, cold–induced changes in transcript levels were observed for about 22 genes involved in lipid biosynthesis, protein synthesis (ribosomal proteins), amino acid metabolism and transport. Most of the cold–regulated genes, however, were only up–regulated about 1.5 to 2 fold indicating that *Psychrobacter* 273–4 may not be physiologically stressed growing at temperatures above 0ºC. Experiments are, therefore, in progress to examine a wider range of growth conditions including subzero temperatures.

Two methods have been used to determine protein profiles in the Proteome project. One involves the development of a novel 2–dimensional liquid fractionation method that employs a pH column–based separation in the first dimension followed by separation of the proteins in each pH fraction using nonporous silica (NPS) reversed phase high–performance chromatography (HPLC). Using the method, we have been able to detect about 500 proteins in *Psychrobacter* 273–4. A comparison of cells grown at 22 versus 14°C has revealed that over 40 proteins are differentially expressed at these two temperatures. The identity of these polypeptides has been determined by using maxtrix–assisted laser desorption/ionization–time–of–flight (MALDI–TOF) mass spectrometry and matching the peptide mass maps against the DNA sequence database that we have generated for *Psychrobacter* 273–4 in the Genome project. Nearly a third of the proteins are conserved hypothetical polypeptides with unknown function, with most of the others being involved in translation or metabolism. Significantly, a comparison of the proteome results with the transcriptome results indicates that posttranslational regulation may play a major role in temperature–regulated gene expression in *Psychrobacter* 273–4.

Proteome analysis has also been conducted using two–dimensional gel separation followed by liquid chromatography–double mass spectrometry. Using this methodology we identified “cold acclimation proteins,” or CAPs, that were preferentially or uniquely expressed at temperatures below 0 ° C in *Psychrobacter cryopegella* , a bacterium isolated from a briny water lens (–12°C) within the Siberian permafrost. *P. cryopegella* was found to grow at temperatures between 28 and –10°C and to remain physiologically active down to at least –20°C. A total of 756 proteins were detected in the analysis, 24 of which were classified as CAPs having identities suggesting the importance of oxidative stress, increased energy needs, and compatible solutes in growth at subzero temperatures.

Identifying genes that enable bacteria to inhabit the permafrost environment will require the development of genetic systems to manipulate (including mutagenize) the genomes of the permafrost isolates, the goal of the Genetics project. Important progress has been made over the past year. Several factors that had been hampering transformation of *Psychrobacter* 273–4 have been identified; a conjugation system for *Psychrobacter* 273–4 has been developed; and conditions for natural competence of *Psychrobacter* 273–4 and *Psychrobacter cryopegella* have been identified. Over the coming year, these systems should enable us to test whether specific genes have important roles

for *Psychrobacter* 273–4 and *P. cryopegella* in life at low temperature.

In the Bacterial Adaptation to Low Temperature project, we are using experimental evolution to adapt lineages of the bacterium *Escherichia coli* to low temperature and examining the genetic basis and functional consequences of the adaptations. We previously developed a primary set of six clonal lineages adapted to 20°C and are currently conducting a comparative proteomic analysis of the adapted lines with their common ancestor. The analysis is preliminary, but intriguing differences have been detected. In particular, the levels of two ribosomal proteins and two elongation factors have been altered, suggesting that the translational machinery may be a target of selection during cold adaptation. In addition, insights have been gained into evolutionary adaptation to freezing and thawing conditions in *E. coli* . We previously demonstrated substantial mortality during repeated freeze–thaw cycles in the absence of cryoprotectant, and that populations evolved at 37°C were more sensitive than were their ancestors. Based on these findings, we designed a 1,000–generation experiment to investigate the potential for evolutionary adaptation to alternating periods of freezing, thawing, and growth at 37°C. The evolution phase of this experiment was completed this past year, and work is now underway to analyze phenotypic and genetic changes in the freeze/thaw/growth evolved lines relative to their ancestors. Competition assays between the evolved lines and their ancestors indicate that significant genetic adaptation has occurred. Improved survival during the freeze/thaw phase, and a shorter lag prior to the start of exponential growth, are two major demographic changes underlying this adaptation.

In the Indigenous Bacteria of Arctic and Antarctic Permafrost project, we are exploring the microbial ecology of the permafrost environment and the physiological state of the resident microbial community. T he terrestrial permafrost provides an analogue of Martian subsurface cryogenic habitats and perhaps has signatures of preexisting life or of viable cryo–adapted life. We isolated and characterized viable microbes from water brines sandwiched between Arctic permafrost strata. These 120,000–yr–old communities living at –10°C could represent Earth analogues of subsurface water brines on Mars, the only possibility for liquid water on present day Mars. Because of the relevance of this habitat for Martian life, we plan to include high coverage sequencing of *P. cryopegella* , the isolate described above that was isolated from this environment, in our genome project. Over the past year, we also examined the phylogenetic composition of the bacterial community present in the 5millionyrold G laciogene Sirius Group permafrost deposits on Mt. Feather (Antarctic Dry Valleys). The most common sequences were of *Proteobacteria* , but about 1/4 of the sequences shared less than 80% similarity with those in the ribosomal database, suggesting the existence of novel genera. Finally, an important goal is to understand the strategy of biotic survival and adaptation in the permafrost. In this regard, we have detected methane production in Arctic permafrost below 0°C, and down to –28°C, that appears to result from microbial activity indicating a type of unknown, chemolithotrophic, psychrophilic energy–producing biota that might have the potential to exist cryogenic terrestrial planets free of oxygen.

Project Report: Bacterial Adaptation to Low Temperatures

Project Investigators:	***Albert Bennett , Richard Lenski , David Lubman***

Project Progress

This project uses experimental evolution to adapt lineages of the bacterium *Escherichia coli* to low temperature, and examines the genetic basis and the functional consequences of that adaptation. We have previously developed a primary set of six clonal lineages and a secondary set of an additional 24 lineages that have adapted to 20°C. We are in the process of developing six new lineages adapted to 14°C.

We are currently conducting a proteomic study that examines differences between the primary six lines adapted to 20°C and their common ancestor. The analysis is preliminary, but intriguing differences have emerged between the cold adapted lineages and warm adapted ancestor. Specifically, levels of two ribosomal proteins as well as two elongation factors have been altered, suggesting that the translational machinery may be a target of selection during cold adaptation. Additionally, changes have been found in a PTS component potentially involved with glucose transport, and in several proteins that appear to be temperature related, including two chaperone proteins (HSP70 and TF), a fatty–acid related enzyme, and a DNA–binding protein reported to have thermal specificity.

In a continuing analyses of evolutionary tradeoffs, we examined performance at high temperature (40 – 41°C) in the secondary group of 24 lineages adapted to low temperature. Competitive fitness at 20°C improved significantly, whereas competitive fitness and cell yield at 40°C declined significantly for the evolved group as a whole. However, there was considerable variation among the low–temperature evolved lines in their performance at high temperature, suggesting that significant tradeoffs need not necessarily occur as part of the low temperature adaptive process.

Insights have also been gained into evolutionary adaptation to freezing and thawing conditions in *E. coli* . We previously demonstrated substantial mortality during repeated freeze–thaw cycles in the absence of cryoprotectant, and populations evolved at 37°C were more sensitive than were their ancestors. Based on these findings, we designed a 1,000–generation experiment to

investigate the potential for evolutionary adaptation to alternating periods of freezing, thawing, and growth at 37°C. The evolution phase of this experiment was completed this past year, and work is now underway to analyze phenotypic and genetic changes in the freeze/thaw/growth evolved lines relative to their ancestors. Competition assays between the evolved lines and their ancestors indicate that significant genetic adaptation has indeed occurred. Improved survival during the freeze/thaw phase, and a shorter lag prior to the start of exponential growth, are two major demographic changes underlying this adaptation.

Highlights

- Proteomic analyses indicate that protein translation may be an important target of selection during cold adaptation.
- During low temperature adaptation, significant loss of performance at high temperature usually, but not universally, occurs.
- Completed an experiment in which *E. coli* populations evolved for 1,000 generations in an environment subject to alternating periods of freezing, thawing, and growth. Competitions between the evolved lines and their ancestors confirm significant adaptation, with improved survival during the freeze/thaw phase as well as a faster transition to growth after thawing.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Project Report: Protenomes of Permafrost Bateria

Project Investigators: ***David Lubman , Michael Thomashow , James Tiedje***

Project Progress

The goal of this project is to identify changes that occur in the proteomes of permafrost bacteria in response to low temperature, high osmolarity, and other conditions associated with the permafrost environment. One line of experimentation involves the development of a novel 2−dimensional liquid fractionation method as a replacement for two−dimensional gel electrophoresis. The method uses a pH column−based separation in the first dimension followed by separation of the proteins in each pH fraction using nonporous silica (NPS) reversed phase high−performance chromatography (HPLC). Using this method, we have been able to detect about 500 proteins in *Psychrobacter* 273−4. A comparison of cells grown at 22 versus 14°C has revealed that over 40 proteins are differentially expressed at these two temperatures, some being essentially qualitative changes. The identity of these polypeptides have been determined by using maxtrix−assisted laser desorption/ionization−time−of−flight (MALDI−TOF) mass spectrometry and matching the peptide mass maps against the deoxyribonucleic acid (DNA) sequence database that we have generated for *Psychrobacter* 273−4 in our genome sequencing project. Nearly a third of the proteins are conserved hypothetical polypeptides with unknown function, with most of the others being involved in translation or metabolism. A comparison of these results with the transcriptome results, suggests that posttranslational regulation may play a major role in temperature−regulated gene expression in *Psychrobacter* 273−4.

Proteome analysis has also been conduced with *Psychrobacter cryopegella* , a bacterium isolated from a briny water lens (−12 ° C) within the Siberian permafrost. *P. cryopegella* was found to grow at temperatures between −10 and 28 ° C and to remain physiologically active at −20 ° C. Two−dimensional gel analysis followed by liquid chromatography−double mass spectrometry was used to identify cold acclimation proteins (CAPs); i.e., proteins that were uniquely or preferentially expressed at temperatures below 0 ° C. Of the total 756 proteins that were detected, 24 were classified as CAPs. Of these, 20 were identified as open reading frames (ORF) within the genome of *Psychrobacter* 273−4. Three of the ORFs were annotated as conserved hypothetical proteins. Of the remaining ORFs, 11 had previously been identified as stress response

proteins in other organisms; these included superoxide dismutase, the ribosomal ribonucleic acid (rRNA)−binding general stress protein Ctc, aspartate−semialdehyde dehydrogenase, the periplasmic component of a TRAP−type transport system, and the protein chaperone ppiB. The identities of these CAPs suggested the importance of oxidative stress, increased energy needs, and compatible solutes for growth at subzero temperatures.

Highlights

- Proteins present only during growth at subzero temperatures were identified in *Psychrobacter cryopegella* and may be involved in relieving the stresses caused by living at low temperatures.
- Methodologies for reproducible, automated proteome mapping have been developed for Psychrobacter strains and used to identify changes in protein composition that occurs in response to temperature.
- Evidence suggests that cold−regulated gene expression in *Psychrobacter* 273−4 may involve posttranscriptional control mechanisms.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Project Report: Indigenous Bateria of Arctic and Antarctic Permafrost

Project Investigators: ***David Gilichinsky , James Tiedje***

Project Progress

The terrestrial permafrost provides and analogue of Martian subsurface cryogenic habitats and perhaps has genetic signatures of preexisting life or of viable cryo–adapted life. We isolated and characterized viable microbes from water brines sandwiched between Arctic permafrost strata. These 120,000–yr–old communities living at –10º C could represent Earth analogues of subsurface water brines that would be the only possibility for liquid water on present day Mars. Because of the relevance of this habitat for Martian life, we are currently having the genome of one of these isolates sequenced. F rom G laciogene Sirius Group permafrost deposits on Mt. Feather (Antarctic Dry Valleys), we isolated viable bacteria (aerobic and anaerobic, Gram–positive and Gram–negative), fungi, yeast, cyanobacteria, and green algae with an age presumably corresponding to the longevity of the permanently frozen soils estimated to be greater than 5 million years. This is the oldest, confirmed, viable microbial community in permafrost and living in conditions most similar to Mars. The viability of microbes frozen this long suggests that microbes can remain viable for the periods of time required for cryogenic meteorites to transit from Mars to Earth, i.e., confirms the possibility of panspermia. We also determined by phylogenetic analysis of 16S rDNA gene sequences from the permafrost, the composition of an Antarctic permafrost bacterial community. The most common sequences were of Proteobacteria but about 1/4 of the other sequences shared less than 80% similarity with those in the ribosomal database suggesting that they are novel genera. An important goal is to understand the strategy of biotic survival and adaptation in permafrost, and includes determining whether these microbes are active in this permanently frozen environment. We detected microbial activity as methane production in Arctic permafrost below 0ºC, and down to –28ºC (Fig. 1), indicating a type of unknown, chemolithotrophic, psychrophilic energy–producing biota that might be expected on cryogenic terrestrial planets free of oxygen.

Highlights

- Found a viable microbial community in >5 million year old Antarctic permafrost, to date, the oldest, confirmed, viable bacteria in a Martian analogue environment.

- Determined that longevity of life due to preservation within the terrestrial permafrost indicates that microbe viability can easily be preserved for the periods of time required to transport cryogenic meteorites from Mars to Earth.
- Described the biodiversity of indigenous, viable, halotolerant–psychrophilic microbial community in the water brines sandwiched in Arctic permafrost.
- Found biogenic methane production in Arctic permafrost of Holocene age incubated at subzero temperatures down to –28°C, establishing that microbial processes can sustain life function at these temperatures.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Project Report: Genomes of Permafrost Bacteria

Project Investigators:	***James Cole , Sophie Kathariou , Michael Thomashow , James Tiedje , David Gilichinsky , David Lubman***

Project Progress

A major objective of our research team is to determine the repertoire of genes necessary for bacteria to live in the permafrost environment. Central to this effort is determining (in collaboration with the Joint Genome Institute and the Lawrence Livermore National Laboratory) the complete genome sequences of two bacteria that we have isolated from Siberian permafrost: *Psychrobacter* strain 273−4 and *Exiguobacterium* strain 255−15, psychrophilic bacteria isolated from permafrost soils thought to have been constantly frozen for some 40,000 and 3 million years, respectively.

Sequencing of the *Psychrobacter* genome has been completed. Considerable effort over the past year went into a “manual curation” of each open reading frame (ORF) to yield the first completely annotated genome of a psychroactive microorganism. A number of interesting findings have emerged. The genome is 2.64−megabases in size, contains 2,147 ORFs including a 20,145 base pair (bp) tandem repeat that encodes an extremely large hypothetical protein of 6,715 amino acids. The genome encodes four histone−like proteins that potentially have roles in cold tolerance as well as enzymes for a complete glyoxylate shunt pathway enabling growth of an acetate. Analysis of genes that were found to be up−regulated in response to low temperature (see transcriptome and proteome projects) revealed the existence of a novel 139 bp sequence present 294 times in the genome that may have roles in cold−regulated gene expression. Phylogenetic analysis has also revealed that an isocitrate lyase encoded by *Psychrobacter* forms a unique cluster with cold−induced isocitrate lyases of the psychrophile *Colwellia maris* and three other microbes that grow at low temperatures. Significantly, this cluster of sequences contains three insertions that may increase flexibility of the enzymes and reduce activation energy, an important factor for function at low temperature.

Significant progress has also been made in sequencing the *Exiguobacterium* 255−15 genome, estimated to be about 2.9 Mb in size. Currently, the sequences are assembled into 70 contigs predicted to encode 2,977 proteins.

Approximately 75% of the *Exiguobacterium* ORFs encode putative homologs of *Psychrobacter* proteins and there appear to be many ORFs that encode putative homologues of genes from Bacillus and other genera that are known to be expressed at cold temperatures including proteins involved in ribosomal binding, membrane alteration, metabolism, DNA replication, and transcription.

Highlights

- Completed sequencing and annotating the first genome of a psychroactive microbe, *Psychrobacter* strain 273–4.
- Found evidence that some of the genes in this genome have evolved to be active at low temperatures.
- Unique repeat sequence was found in the genome.
- Genome of *Exiguobacterium* strain 255–15, an ancient gram–positive microbe, is nearing completion.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Project Report: Genetics of Permafrost Bacteria

Project Investigators:	Sophie Kathariou , Michael Thomashow , James Tiedje

Project Progress

A major goal of our research team is to identify genes that enable bacteria to inhabit the permafrost environment. To accomplish this, we need to develop genetic systems to manipulate (including mutagenize) the genomes of the permafrost isolates. Progress has been slow, but recent results are encouraging. Several factors that had been hampering transformation of *Psychrobacter* 273–4 have been identified. First, a methylation sensitive restriction system has been shown to destroy foreign deoxyribonucleic acid (DNA) that has been methylated. To overcome this, we now propagate plasmids for transformation in *Escherichia coli* GM2163 (*dam* – *dcm* –) which does not methylate critical sites recognized by the *Psychrobacter* 273–4 restriction system. Second, we have found that successful electroporation of *Psychrobacter* 273–4 requires high voltages of 20–25kV/cm (normal *E. coli* conditions are 10–12.5kV/cm) and long recovery times after electroporation (between 8–24 h). Third, antibiotic resistance markers for kanamycin and chloramphenicol have been found to be poorly expressed. But taking these factors into account, we can now transform *Psychrobacter* 273–4 by electroporation. In addition, we have identified conditions whereby we can introduce wide host range plasmids, including pRL412, an RSF1010, into *Psychrobacter* 273–4 by conjugation. Finally, we have examined natural competence of *Psychrobacter* 273–4 and *Psychrobacter cryopegella* . Transformation frequencies (using *Psychrobacter* DNA) of about 10^{-6} to 10^{-7} and 10^{-8} to 10^{-9} transformants per recipient per µg of DNA have been obtained with *Psychrobacter* 273–4 and *Psychrobacter cryopegella* , respectively. The bacteria are transformable in the stationary phase of growth if cultures are initially grown in tryptic soy broth and subsequently incubated with DNA on marine agar (other combinations of growth stage and media have been tried and have not yielded transformants).

Highlights

- We can now introduce wide host range plasmids into *Psychrobacter* 273–4 by both electroporation and conjugation.

- A major barrier to transformation of plasmids into *Psychrobacter* 273–4 is a methylation sensitive restriction system.
- Conditions for natural transformation have been identified.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Project Report: Ecology and Physiology of Permafrost Bacteria

Project Investigators: ***David Gilichinsky , Sophie Kathariou , Lycely Sepúlveda , Michael Thomashow , James Tiedje***

Project Progress

Specific genes and molecular characteristics required for low−temperature growth can be identified via comparative genomics and are aided by the comparison of close relatives, especially those that come from habitats with important features for discerning cryo−adaptation. We established the growth temperature range of 14 *Psychrobacter* species and identified five distinct growth temperature ranges. Importantly, several *Pschrobacter* species grow at −10 ° C, the lowest temperature tested, and may grow at lower temperatures. We have also isolated at least three different *Psychrobacter* strains from fish in Puerto Rican marine waters and used quantitative PCR to determine the organisms' habitat in Puerto Rico since comparison of strains from a warm environment vs. those from permafrost can reveal genes important to cryo−adaptation . One of the Puerto Rican fish isolates can grow up to 42°C, which would definitely be an interesting strain for genomic comparisons. Real−time PCR revealed that *Psychrobacter* is present in mangrove sediment, suggesting that the presence of this genus is not limited to cold environments and that resistance to desiccation could be an important feature in cold adaptation . The samples were collected during the dry season where the salt precipitates in the sediments and the mean radiation is 600 lengleys.

Physiological, biochemical, 16S rRNA gene and *gyr* B gene phylogenies have been used to resolve the taxonomy and phylogeny of the *Psychrobacter* strains. While most strains are more related to some than others, the phylogeny is not clear. This may have some biological basis reflecting the groups' adaptation to different niches. The genome comparisons should help elucidate the underlying explanation. We have also begun the polyphasic analysis of several *Exiguobacterium* strains including strain 255−15 (whose genome is sequenced), 7−3, and 190−11 isolated from the Siberian permafrost and four other reference strains *E. acetylicum* (DSM20416) *, E. aurantiacum* (DSM6208) *, E. antarcticum* (DSM14480), and *E. undae* (DSM14481). 16S rDNA, DNA−DNA similarity and BOX−PCR demonstrated that the strains 255−15 and 7−3 are closely related and are related to *E. antarcticum* and *E. undae* . DNA−DNA hybridization and the 16S rDNA sequence data show that the strain 190−11 is probably the same species as *E. undae* , which is a strain

isolated in a warmer environment (garden pond in Germany), and hence represents a strain form genomic comparison.

Highlights

- Identified strains of *Psychrobacter* and *Exiguobacterium* from warmer environments that can be used for genomic and proteomic comparisons to help identify traits important to cryo−adaptation.
- Determined that *Psychrobacter* also colonizes salty environments whether warm or frozen, suggesting that adaptation to low water activity may be an important common feature.
- Established the growth temperature range of 14 *Psychrobacter* strains and found that they cover a gradient of temperature ranges and hence are an important resource for resolving temperature adaptation features.

Roadmap Objectives

- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Project Report: Transcriptomes of Permafrost Bacteria

Project Investigators:	***Sophie Kathariou , Michael Thomashow , James Tiedje***

Project Progress

The Siberian permafrost is an extreme environment. Average temperatures of −10 to −12°C concentrate solutes to an aw = 0.89 (5 osm) and limit diffusion of available nutrients to the cells. The overall goal of this project is to identify genes that are critical for bacteria to sucessfully inhabit this environment. One line of investigaton is to identify and determine the functions of genes that are activated in response to low temperature and low water activity. In this project, we are monitoring gene expression at the transcriptome level. Taking advantage of our permafrost genome sequencing project, we have developed a 70 mer oligonucleotide array that probes expression of 1990 of the ~2100 genes encoded by *Psychrobacter* 273−4. Using the arrays, we have compared the transcriptomes of *Psychrobacter* 273−4 growing at 22 and 4ºC. Changes in transcript levels were observed for about 22 genes involved in lipid biosynthesis, protein synthesis (ribosomal proteins), amino acid metabolism, and transport. The differential expression of transport genes supports physiological evidence that different carbon sources are utilized at the two temperatures. Most of the cold−regulated genes, however, were only up−regulated about 1.5 to 2 fold, indicating that *Psychrobacter* 273−4 may not be physiologically stressed growing at temperatures between 4 and 22ºC. Experiments, therefore, are currently in progress to examine a wider range of growth temperatures including subzero temperatures.

The oligonucleotide arrays that we have made have also been used to examine changes in the transcriptome induced in response to low water activity. Low water activity presented a greater stress to *Psychrobacter* 273−4 than 4°C growth alone with 10% more differential gene expression. The majority of genes were down−regulated (2−fold or greater) when grown in the presence of 5% NaCl and are involved in cation transport, indicating a response to limit NaCl transport into the cell. Up−regulation of a gene predicted to be involved in cell shape correlates with the physiological determinations of decreased cell surface/volume in the presence of 5% NaCl. In addition, general stress response chaperones were up−regulated under both increased salinity and decreased temperatures. Several other genes with unknown functions were also up−regulated under both stresses, which may indicate their importance in

stress survival.

Highlights

- The transcriptome of *Psychrobacter* 273–4 displays differences at 22 and 4°C, but the differences in transcript levels are small (1.5– to 2–fold) suggesting that these permafrost bacteria are not physiologically stressed at the relatively low temperature of 4°C.
- Transcriptome responses of *Psychrobacter* 273–4 to increased osmotica show relatively small transcript changes, suggesting that 5% NaCl is not a stress condition in itself.
- Coupling low temperature and increased osmotica leads to transcriptome differences in chaperones, transporters, and antioxidants which may be important in permafrost in situ conditions.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
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Team Reports: NAI Central

NAI Central
Executive Summary
Director: Bruce Runnegar

NAI Central Report

The organization of the administrative arm of the NAI is colloquially referred to as “NAI Central.” This designation allows us to report the unique activities and projects led, organized or directly supported by the administrative office. These projects range from administration of the cooperative agreements with the Lead Teams to support for additional collaborations and initiatives of the NAI Director. NAI Central's projects often support or extend the efforts of the Lead Teams as well as reach out into the broader astrobiology community and help support the maintenance of the organization as a whole. The projects are categorized for the purposes of this report into support for collaborations in science and the international community, support for student training and early career programs, K–12 education and public outreach, and NAI's infrastructure. General information regarding these projects can also be found on the NAI's website at http://nai.nasa.gov

Collaborations

International Collaborations

NAI currently has relationships with five international astrobiology organizations. Information regarding these partnerships can be found at http://nai.arc.nasa.gov/institute/intl_partners.cfm . These partners are either Associates or Affiliates of the NAI; Associate status involves the exchange of confirming documentation by the sponsoring organization(s) of the international partner and the head of the NASA Office of External Affairs (on behalf of the NAI, and at the recommendation of the NAI.) NAI's interest in strengthening the international astrobiology community led us to focus our Executive Council meeting in April, 2005 on our present and potential international partners. In addition to representatives from our present Affiliates and Associates, we sponsored attendance by individuals representing potential partnerships in Canada, Japan, South Africa, Russia, Mexico, and Sweden.

In addition to our Associate and Affiliate members, NAI is one of eleven current participants in the Federation of Astrobiology Organizations, FAO. Through FAO astrobiology networks, associations, institutes, research groups, and societies cooperate their individual and international activities. A central emphasis of the Federation is in increasing the opportunities available to

talented students around the globe and supporting activities that develop their academic and research potentials. In collaboration with FAO, NAI supported the presentations of four NAI students at the Seventh Trieste Conference on Chemical Evolution and Origin of Life, a by−invitation meeting celebrating the 50 th anniversary of the Miller−Urey experiment. Dr. Stanley Miller attended the conference, and presented a retrospective of his work; this was a unique opportunity for students to interact directly with a legendary figure of astrobiology. Also in collaboration with FAO, and fellow FAO member the European Exo/Astrobiology Network Organization (EANA), NAI sponsored an informal junior/senior career level social and information exchange at the EANA annual meeting (Madrid, November 2004). More information on the FAO can be found at http://www.astrobiology−fao.org/ .

Astrobiology Drilling Program
NAI Central initiated and supports the Astrobiology Drilling Program (ADP) as described in the Director's Letter for this report. This year, NAI Central provided funding for the Archean Biosphere Drilling Project and organized the steering committee. More information on the ADP can be found at http://nai.arc.nasa.gov/adp/

Josep Comas i Solà International Summer School in Astrobiology
In partnership with the Centro de Astrobiología, NAI Central sponsors an interdisciplinary summer school. The course is intended to bring together students and researchers from Europe and the US to experience a focused workshop type environment on topics relevant to astrobiology. The course is offered at the Universidad Internacional Menéndez Pelayo campus in Santander, Spain. NAI Central provides travel support for the American faculty and travel and logistics for students from each of the NAI Teams to participate. *The Search for Life on Mars* was the first school held July 7−11, 2003. Speakers included Dr. Christopher McKay and Dr. Carol Stoker, both of NASA Ames Research Center, Dr. Paula Grunthaner from the Jet Propulsion Laboratory, Dr. Ricard Amils Pibernat from the Universidad Autónoma de Madrid, Dr. Juan Perez Mercader from the Centro de Astrobiología, and Dr. Bruce Runnegar from the NAI. Information regarding future courses can be found on the NAI website.

Remote Astrobiology Dialogues (RAD)
Another specific international collaboration this year was the implementation of the Remote Astrobiology Dialogues (RAD) between the NAI and the Centro de Astrobiología (CAB). The goal of the RADs was the promotion of astrobiology research collaboration and scientific exchange. Four themes were chosen jointly with CAB and NAI leadership, and researchers were invited to participate using Polycom (room−based or desktop videoconference), WebEx (desktop), and telephone connections. Following each RAD, an interactive web gateway on each theme was available to support ongoing exchange with threaded discussions and ancillary supporting materials. Towards the end of the RAD series, NAI Deputy Director, Dr. Rose Grymes, traveled to the CAB to spend two weeks working remotely, from the CAB site, while meeting with researchers and students at CAB to solidify and expand NAI/CAB collaborations.

Origins of Eukaryotes/Lateral Gene Transfer Workshop
This invitational workshop was jointly organized by NAI and the Canadian Institute for Advanced Research (CIAR). The concept for this meeting was originally proposed by Dr. Hyman Hartman. By July, 2004, at the Gordon Research Conference on the Origins of Life, a steering committee for a workshop on the origins of eukaryotes was identified. Dr. Ford Doolittle, of CIAR;s Evolutionary Biology Program, was a steering committee member. Through Dr. Doolittle's connections, information on a contemporaneously planned Lateral Gene Transfer workshop was exchanged, and a decision made to combine the two for maximal efficiency and impact. The participation of junior career astrobiologists was assured by permitting each member of the steering committee to identify and invite one such participant, without additional cost to the workshop budget. The on−site exchange was fruitful and exposed a consensus among the most prominent researchers in this field that was not yet evident in the published archive. A report on this meeting is being prepared by the NAI Senior Scientist. This partnership between NAI and CIAR led to interest from CIAR in affiliating with NAI, and underlies our plans to partner with CIAR for student travel and scientific sessions at the Second Earth Systems Processes conference in Calgary, August, 2005.

Cross−team and Community Collaborations

Focus Groups
The purpose of the NAI program of Focus Groups is to coordinate expertise from across the Institute and the wider scientific community, and apply it towards the advancement of a defined area of research, mission planning, or other activity of particular importance to astrobiology. Several of the NAI Focus Groups reached the end of their three−year tenure during this past year. For those that renewed, NAI Central worked with the proposing Chair(s) to prepare a renewal proposal, distribute the material for review by the NAI EC, and schedule presentations. During this past year, NAI Central also organized breakout session of nearly all the Focus Groups at the Year 2004 AbSciCon Meeting at Ames Research Center. Throughout the year, NAI Central received requests from the current Focus Groups for funding to support workshops and other activities. These requests for activities received prompt attention and rapid turnaround. As in previous years, every effort was made to meet the schedule needs of the organizers. See the Focus Group section of the Annual Report for a summary of their activities.

Insight Courses
In order to address the challenges of interdisciplinary science, NAI Central sponsored two courses aimed at educating scientists in one discipline in the core concepts and terminology of another discipline. During the summer of 2003, the “Introduction to Planetary Science for Non−planetary Scientists” and the “Introduction to the Microbial World for Non−microbiologists” provided rare opportunities for cross−disciplinary education aimed at career researchers in astrobiology. The planetary science course was led by Dr. Bruce Jakosky of the University of Colorado with lectures also provided by Dr. Vikki Meadows of the Jet Propulsion Laboratory, Dr. Bob Pappalardo from the University of Colorado, and Dr. Greg Laughlin from the University of California Santa Cruz. The course took place in Flagstaff, Arizona on July 31− August 4, 2003 and also included a field trip led by Dr. Jeff Plescia of the US Geological Survey.

The microbial world course was held on Catalina Island, California in August 2003 and was led by Dr. Ken Nealson (PI of the NAI JPL Team) of the University of Southern California. These courses were deemed very useful by the participants, however securing participation by working researchers in cross–disciplinary fields remains a challenge.

Minority Institution Research Sabbaticals

NAI Central supports a program for faculty at certified Minority Institutions to participate in research sabbaticals in astrobiology at NAI research sites. The Minority Institution Research Sabbatical (MIRS) aims to support collaborations in astrobiology that will lead to joint research proposals successful in peer review competitions. The program began in 2002 and has created 4 scientific collaborations to date. Successful applications have been received from Tennessee State University, Florida A & M University, and Howard University. The program also extends support to students of the participating faculty members to attend astrobiology science meetings and to become more familiar with the field of astrobiology. Applications have been accepted year round. The program is currently under review for refinement and more focused achievement of its goals.

Seminar Series

Collaboration in a virtual institute requires multiple approaches. One of the NAI's successful efforts includes several seminar series using our videoconferencing systems and the collaborative meeting software product, WebEx. The Director's Seminars and the Forum for Astrobiology (FAR) seminars have become regular events and have had consistent audience turnout. The presenters of the Director's Seminars are senior scientists invited by the NAI Director. This year, NAI presented nine Director's Seminars. A highlight of this year's series was Dr. David J. Des Marais' presentation in February entitled “ The Mars Exploration Rovers unveil new horizons for astrobiology” at which 14 of the 16 Lead Teams attended in addition to three other sites. Over 90 people attended at the various locations. Overall, the Director's seminars draw an average of eight sites with up to 20 people at each location.

For a complete listing of our seminars and abstracts from each presenter go to: http://nai.arc.nasa.gov/seminars/index.cfm

Workshops and Conferences

The NAI supports numerous workshops, conferences and meetings each year as an additional mechanism for growing the overall community of astrobiology and for specific strategic goals and objectives of the Institute. These activities serve to train future astrobiologists, cultivate relationships with other international astrobiology organizations, and to advise NASA in its mission of exploration. During this past year NAI Central was instrumental in the success of, among others, the following activities:

- Cosponsorship of the Origins of Eukaryotes/Lateral Gene Transfer Workshop. This invitational workshop was jointly organized by NAI and the Canadian Institute for Advanced Research (CIAR). The concept for this meeting was originally proposed by Dr. Hyman Hartman. By July,

2004, at the Gordon Research Conference on the Origins of Life, a steering committee for a workshop on the origins of eukaryotes was identified. Dr. Ford Doolittle, of CIAR;s Evolutionary Biology Program, was a steering committee member. Through Dr. Doolittle's connections, information on a contemporaneously planned Lateral Gene Transfer workshop was exchanged, and a decision made to combine the two for maximal efficiency and impact. The participation of junior career astrobiologists was assured by permitting each member of the steering committee to identify and invite one such participant, without additional cost to the workshop budget. The on−site exchange was fruitful and exposed a consensus among the most prominent researchers in this field that was not yet evident in the published archive. A report on this meeting is being prepared by the NAI Senior Scientist. This partnership between NAI and CIAR led to interest from CIAR in affiliating with NAI, and underlies our plans to partner with CIAR for student travel and scientific sessions at the Second Earth Systems Processes conference in Calgary, August, 2005.

- Co−Sponsorship of the “Seventh Conference on the Chemical Evolution and the Origin of Life” September 15−19, 2003 in Trieste, Italy. Support included attendance by NAI students, who gained exposure to the theme of the conference, "Life in the Universe". The awardees were: A. Erik Boice (Indiana University), Simon (Nicholas) Platts (Carnegie Institution of Washington), Margaret Turnbull (University of Arizona), and Steve Vance (University of Washington).
- NAI Co−Sponsoring of a Short−Course on Planetary Protection, November, 2003 (Baltimore, MD)

- Sponsorship of a Lunar Astrobiology Workshop, March 16, 2003 (Houston, TX), which resulted in a widely−distributed white paper on lunar exploration.
- Support of a Geological Society of America Pardee symposium entitled, "Neoproterozoic Geobiology: Fossils, Clocks, Isotopes, and Rocks” (Nov. 2−5, 2003)
- Cosponsorship and logistics for the Year 2003 Astrobiology Science Conference, held March 30− April 2, 2003 at Ames Research Center.
- Cosponsorship of the Mars Sample Return Meeting, held during February, 2004 in Pasadena, CA.

Student Training and Early Career Programs

Astrobiology Graduate Student Conference 2004

As described in the Director's Letter to this report, the University of Arizona organized and hosted a conference led by and for graduate students in astrobiology. NAI Central assisted the organizer, Maggie Turnbull, with refinement of the concept, logistics for the meeting, production and development of a webpage including online registration, and presentations to the participants about collaboration and funding opportunities within the NAI.

FAR Seminars

The FAR Seminars are another series of video−seminars produced by NAI. They began as a response to graduate student and postdoc requests for a

venue to meet, present their research, ask questions and discuss issues in astrobiology. The presenters are selected from volunteers who wish to give presentations, and this year 11 students presented their work. In April, the students agreed they would prefer to have two 25 minute presentations instead of one 50 minute presentation. That change was made and has been well received.

In 2003 and continuing into 2004, the University of Washington offered another student seminar series. The Graduate Astrobiology Seminar is broadcasted to the NAI community utilizing the NAI videoconferencing and collaboration tools. In the spring of 2004, four weekly lectures were broadcasted.

NAI/NRC Postdoctoral Fellowship Program
The NAI is committed to training future generations of astrobiology researchers. A major component of the NAI's investment towards this objective has been the NAI/NRC Postdoctoral Fellowship Program. Administered in cooperation with the National Research Council, of the National Academy of Sciences, the NAI/NRC Postdoctoral Fellowship Program has now supported 27 NAI Fellows, at 17 different host institutions. During this past year the NAI/NRC Program has increased its flexibility such that candidates can now submit simultaneous applications to the NAI program, as well as to the various NASA Center NRC programs. Our program continues to support two review cycles per year; with application due dates of February 1 and August 1.

NRC Associates selected through the NAI/NRC Program become full members of the NAI, and, as such, are included in the NAI database and online directory, invited to attend and submit abstracts for NAI General Meetings, given access to NAI collaborative tools, and are eligible for additional NAI funding opportunities. NAI/NRC Fellows have, therefore, a wide spectrum of opportunities for further collaboration with NAI researchers, as well as the broader scientific community. In this role, NAI Fellows act as ‘Ambassadors' amongst the NAI Teams, and between the NAI and the broader scientific community, – helping to define and lead the new discipline of astrobiology. Go to the NAI/NRC Fellows section of this report to read about the activities of our current group of 5 Fellows.

NAI Research Scholarship
The NAI Research Scholarship Program offers stipends and research–related travel expenses to allow students (graduate or postdoctoral) to conduct collaborative research amongst two or more of the Lead Teams, including all of the participating institutions of the NAI. The program also supports travel to field–sites when required for the progress of the student's research. Recipients of NAI Student Research Scholarships during this past year included:

- James Hall (CIW), to support his participation in the Flores Workshop for Scientific Drilling in Lake Peten–Itza, Guatemala (August 10–16, 2003)
- Andrew Hock (UCLA), who conducted work on the physical limnology and environment of the Licancabur Volcano crater lake, as an analogue to possible ancient lakes on Mars, and

- Rory Barnes of the University of Washington who visited NASA Ames Research Center to collaborate with Ames researchers in the area of planet formation.

NAI Student Poster Competition

The AbSciCon (Astrobiology Science Conference) 2004 meeting (28 March–1 April 2004) included a Student Poster Competition sponsored and implemented by the NAI. This competition provided motivation, encouragement, and special recognition to the most promising astrobiologists of the future. It carries on a tradition from the AbSciCon Meeting in 2002, with certificates for 3 winners and prizes of $500, $750, and $1000.

Significant efforts for this year's NAI Student Poster Competition for the AbSciCon 2004 were a meeting website description of the competition requirements, abstract submission, poster procedures, and winner criteria. NAI Central managed the poster staff, the student presenters, arranged for the 6 judges to cover the 16 subject disciplines of the meeting poster topics, and prepared the certificates and check payments for the poster winners.

Education and Public Outreach (E/PO)

NAI Central coordinates and leads the overall E/PO program for the Institute by bringing the teams together for monthly telecons to share information, seeking out and sharing collaborative opportunities, supporting specific projects with a broad or national reach, and maintaining webpages for teachers and students. In addition to bringing the teams together for monthly conversations, NAI Central supported travel to the Astrobiology Science Conference and the associated Executive Council meeting for an in–depth meeting on all of the NAI's E/PO efforts. Discussions at these sessions led to changes in the overall program including the development of a fund available for cross–team E/PO collaborations, additional professional development for E/PO Leads, and new representation of the E/PO Leads on the Executive Council.

NAI Central E/PO projects this year ranged from web–based activities for middle school students to support for museum exhibits and national television programming. The details of the NAI Central led E/PO projects are outlined in the E/PO report.

Infrastructure

Collaborative Tools

Designed as a virtual institute with distributed members across the country and even around the globe, NAI has explored various technologies to support scientific collaborations. During the last year, NAI Central reevaluated the approach to collaborative tools. After five years of observing usage of the tools, NAI Central found significant differences in each group, resulting in a wide variety of requirements. As a result, NAI Central focused on providing as many tools as possible, in addition to providing information about the availability of additional tools not currently offered through the Institute. This approach allows the teams to select the tools most appropriate for their needs with NAI Central providing some of the basic or most common ones. NAI Central attempts to customize and tailor tools to individual teams and groups whenever possible to allow for the most flexibility in meeting needs and requirements for unique

collaborations.

The two most commonly used tools in the NAI community have been WebEx and the ***Polycom videoconferencing systems.*** Polycom is one of the industry leaders in videoconferencing systems, providing high quality, simple, reliable, protocol based (H323 and H320) videoconferencing capabilities. Polycom systems have been provided to each Lead Team, enabling simple and high quality videoconferencing capabilities between all the teams at any time. In some cases, Polycoms or the ViaVideo desktop videoconferencing systems have been provided to co−Investigators at additional institutions, expanding the possibilities for both cross−team and intra−team collaborations. Support of ISDN lines for the Polycom systems was discontinued this year, and use of Internet Protocol (IP) connections were substituted after quality and reliability testing were completed. IP connections have been successful, even surpassing the quality of ISDN in some cases. This shift resulted in a significant savings the Institute. ISDN connections are still supported through the Multi−point Controller Unit Bridge at Ames, but the lines are no longer paid for by NAI.

WebEx is a synchronous meeting application that runs over the IP based network. It allows people to share a variety of files and applications real−time from any computer on the internet. With WebEx, shared documents for a meeting are cached locally on each participant's machine, so that when a “presenter” advances a slide, image or document, all the other sites' slides are advanced instantly, ridding the audience of any latency issues seen in comparable software. This has worked extremely well in the virtual seminar series. WebEx also provides real−time chat and polling capabilities, video streaming, Voice−over IP (VoIP), application sharing, desktop sharing and web sharing. With application sharing and desktop sharing, participants can use each other's software or even the entire computer remotely. This allows for real−time collaboration on authoring papers, analyzing data, running experiments etc. For more information about this tool and how your team can use it, please contact Estelle Dodson.

Gateway pages are customized webpages for use by a group or team developed by the staff at NAI Central. Once set up, gateway pages are maintained by the group membership. These pages are used to share files, maintain a calendar, conduct discussions, keep membership/contact information and more. Available features include threaded discussion forums, email lists, calendars, and document management/file uploads. To set up a gateway page for your group, contact Marco Boldt.

Pageseeder is a web−based document sharing and annotating tool that was piloted this year at NAI. It was found to be a well−designed tool with a good interface, but did not fit a need of the NAI community. It will not be further supported through NAI.

A new asynchronous collaborative tool was made available at no cost to NAI through a partnership between NASA Ames Research Center and Xerox PARC. The produce is referred to as ***“NX”*** for NASA Xerox. NX provides users with an online space for collaboration using a variety of features. It offers online file storage and sharing with extensive read/write permissions based on

individual users and specified groups. One features of NX that stands out from the many online collaborative tools are called interact pages. Using interact pages, workgroups can create customized interactive pages, discussion forums, meeting agendas, project management pages, and tables. NX also provides document version control, routing capabilities and archiving. It has an online calendar, group email capabilities, bulletin boards and extensive search capabilities. For information on obtaining an NX account, contact Estelle Dodson.

The ***Member Services*** area of the NAI website contains a variety of useful features, including a section of information related to the operations and meetings of the Executive Council. Logistics information for all in−person meetings of the Executive Council can be found here, and minutes from both in−person and videoconference meetings are posted for all members to review. Other documents relating to the business of the Executive Council, including its charter, are available for download, as is the Handbook for NAI Teams, a highly useful central compendium of the operational precedents, current policies and procedures, expectation of Team participation, and other NAI arcane. Also in Member Services are the NAI e−mailer, online discussion forums, and the Photo Directory.

The ***Photo Directory*** is a simple, but useful, tool provided by NAI Central to all members. It is accessed through Member Services and provides members' names, titles, email addresses, addresses, phone numbers, disciplines, and institution affiliations. The Photo Directory is updated each year when the Lead Teams submit their annual reports.

Executive Council
The NAI's Executive Council (EC) is made up of the Principle Investigators (PIs) of each of the Lead Teams and the Director and Deputy Director of the NAI. NAI Central coordinates monthly meetings of the EC. During this reporting period, Nine of these meetings were held by Polycom, and an additional 3 meetings were arranged in person at Jackson Hole, San Francisco, and Mountain View. NAI Central provided agendas, logistics, technical support, and minutes, as well as video tapes of the virtual meetings. Minutes of the meetings are available at http://nai.arc.nasa.gov/institute/member_services/ec.cfm .

The in−person meeting of the Executive Council in October, 2003, was held in conjunction with a special retreat in Jackson Hole, Wyoming designed to inaugurate new and on−going collaborative and cross−team science initiatives. NAI Central developed the agenda, arranged logistics at the Snake River Lodge, and supported travel for two additional members per team in order to get broader representation of the NAI membership and to begin dialogues on working focal areas for cross−institute collaborations.

Institute Strategic Fund
The NAI has a limited Institute Strategic Fund (ISF) to support new research projects internal or external to the existing NAI Teams. Submission and selection policies may be found at http://nai/institute/fellowship/index.cfm#isf . Submissions are accepted on an ongoing basis, and may be sent to any member of the Executive Council. Several submissions were received during

Year 6, although no proposal was evaluated at a sufficiently high Technical Excellence and Priority Score to be recommended for funding to the Selecting Official.

NAI Annual Report for Year 6
One of the requirements of the Cooperative Agreements is the submission of an annual report of activities. NAI Central coordinates the collection of these reports and combines them into this single report for all of NAI. The report is database driven, utilizing web−based submissions and outputting them in html for web presentation. This year, a record 21 Teams were asked to submit reports due to the overlapping nature of two cooperative agreement periods. NAI Central edited the reports for acronyms and completeness, modified special characters for accurate representation of scientific terms in html, designed a process for online comment submission, and made completed corrections as necessary.

NAI Information Management System (NIMS)
NAI Central maintains a database, which collects nearly all of the Institute's data. The NAI Information Management System (NIMS) is a MySQL database designed by NAI Central staff. The NIMS is a powerful database that is the basis for a suite of products including:

- The NAI Annual Report on the web and CD−ROM.
- The NAI Photo Directory in the Member Services section of the website.
- The NAI Shared Resources Database
- The NAI Emailer in the Member Services section of the website.

In addition, it is also used to generate reports and statistics that form the basis of many presentations produced by the Institute. Examples of NIMS reports include studies of NAI publications, NAI Membership breakdown, E&PO reports, and Information Technology accomplishments reports.

Nearly all NIMS information comes from the teams in the form of yearly submissions to the Annual Report. Updates and minor changes are made throughout the year, but the vast majority of new data are added immediately after submissions are due. The completeness of each NAI team's report is critical to the continued usefulness of NIMS.

Towards this end, considerable effort was made this year to improve the quality of NIMS data. For the first time, the bulk of NIMS data was entered directly by the teams using the online annual report submission form. Previously, the teams submitted reports as Word documents. This switch to online submission proved to be successful in minimizing data entry errors and will continue to be refined.

Between July 2003 and June 2004, NIMS underwent a major transformation. The entire body of NIMS data was migrated from FileMaker Pro 4 to MySQL. This brought a whole new realm of possibilities to data reporting as well as providing a direct link to NIMS data from the NAI websites. Publishing the Annual Reports on the web is just one of the many uses of NIMS that the NAI is exploring. In the coming year, there will be a greater effort to integrate NIMS

data into other areas of the annual report.

Shared Resources Database
http://nai.arc.nasa.gov/institute/member_services/sf.cfm

The Shared Resources Database was created to encourage NAI member institutions to share significant and unique research facilities across the Institute and throughout the astrobiology community. This information is available to foster further collaboration, augment individual research capability, and accelerate the overall advancement of research in astrobiology.

This project was begun in January 2004 by looking at the CAN 2 and CAN 3 proposals for the current NAI Teams and records for NAI funding augmentation for significant Team resource purchases. In early June, database searching modes were determined, resource record contents were written, and records were loaded and searchable in the draft database. At the end of the Year 6 Annual Report period, the database record content is in draft form, and the database is fully searchable. The database will be finalized in the Fall of 2004.

The resource category types are major centralized facilities (including a variety of resources supporting a type of research); state−of−the−art instruments and equipment; models, databases, and sample collections; environmental simulation facilities; and computational resources and astronomical observatories. The database does not include resources related to education and public outreach (EPO), information technology (IT), and administration tools.

NAI Website http://nai.arc.nasa.gov
The NAI website is the primary source of information about the NAI for it's members and the general public. The website is a part of every NAI project at some level.

The ***"Ask an Astrobiologist"*** section of the website allows users to submit questions directly and then receive an e−mailed response. The site received 157 questions last year on topics ranging from the possibility of life on Titan to the reason for the theories of liquid oceans on Europa and the definition of life. While no data is collected on users, it is possible to assess the users by vocabulary and language of the posted questions. The assumption is that the users range from young students to post−graduate members of the astrobiology community and Dr. David Morrison addresses his answers accordingly. All answers are archived and searchable by future users.

The ***NAI Newsletter*** is a web−based source for NAI announcements and news. It is emailed out every two to three weeks to NAI members and additional subscribers. In year six, 15 Newsletters were published with each edition emailed to over 1,000 recipients.

The Newsletter is being used by our members to advertise things such as Postdoctoral Fellowship and Assistant Professorship positions available at their institutions; workshops, courses, summer schools and special sessions at meetings sponsored in part by the NAI or related to the field of astrobiology;

and general announcements and stories about NAI members and/or projects.

Visit http://nai.arc.nasa.gov/newsletter/index.cfm to view all archived Newsletters.

In addition, the NAI website offered 25 featured stories last year. An NAI History section was created. A reference handbook for Lead Teams was created and posted, and a specialized webpages were created for the NAI Executive Council to track agendas, provide logistical information, and archive minutes of the meetings. The Gateway pages described above were originated and customized this year, and the Annual Report submission website was newly created. Finally, a new section on courses and conferences was added. The NAI's site usage is strong averaging 600,000 to 1,000,000 million hits a month.

Cooperative Agreements (CA)

The Sponsored Programs Office of the NAI is responsible for overseeing the preparation, announcement, review, and management of the Cooperative Agreements (CA), which the Institute develops with its Lead Team Institutions. The CA's are the primary funding instrument to support the research, training and E/PO activities of the NAI Lead Institutions, and all of their associated team institutions. This year, NAI completed selections, made awards, and disseminated funds to the 12 Lead Team Institutions from the third Cooperative Agreement Notice. Go to the Lead Team Reports to read about each Team's work.

NAI Staff

NAI Central supports a small staff of civil servants and contractors with a variety of skills to carry out the multitude of projects described here. A complete list of staff members, project assignments, and contact information is available at http://nai.arc.nasa.gov/institute/handbook/1.cfm#_Toc459976658

EPO: NAI Central

These are the Education and Public Outreach activities for the NAI Central.

NAI Minority Institution Research Sabbatical: Engaging Minority Institutions in Astrobiology

NAI Central supports a program for faculty at certified Minority Institutions to participate in research sabbaticals in astrobiology at NAI research sites. The Minority Institution Research Sabbatical (MIRS) aims to support collaborations in astrobiology that will lead to joint research proposals successful in peer review competitions. The program began in 2002 and has created 4 scientific collaborations to date. Successful applications have been received from Tennessee State University, Florida A & M University, and Howard University. The program also extends support to students of the participating faculty members to attend astrobiology science meetings and to become more familiar with the field of astrobiology. Applications are accepted year round. Complete information is available at http://nai.arc.nasa.gov/institute/miSabbatical.cfm.

Astro−Venture: An Interactive Project for Students

Astro−Venture (http://astroventure.arc.nasa.gov) is an educational, interactive, multimedia Web environment focusing on astrobiology. Developed by the Office of Education at NASA Ames Research Center and funded in part by NAI Central, this educational site, designed for students in grades 5 – 8, allows students to role−play NASA occupations to learn about what makes a planet habitable to humans. Astro−Venture is divided into five sections: Astronomy, Biology, Geology, Atmospheric Sciences, and Design A Planet. Each of the first four sections includes on−line multimedia modules and lessons. NAI provides scientific review and experts for webcasts and webchats. This year, the Astro−Venture team led numerous workshops with both teachers and students throughout the country including workshops with first and second−year NASA Explorer School teachers. The Atmospheric Science Mission Module, and Biology and Geology Educator Guides were completed and released, and a nation−wide pilot test of all four educator guides was completed with extremely favorable results. Astro−Venture was featured in three publications including two books and in an exhibit on the Apple Learning Interchange, and the Biology Educator Guide was reviewed and recommended for widespread distribution.

Astrobiology for Teachers: An Online Graduate Course

NAI supports teachers from across the US to enroll in a semester long graduate course in astrobiology. The course is one of several online offerings of the Montana State University in conjunction with the National Science Teacher Association Institute. The two main goals of the course are (1) to provide information on the central concepts related to the field of astrobiology and (2) to provide experiences with using student–centered and inquiry–based curriculum materials for teaching astrobiology that are aligned with the National Science Education Standards. The course materials are astrobiology texts in common use and a specially designed set of lab activities, Life in the Universe Activities Manual published by Prather, Offerdahl, & Slater, 2003, Addison Wesley, to accompany one of the primary texts. While the course is asynchronous allowing participants to complete the work on their own time schedules, teachers must log in daily and complete several group projects during the semester. The course is evaluated summatively using the following data sources: (i) teacher–participant performance in the course overall; (ii) teacher–participant performance on exams; and (iii) teacher–participant comments on the course from the teachers' electronic community discussion groups. The course was taught in both the Fall 2003 and Spring 2004 semesters, and 24 and 23 teachers completed the course, respectively. Information regarding upcoming courses can be found at http://btc.montana.edu/ceres/astrobiology/.

NAI E/PO Representation at Professional Meetings for Scientists

In this past year, NAI Central E/PO has attempted to strengthen the role of education via science organizations. NAI Central sponsored an education session at the American Geophysical Union's (AGU) annual meeting in December, 2003. Daniella Scalice chaired the six invited panelists who discussed issues of "bridging the gap between scientists and educators" with an audience of fifty conference attendees. NAI Central also sponsored two E/PO sessions at the Astrobiology Science Conference in April, 2004. One session provided a forum for discussing issues in science communications, and the other brought in presenters from the realm of informal education to share the challenges and accomplishments of bringing astrobiology into museums.

Additionally, NAI Central supported E/PO staff from its SETI Institute and University of Hawaii teams to conduct an educator workshop in conjunction with Bioastronomy 2004 in Reykjavik, Iceland. NAI Central staff coordinated and shipped educational materials for use in the workshop.

Teachers Experience Astrobiology A Series of Workshops, Short Courses, and Professional Meetings

NAI offers teachers of all levels many opportunities to engage with the science of astrobiology. These opportunities are offered at professional science education meetings, many state and regional conferences, and at our academic and research partner sites as well. Typical offerings include lectures and presentations by scientists combined with exposure to and training with astrobiology classroom materials, and some research into core astrobiology concepts whenever possible. Many of the workshops are often collaborative efforts between the NAI Teams, other NASA missions, and the NASA Office of

Space Science Education Forums. Astrobiology workshops are unique in that they involve interdisciplinary science topics with the focus on life in the universe which both captures student imaginations as well as address the trend in American middle and high schools toward integrated science courses. For more information on the NAI programs for teachers, visit http://nai.arc.nasa.gov/teachers/

NAI Central staff coordinated materials and training for the education professionals conducting a week–long workshop for the educators from the first year of NASA's Explorer Schools Program. The astrobiology–themed workshop was held at NASA Ames Research Center in July, 2004. Daniella Scalice gave a presentation on the latest astrobiology research to the workshop leaders, and trained them on astrobiology classroom materials.

Daniella Scalice proposed and organized a collaborative effort to present a unified astrobiology initiative to educators at the National Science Teachers Association (NSTA) Annual Convention in April, 2004 in Atlanta, GA. The Astrobiology Professional Development Resource Day (aka Room for a Day) combined science lectures, topical workshops, and an ongoing share–a–thon with space science classroom materials. The Room for a Day hosted six consecutive one–hour sessions, presented over a dozen classroom resources, and brought together education professionals from the following organizations: NAI Central; NAI's teams at the SETI Institute, University of Washington, University of Arizona, Carnegie Institution of Washington, NASA Ames Research Center, University of Hawai'i, Marine Biological Laboratory, and Pennsylvania State University; NASA's SOFIA and Kepler missions; the Astromaterials group at Johnson Space Center; the Mars Outreach Program; TERC; the NASA Ames Education Office; and the NASA Office of Space Science Solar System Exploration and Origins Education Forums. A total of 180 educators attended the event throughout the day.

NAI also participated in the NASA–wide exhibit booth at the NSTA convention. NAI Central coordinated materials from its teams to be distributed through the booth, as well as helped staff it.

In conjunction with this effort at the NSTA convention in Atlanta, NAI Central, in collaboration with NAI's SETI Institute team, coordinated an outreach program at a local science museum, the Fernbank Science Center. David Morrison, NAI's Senior Scientist, and Jill Tarter, the Bernard M. Oliver Chair for SETI Research at the SETI Institute, co–presented an evening program for the public on astrobiology topics. Approximately 200 students of all ages attended the event. Classroom materials were also provided for the museum.

NAI Central staff, in collaboration with NAI's Marine Biological Laboratory (MBL) team, hosted two workshops and an exhibit booth at the National Association of Biology Teachers annual meeting in November, 2003 in Portland, OR. In conjunction with this conference, NAI Central and the MBL team coordinated a workshop and a public lecture at the local science museum – the Oregon Museum of Science and Industry. Lorraine Olendzenski and Daniella Scalice presented the workshop, and Peter Ward, NAI's University of Washington Principal Investigator, delivered the public lecture to an audience

of 120. Classroom materials were also provided for the museum.

Extraterrestrial Life Interactive Exhibit at the New York Hall of Science

The New York Hall of Science (NYHoS) is New York City's only hands−on science and technology center. Ranked as one of the best science museums in the country, the Hall is a leading innovator in exhibit technology and educational programming. More than 225 hands−on exhibits explore the wonder and excitement of biology, chemistry and physics. NAI Central and the Astrobiology Program Office have funded part of the production of the 5000 square foot interactive exhibit for children on life beyond Earth and the extremes of life. Under the working title of "Extraterrestrial Life," NYHoS is developing a permanent exhibit and discussing the possibility of a smaller traveling version. NAI scientists are on the review board for the exhibit and the content reflects much of the NAI's research on extremophiles. The exhibit will introduce children and families to the known conditions for life and what is considered extreme on Earth. These interactives will be followed up with explorations of habitable planets beyond Earth. The lead for this project is Dr. Martin Weiss at NYHoS. The exhibit is scheduled to open in November 2004.

Alien Earths: Traveling Museum Exhibit

The 3000 square foot traveling Museum Exhibit, Alien Earths, focuses on the search for habitable planets in the universe, highlighting the processes of star formation which might allow such planets to exist and the conditions for life that make a planet habitable, along with the current efforts in planet detection. NAI has provided both scientific input from microbiologists, John Spears and Brad Bebout, as well as funding to produce educational programming around the exhibit content. NAI's Assistant Director for Communications and Technology also serves as the content lead in the Search for Life component of the exhibit.

The exhibit is scheduled to open in February 2005 at the Lawrence Hall of Science in Berkeley, California and will travel around the US over a 3−6 year life span. The exhibit is targeted at small to medium sized science centers and museums and may also be tied in with NAI Teams under partnerships designed to highlight astrobiology in the Teams' local communities. The exhibit will be distributed via the Association of Science−Technology Centers.

http:// www.alienearths.org

The Astrobiology Education Poster

In response to a call by the NAI E/PO working group three years ago, the Astrobiology Education Poster was conceived and developed by NAI Central. Daniella Scalice, Julie Fletcher worked with the SETI Institute to develop a science background narrative, visual artwork, and three classroom activities which explore the connection between extreme environments on Earth, potential for life elsewhere, and how to search for it. The activities address the National Science Education Standards for high school, and were field tested with middle and high school classrooms. The activities are designed to fit into a variety of discipline−based curricula, as well as integrated science classes.

The poster will reach teachers through a broad distribution network, being featured and inserted into four journals representing the National Science Teachers Association, The American Association of Physics Teachers, and the International Planetarium Society. It will also be distributed by the NASA Solar System Exploration Education Forum teacher packets. In all, 75,500 posters will be distributed in this way.

NAI E/PO Support Services

NAI Central coordinates representatives from the NAI Teams in monthly telecons and facilitates collaborative projects among them in addition to offering them support with educational materials and supplemental funding. Centralizing this information in the form of a webpage, NAI Central shares information on E/PO activities, houses presentations on E/PO projects, and offers general announcements, an interactive forum, and links to other relevant sites. For access to the NAI E/PO page, please contact Daniella Scalice at (dscalice@arc.nasa.gov). NAI Central also maintains webpages with resources for students and teachers (http://nai.nasa.gov/teachers; http://nai.nasa.gov/students).

NAI Central also represents all of NAI to the larger E/PO networks including two forums of the NASA Office of Space Science (OSS) Education Support Network. NAI Central attends monthly telecons and yearly retreats for the Origins Education Forum and the Solar System Education Forum. NAI Central also responds to all reporting requirements including the annual request for input to the education project database known as EdCats and participates in OSS group activities. Specifically, NAI brings information regarding astrobiology to other E/PO programs and returns information on opportunities and new projects back to the NAI Teams. Information on the OSS Education Support Network and contact information is available at http://oss−ecosystem.stsci.edu/.

Voyages Through Time: High School Curriculum

ip with NAI, the National Science Foundation, the California Academy of Sciences, and San Francisco State University, the SETI Institute has developed Voyages Through Time (VTT), a standards−based integrated science curriculum for high school centered on the unifying theme of evolution. Scientists, teachers, curriculum writers, and media specialists have created six CD−ROM modules that integrate astronomical, geological, and biological sciences. The sequence of lessons in each module is designed to promote students' understanding of science and skills as defined by the National Science Education Standards and Benchmarks for Science Literacy. The six modules, Cosmic Evolution, Planetary Evolution, Origin of Life, Evolution of Life, Hominid Evolution, and Evolution of Technology, use the constructivist approach of engage, explore, explain, elaborate, and evaluate (Biological Sciences Curriculum Study, 1996) as an instructional framework. NAI Central funded the VTT National Field Test and a CD−ROM sampler of the curriculum. The National Field Test took place from September 2001 through July 2002 in over 80 classrooms in 28 states. Teacher feedback was very positive, and the curriculum was revised following the national test evaluation summary reports.

NAI Central funded the revision and production of the CD−ROM samplers of the curriculum. The samplers provide astrobiology activities for the classroom. Over 3000 free CD−ROM samplers were distributed at science teacher conferences, science conferences, workshops, and short courses this year. The curriculum was published in August 2003. More information about VTT can be found at http://www.voyagesthroughtime.org.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

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Team Reports: NASA Goddard Space Flight Center

NASA Goddard Space Flight Center
Executive Summary
Principal Investigator: Michael Mumma

The central goal of the Goddard Center for Astrobiology is to understand how organic compounds are created, destroyed, and altered, during stellar evolution leading up to the origin of life on a planet, such as Earth. Planetary systems form by collapse of dense interstellar cloud cores. Some stages in this evolution can be directly observed when stellar nurseries are imaged, while other stages remain cloaked behind an impenetrable veil of dust and gas. Yet to understand the origin of life on Earth, we must first develop a comprehensive understanding of the formation of our own planetary system. To understand the probability of finding life elsewhere we must understand both the similarities and differences between the evolution of our own system and that of a typical star.

Dense cloud cores are very cold (10–50K); their dust grains are coated with ices comprised of water and organic compounds. Many of these organics have potential relevance to the origin or early evolution of life, if delivered to planets. The survival of these organics through the violent birth–phase of a star is less certain. Properties of the young star (its mass, spectral energy distribution, whether it formed in isolation or as a multiple star, etc.) help control the evolution of organic material in the proto–planetary disk. The location within the disk is important since the nature and effectiveness of such processing depends strongly on distance from the young star, on distance above the nebular mid–plane, and on time. The ultimate delivery of these primitive organics to young planets and their moons also evolves with time, as the bodies grow in size and as the nebula clears.

We seek to better understand the organic compounds generated and destroyed in the interstellar and proto–planetary environments, through observational, theoretical, and laboratory work. We have begun to examine the potential for and limitations to delivery of exogenous pre–biotic organics to planets, examining factors that enhance or restrict this potential. To follow these factors over time, from the natal cloud core through the end of the late heavy bombardment (~ 4.1 Ga) and evaluate the possible role of exogenous organic material in terrestrial biogenesis, we have divided the research into four themes as well as our education and public outreach program. These themes are:

Theme 1: *Establish the taxonomy of icy planetesimals and asteroids to evaluate their potential for delivering pre−biotic organics and water to the young Earth and other planets.*

Theme 2: *Investigate processes affecting the origin and evolution of organics in planetary systems.*

Theme 3: *Conduct laboratory simulations of processes that likely affected the chemistry of material in natal interstellar cloud cores and in proto−planetary disks.*

Theme 4: *Develop advanced methods for the in−situ analysis of complex organics in small bodies in the Solar System.*

This first year of our NAI participation saw major emphasis on infrastructure: recruiting students, staff, and permanent employees, updating computational facilities, building laboratories, and furnishing them with equipment. In addition to the five undergraduate students recruited through our summer internship program, we recruited two additional undergraduates and two high school students for part−time work. Beyond this we recruited a graduate student, three post−doctoral researchers, two senior soft money scientists, and hired one civil servant as a result of establishing the Goddard Center for Astrobiology.

Besides positioning ourselves for research activities next year with staff and equipment, and participating in numerous meetings and workshops, we secured time on telescopes for the observation of comets (on the NASA Infrared Telescope Facility (IRTF), the Keck Observatory, and the Five College Radio Astronomy Observatory) and young stellar objects (on the Very Large Array).

In addition to planting these seeds for the future, each of the four themes has made progress in our scientific goals. An important laboratory goal of Theme 1 is to fingerprint late additions to the Moon using the relative abundances of the highly−siderophile elements that occur in high abundance in likely impactors, but extremely low abundance in the indigenous lunar crust. The initial work has consisted of selecting and separating pure melt rock from lunar highlands breccias. 2g of two Apollo 17 breccias (Figure 1) were obtained from the Johnson Space Center curatorial facilities; we have cleanly separated 13 chips from one and 6 chips from the other to measure Os isotopes and other highly siderophile element abundances. Final checks on the chemical blanks for the separation and measurement procedures are being completed. The analytical work; powdering, dissolving, separating elements of interest, and mass spectrometric measurements, start in July, 2004.

Figure 1. Apollo 17 lunar melt rocks have been selected and are ready for analysis of highly siderophile element abundances and osmium isotopic compositions.

A second objective in Theme 1, establishing the taxonomy of icy planetesimals, has also made progress with the measurement of CO, CH_4 , and other volatile organic constituents at high spectral resolution in three comets; one short−period, Jupiter Family Comet (JFC) (2P/Encke) and two long−period, Oort Cloud comets (C/2001 Q4 NEAT and C/2002 T7 LINEAR). In particular, spectra of Comet 2P/Encke were obtained at high spatial and spectral resolution about the nucleus; rotational temperatures of coma gases were between 25 to 30K, methane was severely depleted while the relative abundances of ethane, methanol, hydrogen cyanide, and acetylene in this JFC agreed with those of “typical” Oort Cloud comets.

A vital component of Theme 2 is the observation of proto−planetary disks (proplyds); (near−infrared single−slit cross−dispersed echelle and grating spectrometer (NIRSPEC) operating at the Nasmyth focus on Keck II Observatory, HI) spectra of the proplyd HST 10 in Orion are being processed Using the Very Large Array we have detected the first three carbon sugar (dihydroxyacetone) in star− (and planet−) forming molecular clouds. This detection highlights the role of prebiotic chemistry long before planetary surfaces are amenable to the synthesis of such compounds, and suggests that the chemistry leading to life is widespread throughout the universe. Theme 2 investigators are measuring infrared flux and spectrum of the transiting extrasolar planet HD 209458b and are also using ground−based data to measure the infrared spectrum of the planet from 2 to 5 microns, using a similar technique.

Theme 3 is entirely focused on laboratory work. One aspect simulates the vacuum and low−temperature environment of space using a high vacuum chamber and a cryostat. Ice samples condensed on a cooled mirror inside the cryostat are irradiated with 1 MeV protons to simulate cosmic−ray bombardment or are photolyzed to simulate vacuum−ultraviolet (UV) exposure. Motivated by detections of nitriles in Titan's atmosphere, cometary comae, and the interstellar medium, we completed laboratory investigations of the low temperature chemistry of acetonitrile, propionitrile, acrylonitrile, cyanoacetylene, and cyanogen (CH_3 CN, CH_3 CH_2 CN, CH_2 CHCN, HCCCN, and NCCN, respectively). Trends were sought, and found, in the photo− and radiation chemical products of these molecules at 12 − 25K. In the absence of water, all of these molecules isomerized to isonitriles, and CH_3 CN, CH_3 CH_2 CN, and (CH_3) 2 CHCN also formed ketenimines. In the presence of H_2O, no isonitriles were detected but rather the isocyante ion (OCN^-) was seen in all cases. Although isonitriles, ketenimines, and OCN^- were the main focus of this work, we also examined cases of hydrogen loss, to make smaller nitriles, and hydrogen addition (reduction), to make larger nitriles. HCN formation was seen in most experiments. These results are directly applicable to the nitrile ice chemistry on Titan, in cometary ice, and in the interstellar medium.

Members of Theme 3 have synthesized autofluorescent membranes (Figure 2), and possibly even vesicles, from a realistic interstellar ice mixture (H_2O, CH_3 OH, NH_3, and CO at 15 K) using the same experimental equipment discussed above. The properties of these membranes are being characterized by collaborator D. Deamer (University of California, Santa Cruz).

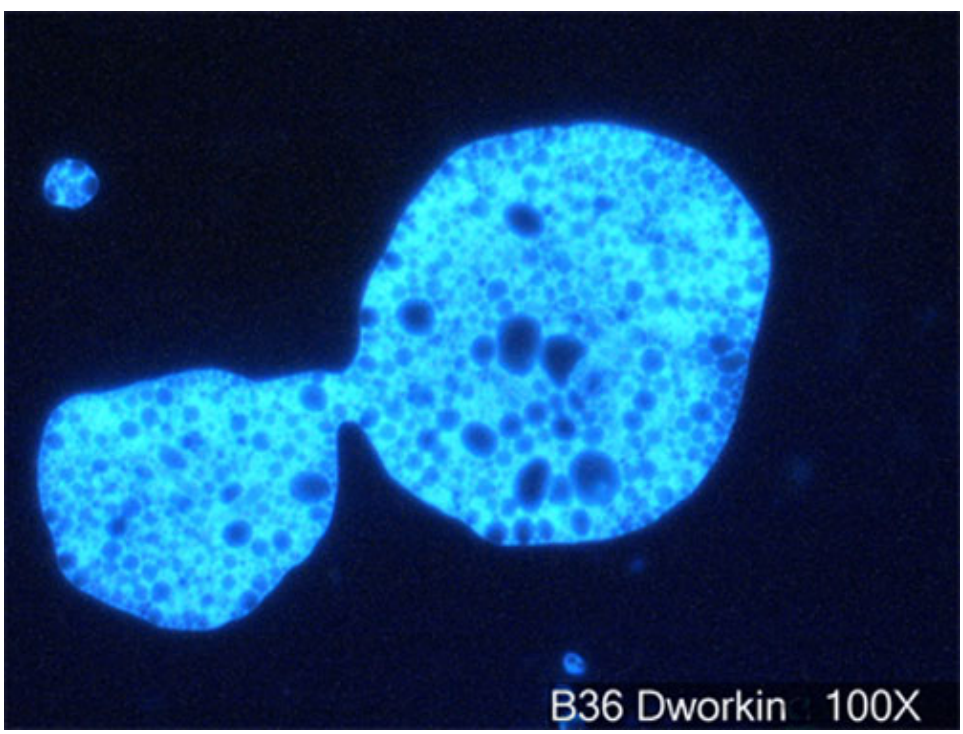


Figure 2. Micrograph of fluorescent membranous material generated by proton irradiation of a realistic interstellar ice dispersed in pH 8.8 10 mM phosphate buffer shown under oil−immersion microscopy at 1000x.

Members of Theme 3 have developed computer codes for chemical kinetic calculations in the solar nebula as a function of temperature, pressure, and mixing rate (parameterized as an eddy diffusion coefficient). Experimental studies of the efficiency of different types of catalysts for conversion of CO + H_2 to CH_4 have been completed. We have also observed that the carbonaceous coating deposited onto the surfaces of amorphous iron silicate and magnesium silicate grains during the surface−mediated conversion of CO, N_2 and H_2 into more complex hydrocarbons (previously believed to “poison” such grain catalysts) also reacts with CO, N_2 and H_2 to form complex organic products. These results imply that, to some degree, nearly all solid materials in the primitive solar nebula could serve as substrates to convert CO, N_2 and H_2 into organic materials.

The development of instruments for organic analysis on space missions is the crux of Theme 4. To prepare for flyby, rendezvous, and sample return missions to comets, the development of advanced organic analysis techniques has been initiated. These techniques include: laser desorption mass spectrometry; pyrolysis mass spectrometry; and the solvent extraction of organic molecules followed by chemical derivatization. In the initial stages of this work a variety of Mars analog materials such as Atacama desert soils, Hawaiian basalts, meteoritic sample s, and solid material generated by some of the nitrile irradiations conducted by Theme 3 have been used to cross compare these techniques. Some of these materials also serve as cometary analogs and the chemistries developed for their analysis may be relevant for future cometary research.

Initial analyses of carbonaceous chondrites and simple carbon−matrix standards with laser desorption methods have contributed to a developing database of refractory macromolecular materials that may be present in comets and other small bodies. This database should lead to increased understanding of (i) parent body synthesis and processing; (ii) impact survival of more fragile incorporated compounds; and (iii) enhanced in situ protocols for determining the full breadth of cometary organics.

Finally, our team has made great progress in our education and public outreach endeavors. In the Spring and Summer of 2004 educational efforts of the Goddard Center for Astrobiology included the implementation of a pilot program called the 2004 Summer Undergraduate Internship in Astrobiology (SUGIA), the initiation of a high school curriculum development project with the Minority Institution Astrobiology Collaborative (MIAC) and the modification of an undergraduate Astronomy course at the University of Maryland College Park (UMCP) to focus on Life in the Universe. In addition, we are working with MIAC to systematically observe comets through emission−line filters at optical wavelengths. This effort is led by Dr. Donald Walter (South Carolina State University), and will utilize telescopes in Arizona. Imaging studies on the Kitt Peak 1.3−m telescope are in the science−testing phase, and should be completed by the end of 2004. Monitoring of comet 9P/Tempel 1 is planned for spring/summer, 2005 to support the Deep Impact mission. Dr. Walter is in residence at GSFC in summer, 2004, through our Summer Faculty Fellowship Program, working closely with Co−I DiSanti on aspects of our database of cometary IR spectra.

Figure 3. The Astrobiology in Secondary Classrooms Curriculum Development team poses for a picture on the last day of their stay at the Goddard Center for Astrobiology, July 2, 2004. Pictured are: (back row) Dr. Michael J. Mumma, Director of the GCA; Kevin Jones, Branchville High School, SC; Michael Cherry, Hillside High School, NC; Jim Poland, Seneca High School, SC; Dr. Leroy Salary, Professor, Norfolk State University; Dr. Michael DiSanti, Co−Investigator, GCA; (front row) Brooke L. Carter, Research Operations Coordinator, GCA; Dr. Donald Walter, Professor, South Carolina State University; Dr. Jennifer Stewart−Wright, Professor, Tennessee State University; Dr. Jason Dworkin, Co−Investigator, GCA; Laurette Cousineau, Williamson County Schools/Brentwood High School, TN; Dr. Nasrollah Hamidi, Visiting Professor, South Carolina State University; Judy Butler, CEO, Dragonfly Enterprises; Stephanie Stockman, E/PO Lead, GCA (not pictured).

Project Report: Establishment of the Goddard Analytical Astrobiology Laboratory

Project Investigator:	***Jason Dworkin***

Project Progress

Establishment of the Goddard Analytical Astrobiology Laboratory

Construction:

This year Dworkin and his team completed construction of the laboratory infrastructure in Goddard Space Flight Center (GSFC) building 2, room W109 (Fig. 1). Since then we have focused on purchasing the best analytical tools for determining the organic composition of the material generated in the Cosmic Ice and Cosmic Dust Laboratories. These are liquid chromatography–time of flight mass spectroscopy (LC/MS–ToF) and gas chromatography–mass spectroscopy (GC/MS).

- LC/MS–ToF (Waters 2695XE HPLC attached to Waters LCT Premier): Injected material flows through a ultraviolet (UV)–Visible diode array and UV fluorescence detectors to the time of flight mass spectrometer with an ESI source. The MS has a mass accuracy of >3 ppm, a resolution of 10,000, and a range of 20 to 30,000 m/z. Installation is expected on July 30, 2004.

- GC/MS (Thermo Finnigan Trace DSQ): This GC/MS has as a mass range from 1–1050 amu, with a scan rate up to 10,000 amu/sec. Installation is expected by August 7, 2004.

In addition, we have recruited two half time researchers (G. Ertem and M. Martin), one graduate student (M. Pasek, advisor: D. Lauretta, U.A.), and one undergraduate (S. Tsitrin, Fall 2004) to help with the analyses.

Fig 1. Astrobiology Analytical Lab before (left) and after (right) construction. Brochures show equipment that has been ordered.

Research:

We have started work on the analysis of the products of the irradiation of various nitriles in water ices using an old GC/MS. We will resume this work as well as begin work on glycolaldehyde when our new GC/MS arrives. We have synthesized autofluorescent membranes (Fig. 2) and possibly vesicles from a realistic interstellar ice mixture (H_2O, CH_3 OH, NH_3, and CO at 15K) under high vacuum via irradiation with various fluxes of 0.8 MeV protons, to simulate cosmic–ray bombardment. The properties of these membranes are being characterized by collaborator D. Deamer (University of California, Santa Cruz).

Fig 2. Micrograph of fluorescent membranous material.

Highlights

- We have completed research and leveraged funds to purchase equipment for analysis of organic compounds.
- We have synthesized autofluorescent membranes from realistic interstellar ice mixtures with proton irradiation.

Project Report: Investigation of the evolution of molecular complexity in the star–forming cores of molecular clouds

Project Investigator:	***Geoffrey Blake***

Project Progress

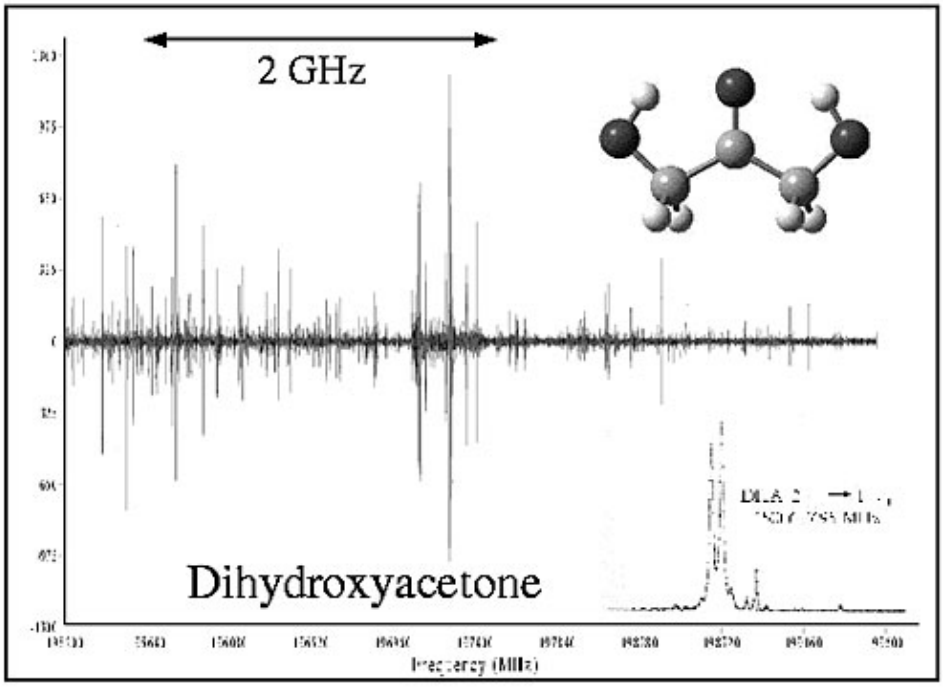
Research by the Blake group centers on an investigation of the evolution of molecular complexity in the star–forming cores of molecular clouds. Both laboratory and observational studies are carried out. This work began with an observational search for dihydroxyacetone (DHA), the simplest three carbon ketoses sugar. Over ten transitions have now been detected toward the galactic center source Sgr B2(N–LMH), a sample line is shown in the figure below. The top portion of the figure depicts the molecular structure and a portion of the laboratory spectrum assigned in our laboratory, while the bottom panel shows one of the DHA lines observed near 1.3mm toward Sgr B2(N–LMH). The rest velocities of the lines are nicely centered on that expected for complex molecules from detailed mapping with the Very Large Array, and a rotation diagram analysis of the integrated intensities yields excitation temperatures consistent with those of acetone and other organics. The column densities are also in line with chemical expectations from the earlier detections of chemically related compounds such as glycoaldehyde (the simplest, two carbon, sugar) and acetone.

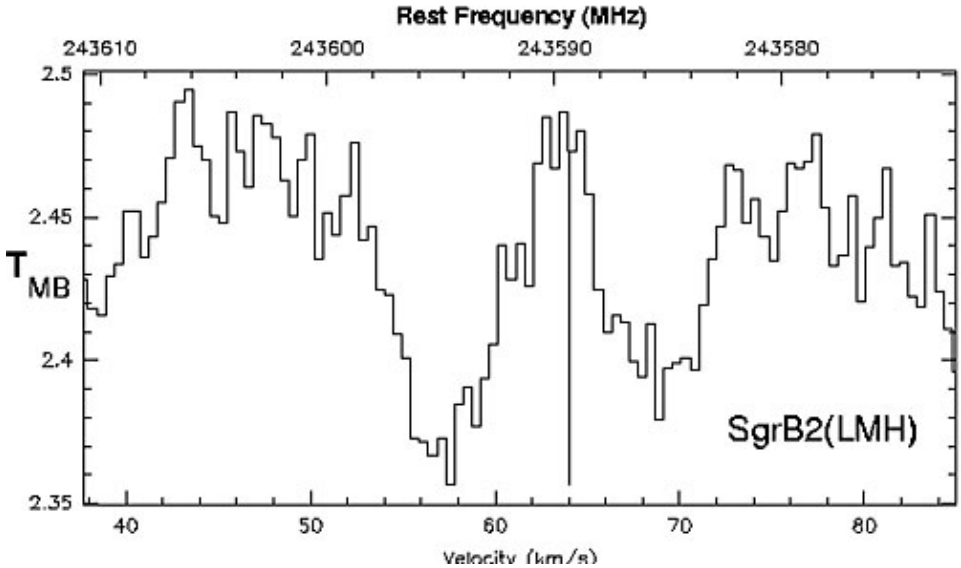
Interestingly, searches by other groups for the three carbon aldose form, glyceraldehyde, have been unsuccessful. Thus, the chemistry that leads to such compounds must be structurally selective. This work is just beginning as part of the thesis work of Susanna Widicus; we plan to investigate the grain mantle and gas phase chemical networks responsible for chemical complexity in molecular clouds. These studies will be used to guide future searches with existing and soon–to–be–operational facilities.

Our detection of dihydroxyacetone shows that more complex species seen in carbonaceous chondrites can be detected in star–forming molecular cloud cores with new telescopes and arrays. We will work with Dr. Steve Charnley on theoretical models of such sources and with meteoriticists and laboratory experimentalists at NASA Goddard Space Flight Center (GSFC) to determine which additional organics to study spectroscopically in order to guide future observational searches with ground–based and space–born sensors.

Highlights

- We have detected the first three carbon sugar in star– (and planet–) forming molecular clouds. This detection highlights the role of prebiotic chemistry long before planetary surfaces are amenable to the synthesis of such compounds, and suggests that the chemistry leading to life is widespread throughout the universe.





Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Project Report: Investigation of the composition of comet 2P/Encke at infrared wavelengths

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Project Progress

Comet 2P/Encke . M. Mumma, M. DiSanti, N. Dello Russo, B. Bonev, K. Magee−Sauer, and E. Gibb investigated the composition of comet 2P/Encke at infrared wavelengths. Six nights of observing time was awarded at the NASA Infrared Telescope Facility and the W.M. Keck Observatory in November, 2003, for this Jupiter−family comet of probable Kuiper−belt origin. Long−slit spectra from the facility instruments CSHELL (Infrared Telescope Facility (IRTF)) and NIRSPEC (Keck) featured both high spectral dispersion and high spatial resolution about the nucleus. H_2O, C_2H_6 , CH_3 OH, HCN, and C_2H_2 were detected (the symmetric hydrocarbons for the first time in Encke), and production rates and rotational temperatures were determined. Rotational analysis of H_2O and C_2H_6 suggested very cold rotational distributions for coma gases (T rot ~ 20 – 30K). Relative abundances for C_2H_6 , CH_3OH, HCN, and C_2H_2 with respect to water were close to those typically seen in Oort cloud comets, while the abundance of hypervolatile CH 4 was severely depleted. This represents the most detailed study of a comet of probable Kuiper−belt origin with high−resolution ground−based infrared spectroscopy, and serves as a model for future studies of faint comets.

Highlights

- High dispersion spectra of Comet 2P/Encke were obtained at high spatial resolution about the nucleus; the rotational temperature of coma gases was between 25 and 30K, methane was severely depleted while the relative abundances of ethane, methanol, hydrogen cyanide, and acetylene were normal.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Project Report: Investigation of parent volatiles in comets at near infrared wavelengths

Project Investigators:	***Michael Mumma , Michael DiSanti***

Project Progress

Cometary Research: Our group (DiSanti, Dello Russo, and Mumma) conducts studies of parent volatiles in comets through ground–based high–resolution spectroscopy at near–infrared (IR) wavelengths (~ 1–5 µm). This has been an exciting year with the availability of 2P/Encke (a short–period comet and member of Jupiter's dynamical family) in Fall, 2003, and of two long–period (Oort cloud) comets (C/2001 Q4 NEAT and C/2002 T7 LINEAR) in Spring, 2004. Our observations of Encke permitted the volatile chemistry of a Jupiter Family comet to be characterized in unprecedented detail. Our studies of Q4 and T7 exploited their large geocentric Doppler shifts to conduct detailed studies of emissions that are normally obscured by atmospheric extinction, in particular transitions of CH_4 and, to a lesser extent, CO. Our research emphasizes the volatile carbon–oxygen chemistry, in particular the efficiency of converting CO to formaldehyde and methyl alcohol on the surfaces of icy grain mantles prior to their incorporation into the nucleus. This process is expected to be temperature–dependent, and comet T7 in particular displayed very strong signatures of both H_2CO and CH_3OH, yet relatively weak CO, suggesting high conversion efficiency. Such measurements are important for establishing the role of comets in replenishing Earth's oceans and for delivery of the seed organic molecules from which life emerged. Along with HCN and NH_3 (both of which we also study), H_2CO is thought to play a particularly significant role in the latter process.

Highlights

- High dispersion spectra of three comets (one short–period Jupiter family comet and two long–period Oort Cloud comets) were obtained this year, including transitions of methane and carbon monoxide normally obscured by the terrestrial atmosphere.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Project Report: Development of simulation methods for particle evolution and motions

Project Investigators:	***Lee Mundy , Derek Richardson***

Project Progress

Co−Is Mundy and Richardson hired a new postdoctoral fellow (Graeme Lufkin) for a two−year term, renewable for a third year, to work on numerical simulations of planet formation and the delivery of organics to the terrestrial region. Graeme is graduating this summer from the University of Washington (UW) with a Ph.D. in physics. His thesis research was done in conjunction with the N−Body Shop in the Astronomy Department at UW and focused on large−scale code development and simulations of giant planet formation and migration. Graeme is also interested in the stability of planetary systems. These areas are interrelated and play a key role in determining the delivery path of icy bodies in the outer solar system to the inner regions. With Graeme we will develop simulation methods capable of modeling the evolution of bodies from the size of planets down to dust particles and for tracking particle motions over large distances. A fundamental unsolved problem in planet formation related to this project is the growth mechanism for dust particles embedded in gas that may be turbulent. Improved understanding of the dynamics in this early phase of planet formation will assist in the interpretation of current and future high−resolution observations of extrasolar dust disks in the sub−millimeter and infrared.

Highlights

- A new post−doc was hired to develop simulation methods capable of modeling the evolution of bodies from the size of planets down to dust particles and for tracking particle motions over large distances.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets

Project Report: Development advanced methods for the in situ analysis of complex organics in small bodies in the solar system

Project Investigator:	***Paul Mahaffy***

Project Progress

Theme 4 of the Goddard Space Flight Center (GSFC) Astrobiology Node develops advanced methods for the in situ analysis of complex organics in small bodies in the solar system. Investigators are presently participating in proposals to NASA for flyby, rendezvous, and sample return missions to comets. In each of these missions, an important focus is on the analysis of complex organic molecules that may have played a role in terrestrial prebiotic chemistry; mass spectrometer or gas chromatograph mass spectrometer investigations are included in each of these mission proposals.

Development of advanced organic analysis techniques has been initiated, including: techniques of laser desorption mass spectrometry; pyrolysis mass spectrometry; and solvent extraction of organic molecules followed by chemical derivatization. In the initial stages of this work a variety of Mars analog materials such as Atacama soils, Hawaii basalts, and meteoritic samples have been used for a cross comparison of techniques. Some of these materials also serve as cometary analogs and the chemistries developed may be relevant for future cometary research.

Initial analyses of carbonaceous chondrites and simple carbon–matrix standards with laser desorption methods have contributed to a developing database of refractory macromolecular materials that may be present in comets and other small bodies. This database should lead to increased understanding of (i) parent body synthesis and processing; (ii) impact survival of more fragile compounds; and (iii) enhanced in situ protocols for determining the full breadth of cometary organics.

Theme IV is presently supporting a postdoctoral research associate Arnaud Buch who, together with a new civil service employee, Danny Glavin, are pursuing chemical derivatization techniques.

Highlights

- We have begun development of advanced organics analysis techniques by analyzing a variety of Mars analog materials such as Atacama desert soils, Hawaii basalts, and meteoritic samples.
- Initial analyses of carbonaceous chondrites and simple carbon–matrix standards with laser desorption methods have contributed to a developing database of refractory macromolecular materials that may be present in comets and other small bodies.

Roadmap Objectives

- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Project Report: Cosmic Ice Laboratory: Organic Synthesis in Energetically Processed Ices

Project Investigators:	***Marla Moore , Reggie Hudson***

Project Progress

Cosmic Ice Laboratory: Organic Synthesis in Energetically Processed Ices

We completed laboratory investigations of the low temperature chemistry of acetonitrile, propionitrile, acrylonitrile, cyanoacetylene, and cyanogen (CH_3 CN, CH_3 CH_2 CN, CH_2 CHCN, HCCCN, and NCCN, respectively). Trends were sought, and found, in the photo and radiation chemical products of these molecules at 12 – 25K. In the absence of water, all of these molecules isomerized to isonitriles, and CH_3 CN, CH_3 CH_2 CN, and $(CH_3)_2$ CHCN also formed ketenimines. In the presence of H_2O, no isonitriles were detected but rather the isocyante ion (OCN–) was seen in all cases. Although isonitriles, ketenimines, and OCN– were the main focus of this work, we also examined cases of hydrogen loss, to make smaller nitriles, and hydrogen addition (reduction), to make larger nitriles. HCN formation was also seen in most experiments. The results are directly applicable to the nitrile ice chemistry on Titan, in cometary ice, and in the interstellar medium.

Start–up activities include:

- The Van de Graaff accelerator used for the generation of the proton beam is being rebuilt to increase beam current and to improve beam positioning and stability. The final stages of this process are nearly complete and a test beam should occur by June 20.
- A new Nicolet infrared (IR) spectrometer and a new cryostat have been installed. The spectrometer is more sensitive and has near–IR capability whereas the cryostat's 6.5K temperature will permit H trapping in ices.
- We will include a simulation of the solar nebula x–ray environment (1–10 keV x–rays are observed for many protoplanetary nebulae). X–rays in this energy range interacting with ice predominantly generate photoelectrons with the same energy. We have visited both an x–ray and electron irradiation facility to evaluate the experimental capabilities and limitations of these beams. A decision about the purchase of similar

instrumentation should be made before the end of this research year.

Highlights

- The irradiation products of nitriles under conditions found on Titan and in the interstellar medium have been determined.
- Major upgrades of the lab facilities are underway.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Project Report: Characterization of the early bombardment through the investigation of lunar breccias

Project Investigator:	***Richard Walker***

Project Progress

The initial phase of work to characterize the early bombardment of the inner solar system has consisted of selecting and separating pure melt rock from lunar highlands breccias. The purpose of this work is to fingerprint the late additions to the Moon using the relative abundances of the highly–siderophile elements that occur in generally high abundance in likely impactors, but extremely low abundance in the indigenous lunar crust. Towards this end, approximately 2g of two Apollo 17 breccias, 73215 and 73255 were requested and have been obtained from the Johnson Space Center curatorial facilities. In collaboration with Dr. Odette James, a longstanding expert on these rocks, Dr. Walker and his students have cleanly separated 13 chips from 73215 and 6 chips from 73255 for processing for Os isotopes and measurement of highly siderophile element abundances. At present (June, 2004), we are doing final checks on chemical blanks for the separation and measurement procedures to be used on these rocks. Analytical work consisting of powdering, dissolving, separating elements of interest, and mass spectrometric measurements will begin in July, 2004.

Highlights

- ***Apollo 17 lunar melt rocks have been selected and are ready for analysis of highly siderophile element abundances and osmium isotopic compositions.***

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets

Project Report: Year 6 Educational Activities and Progress

Project Progress

Educational efforts of the Goddard Center for Astrobiology have included the implementation of a pilot program called the 2004 Summer Undergraduate Internship in Astrobiology (SUGIA), the initiation of a high school curriculum development project with the Minority Institution Astrobiology Collaborative (MIAC), and the modification of an undergraduate Astronomy course at the University of Maryland, College Park (UMCP).

Summer Undergraduate Internship in Astrobiology

The 2004 Summer Undergraduate Internship in Astrobiology is a 10−week program for undergraduate students. Students work with a mentor and participate in weekly seminars, laboratory visits, and a field trip to Greenbank Radio Observatory. The SUGIA program culminates with a poster presentation and a brief seminar given during the August 9th NAI Forum in Astrobiology Research (FAR) Seminar.

Astrobiology in the Secondary Classroom

A team of four high school teachers and three Historically Black Colleges and Universities (HBCU) science faculty were brought to Goddard to develop curriculum materials for high school chemistry and Earth science classes. The project, "Origin and Evolution of Organics in Planetary Systems−Astrobiology in Secondary Classrooms," includes two years of materials development and field−testing followed by three years of summer workshops. The MIAC educators interacted with Goddard Node scientists Mumma, Dworkin, DiSanti, and Moore, the SUGIA interns, and Susan Hoban, principal investigator on the Virtual Telescopes in Education (VTIE) project.

Astro 380−Life in the Universe

Beginning in the fall 2004 semester, Marla Moore will teach Astro 380 (Life in the Universe), a 3−credit course designed for non−science majors of junior standing at the University of Maryland, College Park. Astro 380 is the study of the astronomical perspectives on the conditions for the origin and existence of life in the universe. Moore will incorporate current knowledge from various

laboratories within the node, reflecting the multidisciplinary nature of the problems addressed in astrobiology. Implementing this type of course was one of the goals of our proposal.

Highlights

- The initial session of the MIAC curriculum development project was held on June 28–July 2 at Goddard Space Flight Center.
- The 2004 Pilot SUGIA program includes five students from Connecticut College, Cornell University, Salem College, and Smith College.
- Preparations for undergraduate observations of comets in support of the Deep Impact Discovery Mission are well underway in collaboration with MIAC (under the supervision of DiSanti).

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Deep Impact	Other

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Project Report: Reactions of CO, N_2 and H_2 on the Surfaces of Amorphous Silicates

Project Investigator:	***Joseph Nuth***

Project Progress

Reactions of CO, N_2 and H_2 on the Surfaces of Amorphous Silicates

Studies of the catalytic efficiency of amorphous iron silicate and magnesium smokes in the conversion of CO, N_2, and H_2 gas mixtures into complex hydrocarbons have finally begun to make some sense. The process is greatly complicated due to the deposition of a reactive carbonaceous coating onto the surfaces of the amorphous grains that also acts to catalyze the conversion of both CO and N_2 into complex organics. Analysis of this organic coating reveals a complex mixture of both aromatic and aliphatic hydrocarbons, similar in many respects to that found in primitive meteorites. Amorphous iron silicates easily convert CO plus H_2 gas mixtures to methane plus more complex hydrocarbons as well as N_2 plus H_2 mixtures to ammonia. Amorphous magnesium silicates convert CO plus H_2 mixtures to methane and more complex hydrocarbons less efficiently than do iron silicates and can not initially produce reduced nitrogen compounds until a significant quantity of carbonaceous contaminant has been deposited onto the grain surface. This contaminant is obviously capable of reacting with N_2, though not as efficiently as does the amorphous iron silicate.

Nuth and Johnson, together with an Astrobiology intern, have begun a systematic analysis of the changes in the rates at which CO decreases and CH_4 increases as a function of temperature and the number of experiments done on a particular batch of amorphous iron silicate grains. The initial rates are attributable to the activity of the pure silicate, while later rates are a combination of the relative areas of the carbonaceous and silicate surfaces. By refilling the system with fresh gas mixtures each time the CO is completely depleted, and waiting for the rates to approach a new, but lower, constant value, we hope to determine the relative rates of CO depletion and CH_4 generation for the carbonaceous coating, relative to those of the amorphous iron silicate (after correction for the decreased surface area of the smoke with reactive cycle). Studies of the changing surface area of the grains as a function of temperature and the number of reaction cycles will be carried out by Yuki Kimura using transmission electron microscopy (TEM) at the University of New Mexico.

Highlights

- We have observed that the carbonaceous coating deposited onto the surfaces of amorphous iron silicate and magnesium silicate grains during the surface−mediated conversion of CO, N_2, and H_2 into more complex hydrocarbons (previously believed to "poison" such grain catalysts) also reacts with CO, N_2, and H_2 to form similar products. These results imply that, to some degree, nearly all solid materials in the primitive solar nebula could serve as substrates to convert CO, N_2, and H_2 into organic materials.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Project Report: Observations of comets C/2001, Q4, and C/2002 T7 (LINEAR) at 3mm wavelength

Project Investigator:	***William Irvine***

Project Progress

Irvine collaborated on a review chapter for the book, *Comets. II* , on the subject of the processes undergone by organic matter that is cycled through interstellar cloud environments, into a forming solar system, and then into primitive bodies such as comets. He also edited certain chapters of the book, *Astrobiology: Future Perspectives* , and wrote portions of the final chapter of the book, discussing future strategies and prospects for astrobiology.

Irvine continued as a member of the Working Group on Prebiotic Matter in Space, organized by the International Space Science Institute in Bern, Switzerland. This group meets twice a year for 4 to 5 days to formulate advice on astrobiology for the European Space Agency (ESA) and European universities. At its most recent meeting in January, 2004, the Working Group considered how future ESA missions might incorporate research relevant to astrobiology, and also worked together on a book describing the present state and future goals for astrobiological research.

Irvine continued as Chair of the Management Working Group and as a member of the Science Working Group for the Large Millimeter Telescope (LMT). The LMT is a joint project of the Instituto Nacional de Astrofisica, Optica y Electronica in Mexico, and the University of Massachusetts in the U.S.A., to build the world's largest single–dish radio telescope operating at short millimeter/submillimeter wavelengths. Irvine is working to ensure that the telescope will indeed be a powerful instrument for research in astrobiology.

Irvine participated in planning observations of comets C/2001 Q4 (NEAT) and C/2002 T7 (LINEAR) at the Five College Radio Astronomy Observatory, operated by the University of Massachusetts. Emission was sought from the pure rotational transitions of HCN (J = 1–0) and HCO+ (J = 1–0) at 3mm wavelength.

Project Report: Observations of the hot molecular core in the young stellar object IRAS 16293−2422 using the Very Large Array

Project Investigators:	***Jeffrey Pedelty , Lee Mundy***

Project Progress

Jeff Pedelty and Lee Mundy were awarded time on the Very Large Array (VLA) to observe the hot molecular core in the young stellar object IRAS 16293−2422. Four telescope sessions have been scheduled in July, 2004, to observe ethyl cyanide, methyl formate, and formic acid with approximately 2" spatial resolution in order to provide additional constraints on the molecular abundances and rotational temperatures in this low mass star forming region. A VLA proposal for high resolution (A array), multi−frequency, and high sensitivity observations of the OMC1−S, Trapezium, and BN region is pending, but, if successful, would lead to observing time in late 2004. A poster entitled "Radio Interferometric Searches for the Amino Acid Glycine in High Mass Star Formation Regions" was presented at AbSciCon 2004; a poster entitled "NRAO VLA Searches for the Amino Acid Glycine in OMC−1 and SgrB2 (N−LMH) and Other Molecular Explorations" was presented at the ALMA Science Workshop in College Park, MD.

NIRSPEC observations of the proplyd Hubble Space Telescope (HST) 10 in Orion were processed. As part of this effort Dr. Pedelty ported the Spectrum Synthesis Program (SSP) from the Sun Solaris operating system to both Apple OS X and RedHat Linux. This enabled the comet group to move their processing environment to newer computing platforms (Rowan University to Linux platforms and Goddard Space Flight Center (GSFC) to Apple G5s).

Highlights

- NIRSPEC observations of the proplyd HST 10 in Orion were processed.
- Very Large Array for time to observe the hot molecular core in the young stellar object IRAS 16293−2422 was obtained.

Project Report: Numerical modeling and experimentation of chemical kinetic catalysis

Project Investigator:	***Bruce Fegley***

Project Progress

Fegley's group at Washington University in St. Louis has been working on two topics. The first topic is development of computer codes for chemical kinetic calculations in the solar nebula as a function of temperature, pressure, and mixing rate, parameterized as an eddy diffusion coefficient. Existing codes developed for similar calculations in the atmospheres of gas giant planets will be modified for this purpose. The second topic is experimental studies of the efficiency of different types of catalysts for conversion of $CO + H_2$ to CH_4 . The catalysts studied include pure iron, meteoritic iron alloy, an ordinary chondrite, a commercial iron oxide based catalyst, pure platinum, and pure corundum. These studies have been completed and the results are being written up for publication.

Highlights

- Computer codes for chemical kinetic calculations in the solar nebula as a function of temperature, pressure, and mixing rate, parameterized as an eddy diffusion coefficient, have been developed.
- Experimental studies of the efficiency of different types of catalysts for conversion of $CO + H_2$ to CH_4 have been completed.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

EPO: NASA Goddard Space Flight Center

These are the Education and Public Outreach activities for the NASA Goddard Space Flight Center.

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The 2004 Summer Undergraduate Internship in Astrobiology is a 10−week program for undergraduate students. Students work with a mentor and participate in weekly seminars, laboratory visits, and a field trip to Greenbank Radio Observatory. The SUGIA program culminated with a poster presentation and a brief seminar given by each student during the August 9th NAI Forum in Astrobiology Research (FAR) Seminar. The 2004 Pilot SUGIA program included five students, from Connecticut College, Cornell University, Salem College, and Smith College.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

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Team Reports: Pennsylvania State University

Pennsylvania State University
Executive Summary
Principal Investigator: Hiroshi Ohmoto

The Evolution of a Habitable Planet

The Penn State Astrobiology Research Center (PSARC), created in 1998 as part of the NASA Astrobiology Institute, currently comprises 17 (Co)−PIs and their research teams from The Pennsylvania State University (Mike Arthur, Sue Brantley, Jean Brenchley, Will Castleman, Greg Ferry, Kate Freeman, Blair Hedges, Chris House, Jim Kasting, Lee Kump, Hiroshi Ohmoto, Mark Patzkowsky, Steinn Sigurdsson, and Alex Wolszczan), The University of Pittsburgh (Rosemary Capo and Brian Stewart), and SUNY Stony Brook (Martin Schoonen). During the period of July 1, 2003 – June 30, 2004 , PSARC has supported all or part of the research/education/PO activities carried out by 65 persons (17 (Co−)PIs, 7 research associates and postdoctoral fellows, 22 graduate students, 12 undergraduate students, 3 technicians, and 6 staff in administration/IT/EPO). In addition, 30 Associate Members for Research (who are mostly professors at other institutions) closely collaborate with the 17 (Co)−PIs. Two other Associate Members work closely with the EPO team.

Research

PSARC's research has focused on critical issues concerning *planetary habitability* : (1) the evolutionary history of the biosphere, hydrosphere, and atmosphere on Earth and other planets, specifically the times, causes, and consequences of the emergences of major organisms (e.g., cyanobacteria, methanogens, sulfate reducers, fermenters, sulfide oxidizers, and eukaryotes); (2) the effects of photochemical reactions on the early biosphere; and (3) detection of biosignatures on other planets. Our approaches to these critical issues, and some important achievements during the last year, are briefly summarized below:

I. Investigations of the Geochemical Record of the Earth's Early Biosphere. Freeman's group has found isotopic and molecular biomarker evidence for diverse microbial ecosystems (bacteria, archae, and eukaryotes) and “oxygen oases” in marine environments 2.8−2.5 Ga ago. Determination of an accurate age of a Precambrian paleosol has been difficult, but Capo−Stewart's group was successful in determining the ages of one of the oldest paleosols at Steep Rock , Canada (3.0 Ga) and of the oldest lateritic (ferric−iron enriched) soils at

Hokkalampi , Finland (2.35 Ga) by applying the Nd–Sm and Rb–Sr methods. Ohmoto directed the Archean Biosphere Drilling Project (ABDP), which drilled six deep holes during summer 2003 in the Pilbara district, Western Australia to recover modern–weathering–free rock sequences 3.5–2.7 Ga in age. Mineralogical and geochemical investigations of these rocks yielded evidence that microbes flourished in the oceans and that the atmosphere–ocean system was O_2 –and CO_2 –rich, but CH_4 –poor, during this period.

II. Investigations of Photochemical Reactions of Sulfur and Iron in the Early Earth. To understand the mechanism(s) for the creation of MIF of S isotopes and to aid in the reconstruction of the Precambrian S cycle using the isotope record in rocks, Castleman's group has initiated a series of photochemical reactions of SO_2 by utilizing a reflectron time–of–flight mass spectrometer (RETOF–MS) and a femtosecond laser system coupled with the pump–robe technique. They found an inverse kinetic isotope effect during the photolysis of 32 SO_2 and 34 SO_2 . From laboratory experiments at 35–150 °C, Schoonen's group has found that the hydrogen peroxide and OH radicals, produced by reactions between FeS 2 (pyrite) and water, could have limited the stability of RNA and/or have accelerated molecular evolution through mutagenesis in the early oceans. Kasting's group has made significant progress in coupled ecosystem/atmosphere modeling of the Archean Earth.

III. Investigations of Genomic Record of the Earth's Early Biosphere. Based on analyses of protein and DNA sequences of key organisms, Hedge's group produced a timescale for prokaryote evolution and found that complex multicellular life appeared about a billion years earlier than indicated by the fossil record. Using whole genomic analysis, House's group suggests that sulfur reduction is the most plausible early metabolism for the Archaea.

IV. Laboratory Microbial Simulations: Astrobiological Signatures. In order to relate the biogeochemical signatures in Precambrian rocks to specific organisms and environments, to understand the response of consortia of organisms to their environment, and to provide the references of biogenic gases in remote sensing of possible life–sustaining planets, our group (House, Arthur, Kump, Freeman, Ferry, Ohmoto and their students) has set up a series of microbial microcosms. Special foci are placed on the chemical and isotopic signatures of inorganic substrates, biogenic gases, and microbial lipids, and on the responses of anaerobes to oxygen and aerobes to methane and sulfide. From separate experiments, House's group has found that the Archaeoglobales cannot oxidize methane. Ferry' group has made significant advancement in understanding the effects on carbonic anhydrases (zinc enzyme) from *Methanosarcina thermophilica* of anaerobic reconstitution with Fe^{2+}, Fe^{3+}, Cu^{2+}, Mn^{2+}, Ni^{2+} and Cd^{2+}. To provide insight into the evolution of oxidative stress response strategies by early organisms, Lessner (a NAI post doc under Ferry) has been investigating the oxygen tolerance of *Methanosarcina acetivorans*. They have identified a gene cluster that encodes homologs of novel oxidative stress proteins. Brantley's group has continued to make progress in understanding the mechanisms various microbes extract metals (Fe, Mn, Zn, Ni, Co, and Mo) and P from minerals for their metabolic functions.

V. Investigations of Modern Analogues of Precambrian Microbial Ecosystems. Kump, Arthur, House and their students have initiated a comprehensive geochemical – microbial investigation of Fayetteville Green Lake , New York , as a modern analogue of the Proterozoic marine biosphere. Arthur's group has been investigating N isotope systematics in anerobic environments and at oxic/anoxic interface using the Black Sea and Fayetteville–Green Lake as Proterozoic analogues. Based on a thorough evaluation of biotic extinction record, Arthur and Hu Barnes (Associate Member) have suggested the following: major mass extinctions were caused by large bolide impacts or large igneous eruptions which occurred in carbonate– and sulfur–rich terrains and created large volatile fluxes. Patzkowsky has recognized that the Late Ordovician mass extinction probably occurred within 5 million years, rather than 20 million years as previously thought. Brenchley's group has discovered ultra–small microorganisms (< 0.2 micron size) in a 120,000–year–old Greenland–Glacier ice sample. This discovery is significant for at least two reasons: (1) the ultra–small organisms, previously undetected by normal filteration through the 0.2–micron pore size filters, are probably important constituents in all environments; and (2) microbes survival may be expected in ice on other planets.

VI. Investigations on Planetary Habitability and Life Detection. Sigurdsson's group discovered the oldest jovian planet (~12 Gyr) in a metal poor, distant stellar system. They have also found several candidate planets and low mass dwarfs around nearby DAZ starts. Wolszczan's group has initiated a search for planets around K–giants with the Hobby–Eberly telescope. Kasting's group, working in conjunction with Vikki Meadows' NAI group at Caltech/JPL, have made progress in understanding potential biomarkers on planets around F, G, K, and M stars. A collaboration between Kasting and David Pollard (PSU) has shed new light on the nature of Neoproterozoic Snowball Earth episodes and the question of how the photosynthetic biota survived these catastrophes.

Publications : During the period 7/1/03 – 6/30/04 , the PSARC (Co)–PIs (and their groups) published 45 papers (including those in press or accepted) in referred journals and books; 9 more are being reviewed by journals. They also published 53 abstracts of papers presented at national and international meetings.

Fieldwork : Geologic field work was conducted in: (a) the Pilbara district, Western Australia by Ohmoto and his students to conduct deep drilling under the Archean Biosphere Drilling Project (5 weeks, June–July 2003); (b) the Karelia and Kemi districts, Finland by Ohmoto and Watanabe to investigate ~2.35 Ga paleosols and ~2.0 Ga carbonates (10 days, June 2004); and (c) Fayetteville Green Lake, New York by Kump and students to investigate the microbial ecology and to collect water and microbial samples for laboratory simulators (1 week, July 2003).

Education and Public Outreach

Public Outreach: An annual Astrobiology workshop for high school teachers (~10 attendees) was held under the direction of Jim Kasting during the week of June 21 – June 25 2004 . Space Day at PSU, an annual one–day event to

showcase the exciting space−related research carried out at PSU, was held on April 17. PSARC faculty and graduate students exhibited posters describing their Astrobiology research and worked with the general public on hands−on experiments to increase the public's awareness of Astrobiology. The College of Earth and Mineral Sciences is undertaking of a major renovation of a building that will house a new museum with ~770 sq. feet of space devoted to Astrobiology exhibits. We have began designing the Astrobiology exhibits in close collaboration with Dr. Russell Graham, new museum director.

Undergraduate Education: Astrobiology Minor Program, established in Fall 2000, as inter−college undergraduate program, has attracted about ten students from the Departments of Geosciences, Astronomy, Microbiology, Biology, and Mathematics. It has been administered by Chris House. An undergraduate summer training program in astrobiology was established at Penn State , with the help of a 3−year NSF REU−Site award (Blair Hedges, PI). Last summer it supported 8 students (sophomores and juniors) from colleges and universities other than PSU to participate in research training under the PSARC PIs for a 10 week period.

Graduate Education: A Dual−Title Ph.D. Degree Program in Astrobiology, approved by the Faculty Senate in March 2004, will be inaugurated in August 2004 with a 10−day Astrobiology field trip to southern Canada for ~11 graduate students in this program. The dual−title program is under the direction of Lee Kump.

University Commitment : PSU's strong commitment to support NAI/PSARC programs continues with the hiring of two new tenure−track faculty positions in Astrobiology, one in Geosciences and the other in Biology. From a long list of strong candidates, we have selected Dr. Jennifer Macalady (geomicrobiologist from Carlton College) as a new Assistant Professor in Astrobiology in the Geosciences Department.

Project Report: Laboratory Microbial Simulations: Astrobiological Signatures

Project Investigators:	***Michael Arthur , Susan Brantley , Jean Brenchley , James Ferry , Katherine Freeman , Hiroshi Ohmoto***

Project Progress

This last year saw significant progress on several related projects. We set up five microbial microcosisms related to the early Earth. We are now evaluating their biogeochemistry. We also submitted a paper to the *American Journal of Science* that uses genomics to explore the history of biogeochemistry. In particular, it explores carbon isotopic fractionation and trace metal usage through time. We also submitted a paper that explores trace methane oxidation in six different archaeal species. In this paper, we present evidence that these species can not couple methane oxidation to the reduction of typical oxidants, that the Archaeoglobales can not oxidize methane, and that methanol may be an intermediate product of methane oxidation in Methanosarcina.

Highlights

- We have found that the Archaeoglobales can not oxidize methane even at trace levels.
- We have found that methanol may be an intermediate product of methane oxidation in Methanosarcina based on higher levels of trace methane oxidation during growth on trimethylamine.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	Biomarkers and life detection	Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

These projects aim to understand microbial ecosystems and the impact they have on geochemistry. The results are useful in evaluating biomarkers and other methods for life detection.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: Pennsylvania State University

Project Report: GEOPULSE

Project Investigators:	***Jean Brenchley , James Ferry , Katherine Freeman , Christopher House***

Project Progress

This last year saw significant progress on several related projects. We published a paper in Geobiology that uses genomics to deduce that sulfur–reduction is the most plausible early metabolism for the Archaea. We also published a paper on the microibal ecosystem at methane seeps in Eel River Basin. Also, in collaboration with the Rhode Island group, we have submitted two manuscripts related to the marine subsurface biosphere.

Highlights

- Using whole genomic analysis, we have published a paper showing that sulfur reduction is the most geologically plausible for the base of the Archaea.
- Using fluorescence in situ hybridization–secondary ion mass spectrometry (FISH–SIMS), we have found that archaeal cells near the zone of anaerobic methane oxidation in sediments of the Peru margin are not significantly ^{13}C–depleted.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
3	Biomarkers and life detection	Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

These projects aim to understand microbial ecosystems and the impact they have on geochemistry. The results are useful in evaluating biomarkers and other methods for life detection.

Cross Team Collaborations

This project has two papers submitted that are collaborations with the Rhode Island astrobiology group related to the subsurface biosphere. Also, this last year, we published a paper with Victoria Orphan, who is part of the NASA Ames group.

Project Report: Geochemical Record of the Early Terrestrial Environment

Project Investigators: ***Rosemary Capo , Brian Stewart***

Project Progress

We have focused much of our work on understanding the evolution of ancient soil profiles (paleosols), both syn– and post–pedogenic processes, and their record of Earth's early atmosphere and climate. We are using radiogenic isotopes as tools for geochronologic and provenance information. Our primary work over the past year has been on the following:

1. The Paleoproterozoic Hokkalampi paleosol, Finland. This unconformity on granodiorite parent material provides the opportunity to examine soil development under a variety of conditions, and at a critical time in Earth's atmospheric history. Isotopic analyses by Ph.D. student Sherry Stafford on two profiles suggests that pedogenic rare Earth element (REE) fractionation took place at about 2.35 Ga ago, and that the rubidium–strontium (Rb–Sr) system records metamorphism around 1.8 Ga ago. Work is nearly complete on a manuscript describing our results (Stafford et al., in 2004).
2. The Archean Steep Rock paleosol, Canada. Sherry Stafford has shown that the samarium–neodymium (Sm–Nd) systematics in this profile yield a relatively precise age of 3.0 Ga, and document the preservation of Archean pedogenic REE fractionation. We are using the results from the Steep Rock profile to develop a model for Sm–Nd evolution in paleosols, with a manuscript near submission (Stewart et al., 2004).

In addition to the above studies, we are continuing our investigations of iron isotope studies of sedimentary pyrite with Penn State Astrobiology Research Center (PSARC) investigator Brian Stewart. A portion of this investigation involves NSF–supported experimental determination of Fe isotope fractionation associated with pyrite oxidation, in collaboration with Dr. David Dzombak of Carnegie Mellon University. We are focusing our initial studies on well–characterized pyrite associated with Paleozoic coal and shale units, and will ultimately extend our investigation to Precambrian sulfides.

Highlights

- Determining the age of soil formation in ancient unconformities has always been a significant challenge. Application of the combined Rb–Sr and Sm–Nd geochronologic systems to Precambrian paleosols has allowed us to obtain timing information on both pedogenic and post–pedogenic episodes in some cases.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems

Project Report: Genomic Record of the Earth's Early Biosphere

Project Investigator:	***S. Blair Hedges***

Project Progress

Our research involves molecular clocks and phylogenetics to better understand the relationship between planetary history and the evolution of life. We made progress in theoretical and empirical studies during the past year. In the former area we developed a robust method for estimation of the mode, and tested it with computer simulations (Hedges and Shah, 2003). Such a method is useful for any data, but our immediate use was with molecular clock analyses. We also developed a method for phylogenetic analysis of complete genome sequences (Blair and Hedges, ms). In another paper, I developed a biological trigger model for snowball Earth events (Hedges, 2003).

Our empirical work involved eukaryote and prokaryote studies. We sampled all available protein sequences in the public databases (20–200 genes per node) to develop a tree and timescale of eukaryotes. With that framework we showed that complexity (as measured by cell types) has increased much earlier than previously believed (Hedges et al., 2004). In another study using similar methods we determined time estimates for the colonization of land by metazoans in the late Precambrian (Pisani et al., 2004). Our prokaryote genome work resulted in a detection of early horizontal gene transfer events (Thomarat and Hedges, ms), a more robust timescale for prokaryote evolution, and better constraints on the origin of organisms producing metabolic products that influenced the history of the biosphere (Battistuzzi and Hedges, ms).

Highlights

- Biological trigger for snowball Earths (Hedges, 2003): Although it is commonly assumed that snowball Earths were triggered by a geologic event, the unusual equatorial alignment of continents, we propose instead that they were triggered by a biological event: the colonization of land by fungi and plants. This biological trigger model also may explain the cyclic nature of snowball Earth events and the Cambrian Explosion of animals.
- Early rise in complex life (Hedges et al., 2004): Our molecular clock studies of large numbers of genes revealed that complex multicellular life appeared about a billion years earlier than indicated by the fossil

record.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Background Research
3	Mars and Europa	Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Our research on the early evolution of life on Earth provides background information for any future NASA missions searching for life elsewhere. Our evolutionary timescales help constrain the development and evolution of a planetary biosphere and therefore provide and enhance the general biomarkers for life.

Cross Team Collaborations

The PI (Hedges) is the co–Chair of a cross–team focus group: Evolutionary Genomics Focus Group. This focus group held a workshop at the Gordon Research COnference meeting on Origin of Life in Maine during July, 2003.

Project Report: Evolution of atmospheric O_2, climate, and biosphere – Ohmoto

Project Investigator:	***Hiroshi Ohmoto***

Project Progress

The mass–independent fraction of sulfur isotopes, possibly due to SO_2 photolysis in the atmosphere of early Earth, is of significant scientific interest. Preliminary undertakings were done in our lab employing a pump–probe femtosecond laser technique, coupled with time–of–flight mass spectrometry, to the study of SO_2 photolysis. The results will eventually shed light on unanswered questions regarding the role atmospheric conditions had on the sulfur isotope fractionation in early Earth.

In an experiment performed in our lab, the S–O bond cleavage resulting from dissociation along the ¼ state surface, is found to occur in only 195 fs for the $^{34}SO^{2+}$ species relative to 230 fs for the $^{32}SO^{2+}$ transient. Similarly, the $^{34}SO^{+}$ photolysis product exhibits a growth of approximately 195 fs as compared to a growth of 225 fs, which is observed for the $^{32}SO^{+}$ product. The results indicate a kinetic isotope effect is operative when comparing the excited dynamics of the $^{32}SO_2$ and $^{34}SO_2$ isotopic species. Considering SO_2, where we let k_{32} and k_{34} represent the decay rates of the $^{32}SO_2$ and $^{34}SO_2$ molecules, respectively, k_{32} = 4.34 ps–1 (230 fs) and k_{34} = 5.12 ps–1 (195 fs). The ratio k_{32}/k_{34} = 0.848, indicating a small inverse kinetic isotope effect. This effect was found to be reproducible. Kinetic isotope effects have been observed in a few pump–probe experiments. While a complete review is not appropriate here, it is worthwhile to mention the report of Radloff and co–workers regarding the dissociation of CS_2. It was determined that $C^{32}S^{34}S$ dissociated in 170 fs as compared to $C^{32}S_2$ which dissociated in 210 fs, also indicating a surprising and unexpected inverse kinetic isotope effect similar to that measured and reported by us.

The development of the techniques and the construction of the equipment necessary to perform further high resolution pump–probe and mass spectrometry experiments are underway. We are currently constructing a new detection system using state–of–the–art–equipment to achieve the highest possible mass and intensity resolution with our time–of–flight mass spectrometer. We have purchased a high–sensitivity detection system that will enable the detection of low–abundance isotopes. The high voltage connections needed to transfer the necessary 10,000 V to the detector have been installed in our mass spectrometer along with the high voltage power supply and

associated cables. In addition, mounting hardware for the detector itself is being fabricated. Also, the performance of a broad bandwidth high−speed 8−bit oscilloscope and a lower bandwidth but higher resolution 12−bit digitizer is being evaluated to determine how these devices can be used to quire the ion signal with the highest possible resolution. Also, methods are being developed to calibrate the instrument for the accurate determinations of isotope ratios by using species of known isotopic abundance with a range of masses and isotopic ratios. Improvements and modifications are also being made to the laser system to be used for photoexcitation and photoionization of SO_2 in order to access the electronic excited states relevant to the sulfur isotope fractioning process.

Project Report: EVOLUTION OF A HABITABLE PLANET: Planetary Habitability and Life Detection

Project Investigator:	***Steinn Sigurdsson***

Project Progress

In early July, 2003, a Science paper I was lead author on came out providing strong evidence for an old (~ 12 Gyr) jovian planet in a metal–poor, distant stellar system. The presence of the object had long been suspected; analysis of Hubble Space Telescope (HST) data confirmed many aspects of the nature of the system. The result was presented at a NASA Space Science Update (SSU) on July 10th 2003. Followup paper published in Publications of the Astronomical Society of the Pacific (PASP) Conf Prog in spring 2004, discussed the issues and theoretical concerns in more detail and considered some of the alternative models proposed since the paper. A letter on prospects for detecting transient electromagnetic signatures from catastrophic planet collision around other stars was published (postdoc lead author), and also presented at conferences. Followup research is planned. In collaboration with a student (A. Mandell), we published a letter on the survival of terrestrial planets in systems where a Jovian planet has undergone type II migration and discussed the implications for terrestrial planet search strategies. We plan further theoretical follow–up of this issue and related planet formation scenarios. In collaboration with a student (J. Debes), we started receiving data on a cycle 12 HST project (currently in progress). Preliminary analysis of the data suggests we have found several candidate planets and low mass brown dwarfs around nearby DAZ stars. Follow–up observations to confirm the detections are being requested; if confirmed, we may have made direct–imaging detections of some nearby extra–solar planets. Preliminary results were presented at NAI and Space Telescope Science Institute (STScI) meetings.

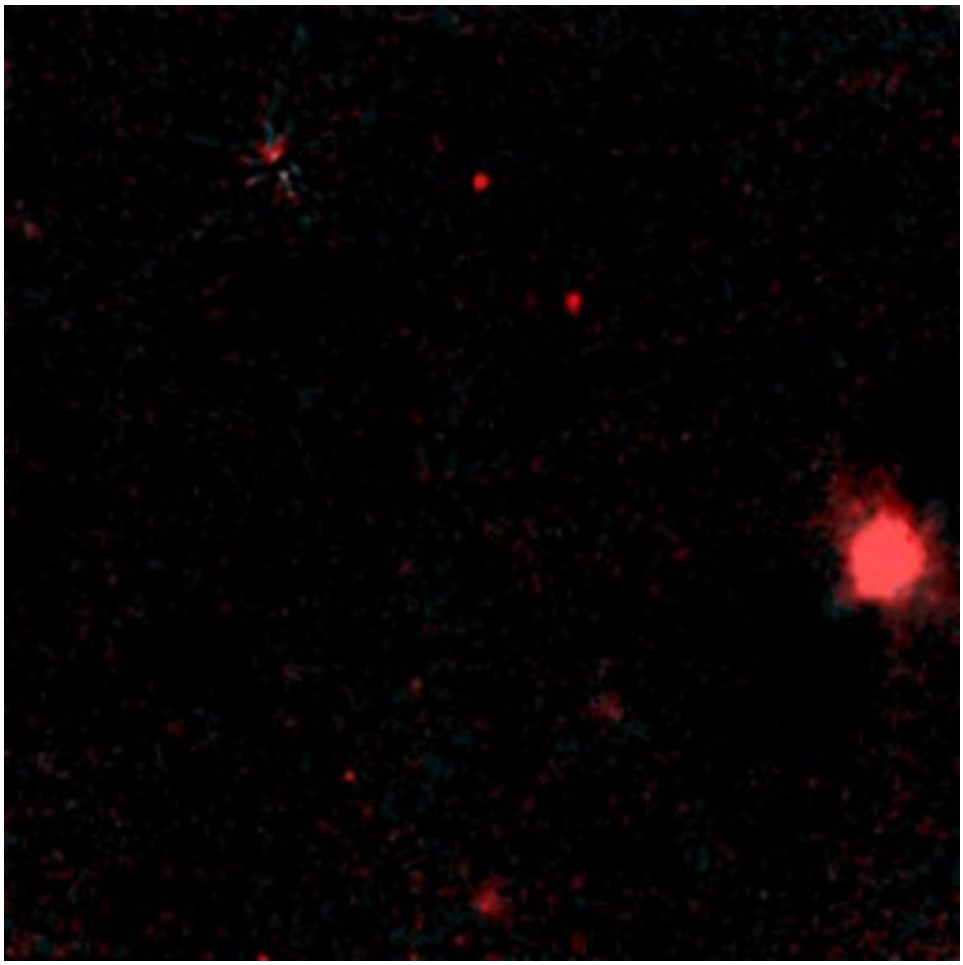

Fig 1: HST infra−red image of a candidate planet near a masked out white dwarf.

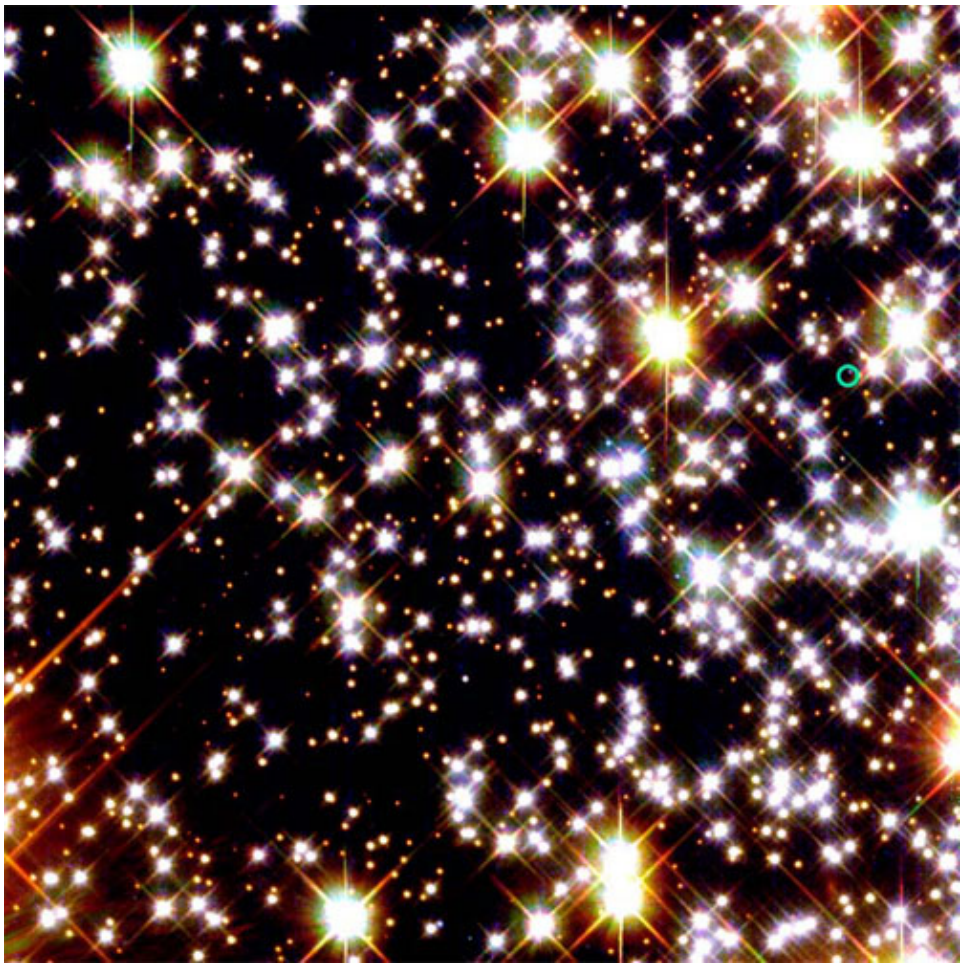

Fig 2: HST image showing (blue star in the green circle) the location of a white dwarf, one of the two stars about which a planet mass object orbits, within the globular cluster Messier 4.

Highlights

- Oldest planet discovered
- Possible “first photo” of extrasolar planet

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
1	Hubble Space Telescope	Project Investigator
1	Spitzer Space Telescope	Project Investigator
2	TPF	Project Investigator

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

PI (with graduate student Debes) on GO–9834, a NICMOS search for nearby Jovians. PI (with graduate student Debes) on recently approved Spitzer followup to above HST project. PI on submitted proposal to followup results from above proposals as lead in to TPF science.

Cross Team Collaborations

Recently initiated an informal collaboration with Prof Brad Hansen (UCLA) on dynamical evolution of planetesimals during the evolution of intermediate mass stars, no results as yet, collaboration just begun.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: Pennsylvania State University

Project Report: Evolution of a Habitable Planet (Kump)

Project Investigator:	***Lee Kump***

Project Progress

We have initiated our study of Fayetteville, Green Lake, a meromictic lake in New York State, as a modern analogue of the Proterozoic ocean. We are collecting data on water–column structure, nutrient and trace metal profiles, microbial diversity, water–column pigment distributions, and their transformation into biomarkers in the sediment.

Theoretical work has focused on the onset and behavior of anoxic oceans (with application to the Precambrian and certain intervals of the Phanerozoic). We find that the chemocline separating deep anoxic and sulfidic waters from oxygenated surface waters is subject to collapse, especially under the lowered atmospheric oxygen concentrations of the Precambrian.

Highlights

- The development of sulfidic surface waters during critical intervals in Earth history, including the mid–Cretaceous, latest Permian, late Devonian, and much of the Proterozoic, is a possible mechanism for mass extinction. Persistent hydrogen sulfide in the Proterozoic atmosphere may have delayed the colonization of the land surface.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems

Field Expeditions

Field Trip Name: Fayetteville Green Lake as a Proterozoic Ocean Analogue

Start Date: October, 2003	***End Date:*** ongoing
Continent: North America	***Country:*** United States
State/Province: New York	***Nearest City/Town:*** Syracuse
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Green Lakes State Park	***Keywords:*** cyanobacteria calcification meromictic sulfur bacteria

Description of Work: Ongoing investigation of the chemical, physical, and biological interactions within this microbially dominated aquatic ecosystem. This stratified lake supports a diverse anaerobic ecosystem in its chemocline. The oxic surface waters promote biocalcification in the water column and the formation of "stromatolites" on the lake margins.

Members Involved:

Project Report: Evolution of a Habitable Planet (Arthur)

Project Investigator:	***Michael Arthur***

Project Progress

We have continued research on several fronts:

1. We have been investigating nitrogen isotope systematics in anaerobic environments and at oxic/anoxic interfaces using the Black Sea and Fayetteville−Green Lake as modern environments for establishing the relative importance of water−column processes (nitrogen fixation, ammonia and nitrate assimilation, denitrification) for determining particulate N fluxes and N isotopic values. We have also examined the sedimentary record of N fluxes and isotope values and have attempted to document the effects of diagenesis. In addition we have analyzed black shales deposited in ancient anoxic marine basins (Cretaceous, Devonian) for comparison. Ultimately, we hope to demonstrate the fidelity of sedimentary nitrogen as a record of nitrogen cycling in ancient environments for application to interpreting Precambrian paleo−nutrient cycles. Thus far it appears that nitrogen fixation is an important process in black−shale forming environments; most black shales have nitrogen isotope values near 0 permil.
2. We have also continued to examine the record of carbon and sulfur cycling in anoxic basins and at times of widespread oceanic oxygen deficiency. We have pursued the record of sulfur isotopic values in sulfate incorporated into carbonates in the Neoproterozoic, near the Permo−Triassic (P/T) boundary and in the Cretaceous, the most recent episode of widespread oceanic oxygen deficiency. There are substantial sulfur isotope variations in the Neoproterozoic, associated with inferred low oceanic sulfate concentrations. The Permo−Triassic boundary event is accompanied by a large increase in δ^{34}S, possibly associated with widespread anoxia and sulfur degassing accompanying the Siberian Trap volcanism. We are investigating sulfide toxicity as an extinction mechanism for the Permo−Triassic event. Our work on carbon cycling and organic C burial in black−shale forming basins continues and we have examined the interplay of sedimentation rate, anoxia, and phosphate cycling, driven by sea level changes, in the origin of organic C rich strata.

3. We have explored biotic extinction records and proposed mechanisms, including extraterrestrial impacts and eruption of large igneous provinces. Our analysis suggests that not all large impacts or volcanic events cause substantial extinctions and that terrain is an important factor. The Cretaceous/Tertiary (K/T) impactor and the Siberian Traps, in the case of the Permo–Triassic event, had more profound effects on global environment because they impacted or erupted through carbonate and sulfur rich rocks, thereby increasing the volatile output.

Highlights

- Not all large bolide impacts or large igneous eruptions have the potential for causing major mass extinctions. The K/T and P/T extinction events were particularly severe because of the type of terrain into which the impactor crashed or the volcanism erupted through. Impacts and volcanism in carbonate– and sulfur–rich terrains create greater volatile fluxes and have consequently larger effects on global climate and biogeochemical cycles.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems

Project Report: The Evolution of a Habitable Planet

Project Investigators:	***Rosemary Capo , Hiroshi Ohmoto , Martin Schoonen , Brian Stewart***

Project Progress

A variety of research was carried out by Ohmoto and his group (Yumiko Watanabe, Research Associate; Katya Bazilevskaya and Tsubasa Otake, graduate students; Denny Walizer, John McGrorey, and David Bevacqua, technicians) to increase our understanding of the evolutionary history of the biosphere, hydrosphere, and atmosphere of early Earth. Our accomplishments during the past year include the following:

1. Geochemical investigations of the Archean Biosphere Drilling Project (ABDP) cores: In summer 2003, under my direction, the ABDP drilled six deep holes in the Pilbara district of Western Australia to recover modern–weathering–free sedimentary and igneous rocks of 3.5–2.7 Ga in ages. In the first drill core, which intersected a 3.46 Ga succession of jasper–chert–pillow basalt, we discovered abundant hematite (Fe^{3+}–oxide) crystals. Results from microscopic observations and chemical mapping of these samples using a Horiba X–ray microscope strongly suggest that the hematite crystals formed as a result of mixing of Fe^{2+}–rich submarine hydrothermal fluids with O_2–rich deep ocean water. This discovery is significant because the presence of free O_2 molecules in deep ocean water is an indication that the atmospheric pO_2 level was already more than 50% of the present level at 3.46 Ga. We also discovered that shales (both marine and lacustrine) in all six drill cores contained abundant organic carbon and pyrite (FeS_2), indicating that microbes, including probably cyanobacteria, fermentaters, methanogens, and sulfate reducers, flourished in the Archean oceans and lakes. We initiated C and S isotope analyses of these shale samples to better understand the nature of the Archean biosphere.
2. Geochemical investigations of banded iron formations (BIFs): Siderite (Fe^{2+}–rich carbonate) frequently occurs as huge massive beds in pre–1.8 Ga marine sedimentary rock sequences. From thermodynamic analyses of the formational conditions of siderite and analyses of C & O isotope ratios of more than 300 siderite samples from Australia and Canada, we (Ohmoto, Watanabe & Kumazawa, 2004) recently

published a paper in Nature suggesting that the pre−1.8 Ga atmosphere was CO_2−rich (pCO_2 >$10^{-1.4\pm0.2}$ atm, i.e., >100 times the present level) and CH_4−poor (<

3. Geochemical investigations of pre−2.0 Ga paleosols and so−called "detrital pyrite pebbles": Our analyses of organic carbon and its host−paleosols (2.7 – 2.35 Ga in ages) from South Africa suggest that land surfaces were fully colonized by microbes by 2.7 Ga ago (Watanabe et al., 2004). Rounded "pyrite pebbles" in some pre−2.2 Ga quartz pebble conglomerate beds have been thought by many previous investigators to be detrital pyrite, and sited as important evidence for an anoxic atmosphere because pyrite is not stable under an oxic atmosphere. Chemical mapping of over 100 "pyrite pebbles" using a Horiba XGT, however, has revealed that the "pyrite pebbles" formed by reactions between rounded pebbles of hematite−rich chert (i.e., oxide BIF) and H_2S−rich fluids long after the sedimentation of the conglomerate beds. Thus, the "detrital pyrite pebbles" are not evidence of an anoxic atmosphere.

Highlights

- Massive siderite beds indicate that the atmosphere was CO_2 rich and CH_4−poor before ~1.8 billion years ago: Many researchers wondered why gigantic beds of siderite (Fe^{2+}−rich carbonates) are so common in pre−1.8 Ga sedimentary rocks, but absent in younger rocks. In a paper published in the journal *Nature*, Ohmoto et al. (2004) suggests the reason was that the pre−1.8 Ga atmosphere contained more than 100 times the present atmospheric level of CO2; this level of CO_2, without a contribution from CH_4, would have provided a sufficient greenhouse effect to counter the lower solar flux and maintain the habitable conditions on early Earth.
- The abundance of red jasper, hematitized pillow basalt, and organic carbon in a deep drill core from Australia indicates that the atmosphere−ocean system was fully oxygenated and that microbes flourished in the oceans 3.46 billion years ago.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems

Cross Team Collaborations

Astrobiology Drilling Project: Bruce Runnegar (NAI HQ; UCLA), Ariel Anbar (UW), Roger Buick (UW).

Project Report: Prebiotic Synthesis: Experimental Studies

Project Investigator:	***Martin Schoonen***

Project Progress

Research in this reporting period concentrated on two topics: fate of formate and the interaction of RNA with pyrite. Graduate student Alex Smirnov built an experimental setup to measure the decomposition of formate over a temperature range from 35 to 150ºC. To avoid degassing, the experiments were conducted without the presence of a head space. The rates obtained by Alex are, however, several orders of magnitude higher than those obtained by extrapolating existing hydrothermal data down to the temperature range of interest. This discrepancy either means that there is still an artifact in our setup that leads to an acceleration of the decomposition or there is a fundamental change in the reaction mechanism at low temperature. In the fall of 2004, Alex Smirnov will work with Tom McCollom, University of Colorado and NAI, to resolve this issue.

Our work on the interaction between RNA and pyrite started with our discovery that pyrite, when contacted with water, produces hydrogen peroxide and OH radicals. The formation of OH radicals could have limited the stability of RNA and/or have accelerated molecular evolution through mutagenesis. Using batch experiments we have shown that RNA is rapidly decomposed, i.e., the strands are broken into smaller fragments as demonstrated with gel electrophoresis. The gel electrophoresis work was conducted in collaboration with post doc Steffen Mueller, Department of Microbiology at Stony Brook. Recombination of these fragments could have led to an acceleration of the molecular evolution. We have also shown that NiS_2 is reactive in this respect and we are now exploring other common minerals. We are currently using advanced spectroscopic techniques to understand the fundamental reactions that lead to the formation of the radicals.

Highlights

- Pyrite leads to the decomposition of RNA, which could have limited the stability of RNA on early Earth or may have accelerated molecular evolution by recombination of RNA fragments.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Cross Team Collaborations

Graduate student Alex Smirnov consulted with Tom McCollom at Colorado University. This led to the submission of a student supplement for him to conduct experiments at Colorado University this upcoming Fall.

Project Report: No Title: Alexander Wolszczan

Project Investigator:	***Alexander Wolszczan***

Project Progress

During the period covered by this report, I have initiated a search for planets around K−giants with the Hobby−Eberly telescope (HET). Collaborators in this research are Drs. M. Konacki (Caltech) and A. Niedzielski (Toru Centre for Astronomy, Poland). Searches for and studies of planets around post−main sequence stars are important for our understanding of the formation and evolution of planetary systems. They probe the very old planetary systems that could have undergone a significant dynamical evolution driven by changes in their parent stars over billions of years. Although the identification of planets around K−giants is seriously complicated by their intrinsic radial velocity (RV) variability, we conservatively estimate that new planets can be detected around no less than 10 of the ~300 stars included in our survey.

Our K−giant survey is part of the campaign to select astrometric reference stars for 24 target stars to be searched for Earth−mass planets by the Space Interferometry Mission (SIM). These targets comprise the northern part of the list to be observed by the EPIcS team (http://planetquest.jpl.nasa.gov/SIM). A ~1 ¼as precision of the survey calls for reference stars that will keep the astrometric noise below that level. They also have to be prevalent enough to be easily found within 1º of a target for narrow−angle astrometry. These conditions appear to be best satisfied by K−giants at distances ~1 kpc away.

Highlights

- Our initial analysis of numerous test measurements performed in the first three months of 2004 under a variety of conditions clearly indicates that a 10−15 m/s RV precision is routinely achieved with the adopted observing scheme.
- We have initiated a routine radial velocity monitoring of the ~300 program stars with the HET.
- We are also planning to begin another HET search for extrasolar planets that will target close binary stars.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	SIM	Science Team Member

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Project Report: Bioextraction of Nutrients and Micronutrients from Minerals

Project Investigator:	***Susan Brantley***

Project Progress

Fe, Mn, Zn, Ni, Cu, Co, and Mo are extremely low in abundance in natural waters, but each of these metals is used in bacterial enzymes, coenzymes, and cofactors. While it is well known that microbes secrete siderophores to extract Fe from their environment, it is not understood how these siderophores attack minerals to provide the FeIII, nor is it understood how bacteria extract other micronutrients. In previously reported work, we have shown that microbes can mobilize Mo (*Azotobacter vinelandii*), Ni (*Methanobacterium thermoautotrophicum*), and Cu (*Bacillus sp.*) from silicates. In addition, we have observed that macronutrients such as P can be extracted from earth materials and that elements found in minerals such as S and Fe can be used as electron acceptors. Our work investigates the mechanisms and isotopic effects of these processes as well. Specifics are given below.

We showed that methanogens can grow without dissolved Ni as long as Ni is present in a solid substrate. Over the last year we tested whether this growth was due to 1) release of a ligand that extracted Ni, 2) release of lysates after cell death, 3) release of extracellular proteins that interact with the Ni substrate, or 4) pH changes associated with growth of the methanogen. Graduate student L. Hausrath has clearly shown that the Ni extraction that occurs is due to pH changes related to utilization of carbon dioxide. We have found little to no other evidence for how methanogens condition their environment for growth. We have similarly observed no evidence for release of ligands by hyperthermophiles living in medium without dissolved *W.*

Anabaena, a cyanobacterium, was grown with fluorapatite as sole phosphorous (P−) source for 7 days. An inorganic control, apatite + medium was also run without inoculation. At the end of the experiment, fluorapatite grains from the various treatments were compared using scanning electron micrograph (SEM). Enhanced etching of the apatite in the presence of the cyanobacterium as compared to the abiotic control accompanies the enhanced clumping of the *Anabaena* when grown in the absence of soluble P. We are still investigating what controls the clumping and the etching.

We continue to analyze respiration of Fe oxides using an *in vitro* model for *Shewanella oneidensis*. A paper was submitted to *Environ. Sci. Technol.* on this topic. In addition, we have been investigating the isotopic fractionation of Cu during bacterial oxidation of chalcocite, and we are writing a paper on this topic.

Highlights

- Of the metal micronutrients, Fe, Mo, Ni, and W, we have found that the prokaryotes studied only release ligands to extract Fe and Mo: no ligands have been found to extract Ni and W by methanogens and hyperthermophiles, respectively. We hypothesize that these latter two types of organisms may live upon a chemical reaction that yields energy at a low enough level that it is not energetically feasible to release high affinity ligands.
- Aqueous copper in leach fluids released during abiotic oxidation of chalcocite ore are isotopically heavier (δ^{65}Cu = 5.3‰) than the initial chalcocite starting material (δ^{65}Cu = 2.6‰). This fractionation is attributed to the precipitation of secondary copper minerals. In the abiotic experiments, the heavier isotopic signatures of aqueous copper can be explained by mass balance between the starting material, aqueous copper, and the new precipitates. In contrast, the copper isotopic composition of aqueous copper in the similar experiments inoculated with Thiobacillus ferrooxidans is similar to the starting material throughout the leach cycle; however, the residual materials become significantly lighter for the last period of leaching (δ^{65}Cu = 0.6‰). This change in the isotopic signature of precipitated copper minerals can only be explained by incorporating a sink for isotopically heavy copper (δ^{65}Cu = 5.6‰) in the mass balance: this sink is inferred to be uptake into the bacteria cells. Mass balance is achieved for the biotic experiments when the bacteria, the precipitants, and the aqueous copper are considered. The generation of ‘heavier’ leach solutions during oxidation in these experiments would suggest that minerals precipitating in later stages of supergene enrichment processes (in naturally oxidative environments) would possess heavier copper isotopic signatures. The average δ^{65}Cu of five supergene samples analyzed are isotopically heavy and these results are in accord with other analyses of supergene minerals found in the literature.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: Pennsylvania State University

Project Report: Examinations of the Microbial Diversity found in Ice Cores

Project Investigator:	***Jean Brenchley***

Project Progress

Our project designed for Penn State Astrobiology Research Center (PSARC) emphasis is the investigation of microorganisms deposited over 100,000 years ago in the basal portion of a Greenland glacier (GISP2) ice core. Research with this ice core serves as a model for the severe conditions, such as cold temperatures, nutrient and oxygen limitations, desiccation, pressure, etc. that could exist extra terrestrially. Detecting and isolating microorganisms surviving these conditions is important to NASA's future exploration for life elsewhere, especially in light of the recent exciting results from Mars. Of particular interest was the discovery in the melted ice of many ultra–small cells that would have been excluded by filtration through the 0.2–micron pore size filters used to concentrate cells for microbial diversity studies. Because this finding is significant to detecting microorganisms in all environments, including extraterrestrial habitats, one of our ongoing projects includes developing methods for examining and identifying these ultra–small cells. Dr. Miteva, in my research program, has used several methods for examining these cells including: repeated enrichments for small cells by successive filtrations followed by cultivation in different media, optimizating flow cytometry protocols for analyzing the numbers, size, and viability of cells in ice core samples, and the diversity studies using both extracted DNA and isolate characterization. Of special interest are isolates where the cells remain small during cultivation and that appear distantly related to other known isolates.

Highlights

- The small, cold, and hungry: a study of mini–microbes from a 120,000–Year–Old Greenland Glacier ice sample.
- The cultivation of ultra–small cells from a 120,000–year–old Greenland glacier ice core sample.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms

- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: Pennsylvania State University

Project Report: Molecular and Isotopic Biogeochemistry

Project Investigator:	***Katherine Freeman***

Project Progress

Archean Biosphere
Based on an integration of lithologic, carbon isotopes, and molecular biomarker data, we documented evidence for diverse microbial ecosystems in marine environments during the late Archean (ca. 2.8–2.5 Ga). This work supports the existence of “oxygen oases” in shallow settings at that time, and demonstrates the gradual expansion of these environments into deeper waters during the 100 million years prior to events marking the oxidation of the atmosphere. This work is reported in Ono et al., 2003, and Eigenbrode, 2004 (Ph.D. thesis; several ms. in prep.).

Molecular and Isotopic Biosignatures
Using measurements of hydrogen isotopic compositions of individual biomarkers, my group has been exploring the utility and preservation of these signatures for paleohydrologic reconstructions (Pedentchouk, 2004; Ph.D. thesis) in early Cretaceous rift basin lakes along western Africa. An important finding in this work was that organic hydrogen exchanges with other hydrogen sources (such as formation waters, etc.) at temperatures approaching the oil window.

We have established methods for the analyses of lipids from Archaea using liquid chromatography–mass spectrometry. We have also evaluated numerous new methods for the isolation and isotopic analysis of microbial RNA. Both methods open up a wide spectrum of applications within microbial biogeochemistry. NSF provided a new grant to support the development of analyses of Archaea lipids for paleosalinity and other paleoceanographic applications.

Project Report: Modeling early atmospheric composition and climate_Kasting

Project Investigator:	***James Kasting***

Project Progress

Kasting spent 8 months of this year on sabbatical at JPL/Caltech working with Vikki Meadows' NAI group. I will describe those efforts separately as part of Vikki's report. My work with Penn State was divided into three parts: 1) coupled ecosystem/atmosphere modeling of the Archean Earth with my graduate student, Pushker Kharecha, 2) modeling of Snowball Earth with climate modeler David Pollard, and 3) modeling of BIF deposition with my graduate student, Shawn Goldman. In Project 1, we showed that an anaerobic ecosystem on the early Earth should have produced methane at approximately the same rate as today's combination aerobic/anaerobic ecosystem. This strengthens the argument that methane could have been an important factor in warming the climate of early Earth and offsetting the fainter young Sun. In project 2, we showed that "thin–ice" solutions can be found in the tropics, either globally or locally, despite the flow of sea ice from the poles to the equator. This provides a possible explanation for how photosynthetic algae and other light–dependent organisms survived the Snowball Earth episodes of the Late Proterozoic. In Project 3, we made a preliminary attempt to show that hematite–rich banded iron–formations (BIFs) could have formed in an anoxic environment. We argued that H_2 consumption by iron–reducing bacteria could have kept oxygen fugacities in iron–rich sediments below the crossover point between hematite and magnetite.

Highlights

- We showed that methane should have been produced by an anaerobic Archean ecosystem at approximately the same rate that it is generated today.
- We showed that thin ice may have existed within the tropics during Snowball Earth episodes. This may explain how photosynthetic algae were able to make it through these catastrophic episodes.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Cross Team Collaborations

As mentioned above, I spent the entire winter on sabbatical visiting Vikki Meadows' NAI group out at JPL/Caltech. Many of my Penn State projects overlap with their project.

Project Report: Late Ordovician Mass Extinction and Recovery: Diversity Dynamics and Geographic Variability

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Project Progress

This year, our efforts went into expanding the database beyond Laurentia to other paleocontinents so that we can test for geographic variability in the Late Ordovician mass extinction and post–extinction rebound. Much of the time was spent vetting the data for stratigraphic resolution, depositional environment, and taxonomic assignments.

Significant progress was made for the paleocontinent of Baltica (greater part of northern Europe); the data now comprise 251 collections and 2976 occurrences. A preliminary sample–standardized analysis of diversity in Baltica indicates that diversity did not rebound significantly from the Late Ordovician mass extinction and resembles more the global unstandardized data of Sepkoski. We are still trying to work out what this means, but it shows clearly that there is geographic variability to the recovery from the Late Ordovician mass extinction. Why Laurentia recovered so much more quickly is still not known, but it may have oceanographic explanations such as Laurentia was positioned in the path of a major marine invertebrate larval dispersal route, whereas Baltica was not. We also began collecting data for the paleocontinent of Avalonia (England, Wales, and parts of Ireland, France, Belgium, Newfoundland, Nova Scotia, New Brunswick, and New England), which will give us good latitudinal coverage from the equator (Laurentia) to the subtropics (Baltica) to nearly 60 degrees South (Avalonia).

Recently, there was a suggestion that the Late Ordovician glaciation and mass extinction were caused by a gamma ray burst from a nearby supernova. The authors of this hypothesis made some predictions of extinction patterns, such as shallow marine organisms should be affected preferentially over deep marine organisms. Ultimately, we will be able to test this and other geographic patterns of extinction with our database.

Highlights

- Once adjustments have been made for variations in sampling intensity, recovery from the Late Ordovician mass extinction appears to have occurred within 5 million years rather than 20 million years as previously

thought. This suggests the need for similar adjustments of sampling intensity in studies of all other Phanerozoic mass extinctions.

Roadmap Objectives

- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

Project Report: Enzymes of Ancient Metabolic Pathways

Project Progress

Since 1933, carbonic anhydrase research has focused on enzymes from mammals (α class) and plants (β class); however, two additional classes (γ and δ) were discovered recently. Cam, from the procaryote *Methanosarcina thermophila*, is the prototype of the γ class and the first carbonic anhydrase to be characterized from either an anaerobic organism or the *Archaea* domain. All enzymes characterized from the four classes have been purified aerobically and are reported to contain a catalytic zinc. Herein, we report the anaerobic reconstitution of apo–Cam with Fe^{2+} which yielded Cam with an effective k_{cat} which exceeded that for the Zn^{2+}–reconstituted enzyme. Mössbauer spectroscopy showed that the Fe^{2+}–reconstituted enzyme contained high–spin Fe^{2+} that when oxidized to Fe^{+3} inactivated the enzyme. Reconstitution with Fe^{+3} was unsuccessful. Reconstitution with Cu^{2+}, Mn^{2+}, Ni^{2+}, or Cd^{2+} yielded enzymes with effective k_{cat} values that were 10% or less than the value for the Zn^{2+}–reconstituted Cam. Cam produced in *Escherichia coli* and purified anaerobically contained iron with effective k_{cat} and k_{cat}/Km values exceeding the values for Zn^{2+}–reconstituted Cam. The results identify a previously unrecognized biological function for iron.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.3:*** Origins of energy transduction
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Fellowships: Pennsylvania State University

The NAI–NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Daniel Lessner
Project Title: Oxygen Adaptation in the Anaerobic Methanogenic Archaeon Methanosarcina acetivorans.
Advisor: James Ferry, Project Investigator
NAI Lead Team: Pennsylvania State University
Fellowship Began In:

Project Report: Oxygen Adaptation in the Anaerobic Methanogenic Archaeon Methanosarcina acetivorans.

NAI–NRC Postdoctoral Fellow : ***Daniel Lessner***

Project Progress

The ability of strict anaerobic prokaryotes to tolerate and even actively remove oxygen and reactive oxygen species (ROS) is becoming increasingly evident. Indeed, many anaerobic bacteria and archaea contain novel enzymes that are capable of reducing ROS. To provide insight into the evolution of oxidative stress response strategies, our focus is to characterize the enzymes and mechanisms used by the ancient anaerobic methanogenic archaea. We have chosen *Methanosarcina acetivorans* C2A as our model organism. *Methanosarcina* sp. are reported to be the most oxygen–tolerant methanogens and the genome of this species has recently been sequenced.

We have determined that *M. acetivorans* C2A can tolerate prolonged exposure to oxygen and hydrogen peroxide. A gene cluster (MA4664–MA3743) has been identified that encodes homologs of novel oxidative stress proteins, including superoxide reductase (MA3737) and rubredoxin:oxygen oxidoreductase (MA3743). The other characterized proteins encoded by the cluster include an iron–sulfur flavoprotein (MA3740), found only in anaerobes, and a flavoprotein (MA3741) that is unique to anaerobic Archaea. The remaining genes within the cluster encode hypothetical or predicted proteins with no known function. More detailed bioinformatic approaches has allowed putative functions to be proposed for the remaining genes. These include a desulphoredoxin homolog (MA4664), zinc–finger proteins (MA3734/MA3735), an alkylhydroperoxidase homolog (MA3736), and a ferritin–like diiron protein (MA3742). Thus, it appears that the majority of the putative proteins encoded by this cluster are involved in redox reactions and may function to directly detoxify ROS or be involved in electron transfer.

Transcriptional analysis determined the MA4664–MA3743 gene cluster is co–transcribed as an operon and is expressed under normal growth conditions. In addition, MA3742 has been over–expressed and purified from *E. coli*. Iron analysis indicated MA3742 does contain a diiron center. However, initial characterization revealed MA3742 is a tetramer and does not have ferroxidase activity, inconsistent with ferritins. Future work will focus on elucidating a function for MA3742 and the role of other proteins encoded by the

MA4664–MA3743 operon.

Highlights

- The strict anaerobe *Methanosarcina acetivorans* C2A was shown to tolerate prolonged exposure to oxygen and hydrogen peroxide.
- The MA4664–MA3743 gene cluster, proposed to play a role in the oxidative stress response in *Methanosarcina acetivorans* C2A, was shown to be transcribed as an operon.
- Recombinant MA3742 was over–expressed and purified to homogeneity from E. coli. Initial characterization demonstrated MA3742 is a diiron protein, but does not function as a ferritin.
- MA4664 (desulphoredoxin) and MA3736 (putative alkylhydroperoxidase) have been successfully cloned and subsequently over–expressed and purified from *E. coli*. Biochemical characterization of each recombinant protein is currently underway.

Roadmap Objectives

- ***Objective No. 3.3:*** Origins of energy transduction
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

EPO: Pennsylvania State University

These are the Education and Public Outreach activities for the Pennsylvania State University.

Astrobiology: The Origins and Early Evolution of Life (Educator Workshop)

This five−day, 2−graduate−credit Astrobiology workshop was designed to expose middle and high school science teachers to current thinking about the origin and early evolution of life in a way that they could pass on to their students. Dr. Jim Kasting, a Penn State Astrobiology Research Center (PSARC) co−investigator, was the lead instructor. The course combined lectures by Penn State faculty and graduate students, hands−on classroom activities, field trips to local anaerobic water environments, and a trip to the Penn State Earth and Mineral Sciences museum to interact with the Astrobiology museum kiosk developed by the Carnegie Institute of Washington. Jen Biddle, a graduate student at the Penn State Astrobiology Research Center, and Pamela Harman of the Search for Extraterrestrial Intelligence (SETI) Institute, facilitated activities taken from the SETI Institute's Voyages Through Time curriculum and Technical Education Research Center s (TERC's) Astrobiology Educator Resource Guide. Irene Schneider demonstrated Celestia, an open−source educational software program for teaching astronomy. Following the workshop, the teachers were added to our existing listserv discussion group to facilitate and track the application of knowledge from the workshop back in the classrooms. The Penn State Astrobiology Research Center and the Pennsylvania Space Grant Consortium provided funding for the workshop. Housing, meals and partial travel support were provided. Nine teachers were awarded tuition subsidies. The workshop was approved by the Pennsylvania Department of Education for Act 48 Professional Development credit.

The workshop evaluation included a summative professional development questionnaire developed by the Horizon Research, Inc., two full full−time observers in each workshop collecting qualitative and quantitative information about pedagogical and curriculum approaches, content analysis of the curriculum, follow−up interviews with each of the lead instructors, and a doctoral dissertation research project including a questionnaire intended to measure potential change in a teachers' understanding of the nature of science experienced during the workshop. The workshop was also videotaped to verify all collected data. The evaluation techniques were intended to measure the effectiveness of workshop design for improving student learning in the middle and secondary classroom. At this time, we have not received the evaluation

summaries.

Astrobiology: The Search for Life in the Universe (Magazine)

This color publication provides an overview of the field of Astrobiology written at the high school level. The piece was originally published by Research Penn State magazine in their January 2001 issue and is based on a lecture series that was held at Penn State University in January 2000. The lecture series and the magazine supplement features NASA Astrobiology Institute scientists from Penn State University, The University of Colorado, and Harvard University as well as researchers from the SETI Institute and Rice University. The Penn State Astrobiology Research Center and Pfizer, Inc provided funding for the publication. The Pennsylvania Space Grant Consortium is distributing the publication to interested educators, students, researchers and others across the country and internationally. Over 1000 publications have been distributed since October 1, 2004. PDF and web versions are also available.

Astrobiology public lectures, short courses, and websites: Penn State Astrobiology Research Center

The Penn State Astrobiology Research Center (PSARC) team gave a number of lectures for the general public, civic groups, and various short courses. This year's presentations were as follows: Dr. Jim Kasting: 1) Methane greenhouses and anti–greenhouses on the early Earth (University of Texas, Arlington public seminar, November 2003), 2) Climate of early Mars (McGill University, Montreal, public talk and panel discussion, March 2004), 3) Can Mars be terraformed? (Astrobiology Magazine panel discussion, April 2004); Dr. Martin Schoonen: 1) Life and Water on Mars (Soundbeach Elementary School, Miller Place, NY, January 2004); Dr. Alexander Wolszczan: 1) "Searches for Planets and Life in the Universe" (N. Copernicus University, Torun, Poland, A. Jablonski Lecture Series, February 2004), 2) "Searches for Planets and Life in the Universe" (Helena Modjeska Club, Los Angeles, CA, March, 2004), 3) "Life in the Universe" (N. Copernicus University, Torun, Poland, Feb, May 2004). Several PSARC scientists have developed websites or are featured on websites targeted to the general public: Dr. Blair Hedges: 1) maintains the Evogenomics web site http://www.evogenomics.org of the Evolutionary Genomics Focus Group; Dr. Steinn Sigurdsson: 1) Space.com report Pushing the Limit: Possible First Photo of Extrasolar Planet http://space.com/scienceastronomy/mystery_monday_040510.html was followed up with interviews for the British Broadcasting Company, Nature, Boston Sun and Baltimore Globe and picked up by foreign press in Brazil, Germany, Iceland and India, 2) press interview and radio interview for Morgunbladid magazine http://stjornuskodun.is/ while attending the 2004 BioAstronomy Conference.

Astrobiology Undergraduate Minor

Undergraduate students at Penn State can participate in the Astrobiology Undergraduate Minor, which is designed to educate students in the varied scientific disciplines that contribute to our general understanding of life, the origin of life, the past history of life on Earth, possible futures for life on Earth,

and the possible existence of life on other planetary environments. The principle goal of the minor is to develop students' literacy in astrobiology so that they can critically evaluate claims related to this field. Dr. Chris House, PSARC co−investigator, manages the program.

Over 1300 students per year are enrolled in the following Astrobiology−related courses: Earth 002 (Earth System History), Geosc 021 (Origin and Evolution of the Earth and Life), Astro 140 (Life in the Universe), Geosc 204 (Geobiology), Biol 427 (Evolution), Geosc/Biol 474 (Astrobiology), and Meteo 466 (Planetary Atmospheres). Geosc/Biol 474, the senior−level core course of the Astrobiology minor, fills up each year with 27 students currently enrolled for Fall 2004.

PSARC also supports an undergraduate student research program for students who are enrolled in the Astrobiology Minor, have taken undergraduate Astrobiology classes, or have expressed particular interest in Astrobiology. Students from this program also often participate in the yearly Penn State Undergraduate Research Poster Session.

Dual Title Ph.D. Program in Astrobiology

Graduate students at Penn State are now able to obtain a dual−titled Ph.D. in their primary field of endeavor and Astrobiology. The program enables students from several graduate programs to gain the perspectives, techniques, and methodologies of Astrobiology, while maintaining a close association with primary program areas of application. The program is chaired by Lee Kump (co−investigator) and administered by the Department of Geosciences. Five other Penn State Astrobiology Research Center (PSARC) co−investigators serve on its program faculty. Students take three core courses (Planetary Habitability, Astrobiology Field Experience and Astrobiology Seminar), a fourth course outside of their primary area of relevance to astrobiology, and must incorporate astrobiology into their candidacy and comprehensive examinations and their dissertation research. PSARC faculty teach all of the Astrobiology courses, and help fund the field experience and seminar classes.

Space Day 2004 at Penn State

During Space Day 2004 at Penn State, scientists, engineers, and students shared presentations and hands on activities with over 1500 adults and children as they explored Earth, air, and space research at Penn State, including research on the origin, evolution, distribution, and destiny of life in the universe. Nine scientists and students associated with the Penn State Astrobiology Research Center (PSARC) facilitated exhibits on extreme life, Early Earth and history of the universe, and collaborated with students from the science education program at Penn State to develop activities. Jen Biddle, a graduate student at the Penn State Astrobiology Research Center, developed and offered two workshops for children: "Be a Microbe Detective" for K−4 students and "Life in the Extreme" for 5−8 students. The interactive version of the award−winning poster, Astrobiology: Discovering New Worlds of Life, developed by the Carnegie Institute of Washington, traveled to Penn State for the Space Day event.

Space Day 2004 at Penn State also included a multimedia lecture series on Mars and the Future of Space Explorations featuring former astronaut Dr. Jim Pawelczyk, Penn State; Dr. Ann Schmiedekamp Penn State, NASA Jet Propulsion Laboratory Solar System Ambassador; Dr. Pascal Lee, Mars Institute; Dr. John Nousek, Penn State, NASA SWIFT mission; and Dr. David Spencer, Penn State. Penn State students collaborated with Dr. Pascal Lee, Mars Institute, to plan, develop and engage in Mission Earth, the first student–led simulated human mission to an "alien environment" (Tytoona Cave). Communication between Mission Earth's Mission Control, located at the Space Day event, and the "terranauts" inside the cave took place via a remote wireless computer network set up inside the cave. The Penn State Mars Society exhibited their Modular Research Rover, which was tested at the Mars Desert Research Center in Utah, and featured a Mars Yard, a simulation of the Mars surface developed for an interactive exhibit at the Carnegie Science Museum in Pittsburgh, PA. Dennis Christopher, NASA Solar and Heliospheric Observatory (SOHO), facilitated a "How to Access NASA Education" booth and Dr. Chris Palma, Penn State Department of Astronomy and Astrophysics, led planetarium tours.

Four large school groups from Pennsylvania attended the Space Day celebration, including a group of 100 students from the Philadephia Area School District, 65 students from Otto Eldred Middle School, 60 students from Troy Area Middle School and 75 students from Juniata Valley Elementary School. Eight students from Claysburg–Kimmel Elementary School exhibited their official Space Day Design Challenges.

The Astrobiology Summer Program (ASP)

The Astrobiology Summer Program (ASP), an undergraduate summer training program in astrobiology, was established at Penn State with the help of a 3–year National Science Foundation REU–Site award (S. Blair Hedges, PI). During the summer, eight students (five males, three females, one minority student) from colleges and universities other than Penn State participated in research training under the guidance of Penn State Astrobiology Research Center (PSARC) faculty mentors. Women and minorities were encouraged to apply. The program has a director (Dr. Blair Hedges) and a coordinator (Dr. Carla Hass). Four PSARC faculty hosted students during the 2004 summer: Drs. Kate Freeman, Chris House, and Jim Kasting in the Department of Geosciences, and Dr. S. Blair Hedges in the Department of Biology. Dr. David Geiser, Department of Plant Pathology, also hosted a student. The students presented the results of their work as an oral presentation during a symposium during the last week in the program.

Besides laboratory research, ASP students had the opportunity to participate in a weekly seminar with graduate students in Astrobiology, a Friday discussion group focusing on different topics in Astrobiology, a tour of the Penn State Department of Astronomy and Astrophysics observatory, and a field trip to NASA Goddard Space Flight Center in Greenbelt, MD where they toured the integration and testing facility. Dr. Lou Mayo spoke with them about his research on Titan. The following day, they visited the National Air and Space Museum in Washington, D.C. Dr. Jim Zimbleman lead them on a behind the

scenes tour of the Earth and Planetary Sciences department; that was followed by a guided tour of the museum, focusing on space exploration.

Astrobiology Traveling Museum Kiosk at Penn State

5{ive version of the award−winning poster, Astrobiology: Discovering New Worlds of Life, developed by the Carnegie Institute of Washington, traveled to Penn State during April−July 2004. The poster was initially exhibited during Space Day 2004 at Penn State before it resided in the Penn State Earth & Mineral Sciences Museum. The Astrobiology poster is mounted on a touch−sensitive screen, connected to a computer hard drive and a flat screen monitor. When touched, several of the features on the poster activate the monitor to display exciting video footage of life in hydrothermal vents, the scientists and their research of such communities, piloting the Alvin and more. Over 400 students and adults visited the museum during the summer, and teachers attending the Penn State Astrobiology Workshop for Science Educators took a guided tour to the museum to interact with the poster.

Women in Science and Engineering Research (WISER) program

Faculty members from the Penn State Astrobiology Research Center (PSARC) participate in this two−semester research internship program, which is sponsored by the Pennsylvania Space Grant Consortium. The program is designed to retain women students in the science and engineering fields by providing first−year students invaluable experience and mentoring at the critical early stages of their undergraduate career. Students begin their research in the spring semester and continue during either the subsequent summer or fall semester. Since the program began in 1994, 437 women students have been hosted by over 80 faculty members from all of the science and engineering colleges at Penn State. Dr. Blair Hedges, PSARC co−investigator, hosted a student.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Team Reports: Scripps Research Institute

Scripps Research Institute
Executive Summary
Principal Investigator: M. Reza Ghadiri

For information about the astrobiology research and activities going on at the Scripps Research Institute visit http://www.scripps.edu/e_index.html

Team Reports: SETI Institute

SETI Institute
Executive Summary
Principal Investigator: Chris Chyba

The NASA Astrobiology Roadmap asks three fundamental questions: (1) How does life begin and evolve? (2) Does life exist elsewhere in the universe? and (3) What is the future of life on Earth and beyond? The SETI Institute NASA Astrobiology Institute (NAI) team is conducting a set of coupled research projects in the co−evolution of life and its planetary environment. These projects begin by examining certain fundamental ancient transitions that ultimately made complex life possible on Earth. They will conclude with a synthesis that will bring many of the team's investigations together into an examination of the suitability of planets orbiting M stars for either single−celled or more complex life.

The astrobiology roadmap calls for a strategy "for recognizing novel biosignatures" that "ultimately should accommodate a diversity of habitable conditions, biota and technologies in the universe that probably exceeds the diversity observed on Earth." Some of our results, especially those concerning abiotic mechanisms for the oxidation of planetary atmospheres, will speak to the interpretation of extrasolar planet atmospheric spectra (and in particular, the role of oxygen as a potential biosignature) in terms of the presence of photosynthesizing life. The team's M−star project addresses the roadmap's observation that "although technology is probably much more rare than life in the universe, its associated biosignatures perhaps enjoy a much higher signal−to−noise ratio. Accordingly, current methods should be further developed and novel methods should be identified for detecting electromagnetic radiation or other diagnostic artifacts that indicate remote technological civilizations." As the roadmap recognizes, there is a continuum of investigations that comprise astrobiology, from prebiotic evolution to the evolution of technology. We believe that we are the only NAI team whose investigations run the gamut of the roadmap's range.

The SETI Institute's NAI team's research emphasizes the elucidation of the co−evolution of life and its planetary environment, investigating global−scale processes that have shaped, and have been shaped by, both. Throughout, the team recognizes the importance of pursuing the planetary evolution aspects of this research in the context of comparative planetology: since laboratory experiments are impossible over many (but not all) of the time and spatial scales relevant to early Earth, we supplement laboratory data with insights

gained by exploring extraterrestrial environments that provide partial analogs to the early Earth environment and its processes.

The SETI Institute team is pursuing two investigations into the oxidation of early Earth's environment. While the biological aspects of this "oxygen transition" have been emphasized, our team is exploring non−biological contributions to this transition. Dr. Friedemann Freund and Dr. Lynn Rothschild are investigating oxidation driven by diffusive loss of hydrogen formed within igneous and metamorphic rocks that incorporate water during crystallization. Subsequent weathering of the rocks released hydrogen peroxide into the environment; the previous loss of the hydrogen indicates that this is a net oxidizing mechanism. Experiments are underway (see Fig. 1 for preliminary results) to quantify the importance of this effect for a variety of powdered crystals; new data include the observation of oxygen evolution from finely powdered magnesium oxide crystals grown from melt.

In a second investigation, oxidation driven by atmospheric hydrocarbon (and, more broadly, organic) polymerization is being investigated by Dr. Emma Bakes. Dr. Bakes' research for the early Earth builds on analogies to processes now occurring in the atmosphere of Saturn's moon Titan. With her collaborators, Dr. Bakes is completing a comprehensive theory paper describing the chemical foundations of nitrogenated macromolecules in the Titan haze. This foundation enables the next stage of her research, the theoretical building of prebiotic macromolecules from the haze constituents. This work is complemented by ongoing laboratory work performed by Dr. Bishun Khare and Dr. Hiroshi Imanaka on Titan analog materials, and infrared observations of the Titan haze.

If the oxidation mechanisms being explored were shown to be quantitatively significant—modeling to be done later in the course of this grant—this would suggest that the oxygen transition on an Earth−like world could take place independently of the invention of any particular metabolic pathway (such as photosynthesis or methanogenesis) that have previously been proposed to drive this transition. Since Earth's oxygen transition ultimately set the stage for the oxygen−based metabolism evidently essential for metazoa, understanding this transition is crucial to elucidating both Earth's evolution and the evolution of complex (including intelligent) life. The team's geological investigations are therefore tightly coupled with microbiological experiments, led by Dr. Rothschild, to understand the extent to which the proposed mechanism might have led to the evolutionary invention of oxidant protective strategies and even aerobic metabolism.

Understanding the oxygen balance on early Earth requires attention to sinks as well as sources of oxygen. One major sink for oxygen on early Earth would have been reduced iron. Iron could have simultaneously provided shielding against ultraviolet (UV) light that would have been reaching Earth's surface in the absence of the ozone shield generated by atmospheric oxygen. Nanophase ferric oxide minerals in solution could provide a sunscreen against UV while allowing the transmission of visible light, in turn making the evolution of at least some photosynthetic organisms possible. Dr. Janice Bishop and Dr. Rothschild are testing this hypothesis through coupled mineralogical and microbiological

work in both the lab and the field, and examining its implications not only for Earth but for Mars as well, with an emphasis on implications for upcoming spacecraft observations. UV, visible, and infrared spectra have been measured for a collection of iron–oxide–bearing samples, and experiments have been performed on cultures of two photosynthetic microorganisms, Euglena and Chlamydomonas, with and without iron species (see Fig. 2). The spectral data and growth patterns indicate that certain ferric oxide–bearing minerals could indeed have provided protection from UV radiation for early photosynthetic organisms, while still permitting the transmittance of the visible and infrared light required for photosynthesis. These results are consistent with the hypothesis that early photosynthetic organisms may have existed in specific, perhaps small, niches protected by ferric–oxide–bearing material.

The survival of microorganisms in very high UV environments can also be tested empirically through the exploration of Earth's highest altitude lakes and ponds, in Bolivia and Chile. Dr. Nathalie Cabrol and Dr. Edmond Grin (both of whom also this past year served on the Mars Exploration Rover team) have led a series of investigations of these lakes to examine the strategies employed by these microorganisms. The group they lead is currently analyzing samples and data from its 2003 expedition to Licancabur (6,014 m altitude) and lower lakes (Laguna Verde and Laguna Blanca, 4,430 m altitude), on the Bolivia/Chile boundary. Discoveries include an active community of modern stromatolites; the culture and phylogenetic characterization of apparently new bacterial species; and physical and chemical characterization of the lakes.

Just as global–scale changes in oxygen (or iron) were critical for the early biosphere, so too would have been global processes involving other key "biogenic" elements such as carbon (for which Dr. Bakes' work provides insight) or nitrogen. Dr. Rocco Mancinelli, Dr. Amos Banin, Dr. David Summers, and Dr. Khare are pursuing coupled laboratory and field research to understand the partitioning of nitrogen on early Earth and on Mars between different possible reservoirs, and (at least for Earth) the abiotic to biotic transition in this cycling.

Dr. Banin has begun the analysis of soil samples from the Atacama Desert, an extreme terrestrial environment with very low biological activity. In particular, it is as yet unclear what properties of the soil and environment are the limiting factors for biology, and the importance of nitrogen levels in this. Dr. Mancinelli and Dr. Banin have defined new field sites for their work in the Atacama that will begin this fall. Finally, they are experimentally investigating the possibility that binding of nitrogen as NH_4^+ in silicate minerals could account for the “missing” N on Mars, examining representative silicate minerals and Mars soil analogs and the biological availability of N when present in this form.

Dr. David Summers and Dr. Khare have begun their experimental work focusing on the demonstration of the abiotic fixation of nitrogen under the CO_2/N_2 atmosphere expected on early Mars. Nitrogen is theoretically predicted to be fixed via the production of NO via shock heating, followed by UV irradiation over liquid water. These experiments should provide a different perspective into the astrobiologically important question of the fate of N on early Mars.

The work described so far examines the evolution of planetary surface habitability. With the recognition that a subsurface ocean likely exists on Jupiter's moon Europa, we know that habitability in possibly entirely subsurface environments must also be explored. Dr. Cynthia Phillips, Dr. Christopher Chyba, and Mr. Kevin Hand (a Stanford PhD student advised by Dr. Chyba) are pursuing spacecraft data analysis and modeling to examine the geology of Europa and its implications for the free energy sources that would be needed to power a Europan biosphere. Dr. Phillips and Dr. Chyba are completing a major project, using Galileo high−resolution imaging of Europa, to quantify the impact cratering “gardening” rate on Europa. This is important in its own right as a fundamental planetary process, but also is important in some astrobiological models because it will allow the quantification of the amount of biologically relevant material, created at Europa's surface through radiogenic processes, that can be mixed down to the gardening depth, and thereby sequestered below the sputtering depth and significant radiolysis depth at the surface.

These results will be coupled with the results of low−temperature laboratory experiments to make predictions about the possible abundance and survivability of any oceanic biomarkers that might reach Europa's surface through active geology, with implications for the astrobiological exploration of Europa from either an orbiter or a surface lander. Mr. Kevin Hand, in collaboration with Dr. Robert Carlson and Dr. Chyba, is pursuing this research in Dr. Carlson's laboratory at the Jet Propulsion Laboratory. Over the past year, Mr. Hand and Dr. Carlson have constructed the irradiation apparatus (including ice deposition chamber and diagnostics) and have preliminary experiments now underway. Dr. Max Bernstein, in his laboratory at NASA Ames, has measured the mid−infrared spectra of several polycyclic aromatic nitrogen heterocycles in both neutral and cationic forms, and finds good agreement between theoretical prediction and experimental observation. Ultimately the behavior—and detectability—of such compounds under Europan conditions will also be determined.

Dr. Peter Backus, Dr. Jill Tarter, Dr. Mancinelli, and Dr. Chyba are beginning their examination of the prospects that planets orbiting dwarf M stars are habitable for either microscopic or complex life. The SETI Institute NAI team's proposal calls for a series of workshops to bring together planetary scientists, biologists, atmospheric modelers, astrophysicists, and SETI scientists to address these issues, to begin in year two of this proposal. Preliminary work so far includes a literature review, identification of workshop participants, and obtaining the full Tycho−2 star catalog and the database software that will be used to produce the list of M stars. The results of this project will ultimately help the next generation scientific Search for Extraterrestrial Intelligence (SETI) choose the million target stars (see the second figure) that it will survey for signs of technical civilizations using the new Allen Telescope Array (ATA), being built by the SETI Institute in partnership with the University of California, Berkeley.

Finally, education and public outreach are major and integral parts of the work of the SETI Institute's NAI team. They are addressed elsewhere in our first−year summary, so are not presented here.

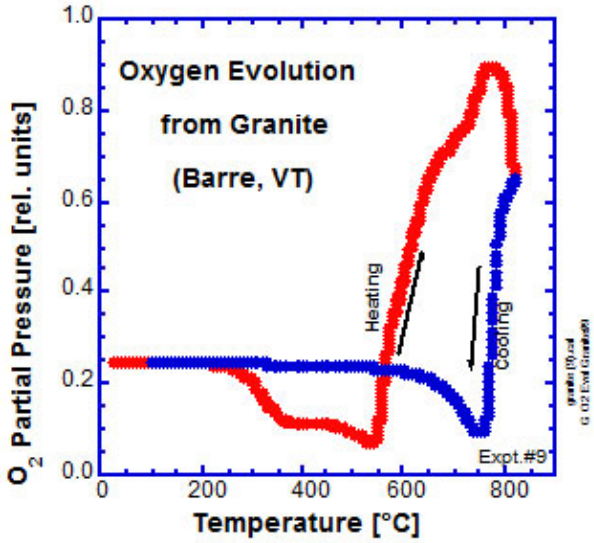

Fig. 1. Preliminary data showing O_2 evolution from crushed granite from the type location Barre , VT , during heating in a stream of N 2 with 100 ppm O_2 . Between 250–550°C O_2 is consumed, but above 550°C excess O_2 is released. The amount of O_2 gives an estimate of the average peroxy content in this rock of at least 500 ppm.

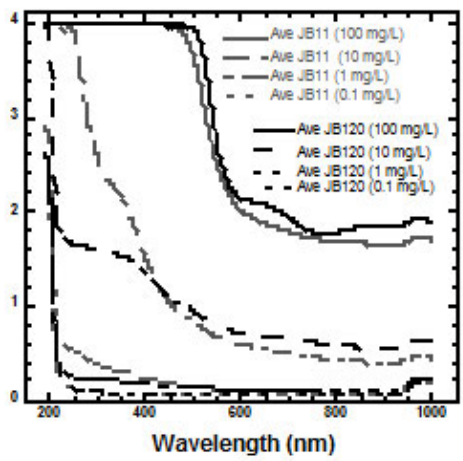

Fig. 2. Absorbance of Euglena and Chlamydonomonas in suspensions. The spectral absorbance due to chlorophyll in these organisms is clearly observed near 450 and 670 nm.

Project Report: Planetary Biology, Evolution and Intelligence

Project Investigators:	***Peter Backus , Emma Bakes , Amos Banin , Max Bernstein , Janice Bishop , Nathalie Cabrol , Chris Chyba , Edna DeVore , Friedemann Freund , Edmund Grin , Bishun Khare , Rocco Mancinelli , Cynthia Phillips , David Summers , Jill Tarter , Lynn Rothschild***

Project Progress

Friedemann Freund and Lynn Rothschild are investigating oxidation driven by diffusive loss of hydrogen formed within igneous and metamorphic rocks. New data include the observation of oxygen evolution from magnesium oxide crystals.

Emma Bakes is completing a paper describing the chemical foundations of nitrogenated macromolecules in Titan's haze. This work is complemented by laboratory work by Bishun Khare and Hiroshi Imanaka.

Janice Bishop and Rothschild have measured ultraviolet (UV), visible, and infrared (IR) spectra for iron–oxide–bearing samples, and experiments have been performed on cultures of two photosynthetic microorganisms. Data indicate that certain ferric–oxide–bearing minerals could have provided protection from UV radiation on early Earth.

Nathalie Cabrol and Edmond Grin have led a series of investigations of high–altitude lakes to examine the strategies employed by their microorganisms. The group they lead is currently analyzing data from its 2003 expedition. Discoveries include an active community of modern stromatolites and the culture and phylogenetic characterization of apparently new bacterial species.

Amos Banin has begun the analysis of soil samples from the Atacama Desert. Rocco Mancinelli and Banin are experimentally investigating whether binding of N as NH_4+ in silicate minerals could account for the “missing” N on Mars.

David Summers and Bishun Khare have begun experimental work on the abiotic fixation of nitrogen under atmosphere expected on early Mars.

Cynthia Phillips and Christopher Chyba are completing a major project, using Galileo imaging of Europa, to quantify the impact cratering “gardening” rate on Europa.

These results will be coupled with the results of low−temperature laboratory experiments. Mr. Kevin Hand, in collaboration with Robert Carlson and Chyba, is pursuing this research at JPL. Over the past year, Hand and Carlson have constructed the irradiation apparatus and have experiments underway.

Max Bernstein, in his lab at NASA Ames, has measured the mid−IR spectra of several polycyclic aromatic nitrogen heterocycles.

Peter Backus, Jill Tarter, Mancinelli, and Chyba have begun their examination of the prospects that planets orbiting dwarf M stars are habitable for either microscopic or complex life.

Finally, education and public outreach are major and integral parts of the work of the SETI Institute's NAI team. They are addressed elsewhere in our first−year summary, so are not presented here.

Highlights

- An active community of modern stromatolites producing limestone and developing in the highly saline shallow (50 cm) Laguna Blanca was discovered. From our 2003 reconnaissance, we believe that this community covers the entire floor of the lake (3 km x 1 km).
- The successful culture and phylogenic characterization in laboratory of two isolates from Laguna Blanca are determined to be two new species of the genus *Pseudomonas* and *E. Coli* . (analysis in progress).
- Ongoing characterization of the three lakes microbial communities and ecosystems details can be provided upon request.
- Diatoms (*Haslea*) developing UV shielding strategies (mucilaginous knobs and mesh) have been observed.
- Percentages of malformation and deformities are 10% higher than standard count in other lakes.
- Successful surface, subsurface, and subaqueous sampling (through diving and plankton netting) of water, life, and sediment in the lakes at 6,014 m and 4,430 m was performed.
- An Eldonet UV Dosimeter measuring ultraviolet A (UVA), ultraviolet B (UVB), photosynthetically active radiation (PAR) and Temperature was positioned at the Licancabur summit lake. The dosimeter is now the highest of its kind in the world and will record a year’s worth of data at 6,014 m. Because of its geographical position, it may also record the advances of the Antarctic ozone hole in this region of the Andes. Another identical dosimeter was positioned on the shore of Laguna Blanca as well as 7 UV acrylite plate stations. The underplate of these stations (each composed of one UV transmitting and one UV blocking plate) will be sampled in the coming years to study the effects of UV on immobile periphyton.
- Data of water temperature profiles (one year's worth) were collected and chemical analysis of the water for all lakes was performed. Laguna

Verde seems to be a very close analog to the Meridiani Planum paleo aqueous environment explored by the rover Opportunity. We report comparable levels of sulfate, bromine and chlorine. Carbonates are present in that lake, but they have not been identified on Mars.
- First Mapping and sonar sounding of Laguna Verde was performed, and sonar mapping of the Licancabur summit lake was initiated.
- Investigation continues to determine if the Atacama Desert soil is a real Mars soil analog.
- The missing nitrogen on Mars may be hidden as fixed ammonium in the Mars soil and regolith.
- There is a suggested possibility that early photosynthetic organisms may have existed in small niches protected by ferric–oxide–bearing material.
- A list of potential workshop participants has been compiled.
- The first star catalog of 2.5 million stars has been obtained.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

EPO: SETI Institute

These are the Education and Public Outreach activities for the SETI Institute.

Voyages Through Time Dissemination

In partnership with NASA Fundamental Biology, the NASA Astrobiology Institute, The National Science Foundation, The California Academy of Sciences, and San Francisco State University, the SETI Institute has developed Voyages Through Time (VTT), a National Science Education Standards (NSES)−based integrated science curriculum for high school centered on the unifying theme of evolution. Scientists, teachers, curriculum writers, and media specialists produced six CD−ROM modules that integrate astronomical, geological, and biological sciences. The sequence of lessons in each module is designed to promote students' understanding of science and skills as defined by the NSES and American Association for the Advancement of Science (AAAS) Benchmarks for Science Literacy. The six modules, Cosmic Evolution, Planetary Evolution, Origin of Life, Evolution of Life, Hominid Evolution, and Evolution of Technology, use the constructivist approach of engage, explore, explain, elaborate, and evaluate (Biological Sciences Curriculum Study, 1996) as an instructional framework. NAI Central funded the revision and production of the CD−ROM samplers of the curriculum. The samplers provide astrobiology activities for the classroom. Over 3000 free CD−ROM samplers were distributed at science teacher conferences, science conferences, workshops, and short courses this year. The VTT national field test took place from September 2001 through July 2002 in over 60 classrooms in 28 states. Teacher feedback was very positive, and the curriculum was revised following the national test evaluation summary reports. The curriculum was published in August 2003. More information about VTT can be found at http://www.voyagesthroughtime.org

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NASA Astrobiology Institute Lead Team EPO

Professional development workshops are conducted for educators. Workshops feature Life in the Universe curriculum guides by the SETI Institute, and the Life on Earth and Elsewhere educator resource guide by NAI and TERC. The workshops are aligned with National Science Education Standards Professional Development Standards, and provide astrobiology science content, and pedagogical content knowledge.

SETI Institute NAI scientists contributed images and animation to the California Academy of Sciences astrobiology exhibit. Astrobiology science lectures are

conducted for educators and the general public covering many of the objectives described in the Astrobiology Roadmap.

The first Astrobiology Summer Science Experience for Teachers (ASSET) was held August 1 – 7, a science, pedagogy, and leadership institute with presentations by leading astrobiology researchers from the SETI Institute, NASA, and the California Academy of Sciences. Scientists share the latest in astrobiology research on the origin of life on Earth, the extreme conditions in which life exists, Mars exploration, the formation of planetary systems around Sun–like stars, and the search for life in the universe. The Institute features a combination of cutting edge science, inquiry–based teaching and learning, and leadership skills development in alignment with National Science Education Standards Professional Development Standards.

ASSET participants received the entire Voyages Through Time (VTT) curriculum and complementary astrobiology materials, developed by NASA's Astrobiology Institute, for use in their classrooms. VTT is a standards–based integrated high school science curriculum, delivered on CD–ROMS. VTT consists of six modules: Cosmic Evolution, Planetary Evolution, Origin of Life, Evolution of Life, Hominid Evolution, and Evolution of Technology. Together these modules comprise a yearlong, integrated science course; or they may be used individually in discipline–specific courses. ASSET participants will implement at least one curriculum module, and conduct and report upon two significant outreach activities within two years. To learn more about VTT visit http://www.voyagesthroughtime.org

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

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Team Reports: University of Arizona

University of Arizona
Executive Summary
Principal Investigator: Neville Woolf

Overview

In 2003, the University of Arizona (UA) and the National Optical Astronomy Observatories (NOAO) began their partnership as part of the NASA Astrobiology Institute (NAI). Much of the activity in the first six months of the funding period has been spent in starting up programs and instituting collaborations within and between the two organizations and with other entities. First postdoctoral workers are starting to arrive, and equipment is under construction. Those activities that have made most progress are those in which least preparatory activity was required. Good progress is underway in all areas including observational, experimental and theoretical work.

The Arizona NAI team is strongly focused on the astronomical activity needed to support astrobiology. We have three research modules. The first is "Building blocks of life", which asks the question: which molecules are present in potentially pre−planetary space, and therefore might become available for the origin or development of life? We are developing equipment to determine the laboratory spectra of complex organic molecules that are potentially important to the origin of life, so that searches can be made for them in space. We are continuing astronomical searches at millimeter (mm) and sub−mm wavelengths for spectral features of sugars and other pre−biotic molecules in star−forming environments analogous to conditions that may have given rise to our solar system. We are developing experiments in gas phase chemistry to explore the gas phase polymerization of formaldehyde to more complex sugars, and we have initiated quantum mechanical calculations to explore gas phase processes that might lead to pre−biotic molecules. These molecules can arrive at a young terrestrial planet either by accretion in a preplanetary disk or as material incorporated in the infall of comets or planetesimals. This module is also searching for these molecules in the spectra of comets.

Our second module, "Formation of Habitable Worlds", is concerned with the development of planets and planetary systems out of disks of gas and dust that commonly surround young sun−like stars. There are both observational and theoretical activities within this module: observing disks from the ground and space and studies of planet formation and dynamical studies of disks. Our goal in this work is to better understand the frequency of giant planet formation and

the influence such planets have on the formation of terrestrial planets and their suitability for life. In this module we also include a study of the variability and magnetic activity of solar type stars of various ages. This information will be incorporated into studies of Earth climate and environment.

The third module, "Nature of Planetary Systems", is concerned with the detection of planets and the characteristics of other planetary systems. This module supports theoretical work on characteristics expected of extrasolar planets, searches for those planets, and studies of the terrestrial spectrum to understand extrasolar terrestrial planets. This last work is to assist the development of Terrestrial Planet Finder (TPF) and other means of detecting extrasolar planets. We have added to this work the development of a star list for the TPF missions.

In addition to these activities in research, we have an active program to develop our local astrobiology community by expanding our Life and Planets Astrobiology Center (LAPLACE) to include existing and new programs in astrobiology in Tucson, and especially to develop links with Life Science studies at the University of Arizona (UA).

A wide array of astrobiology−related research is ongoing in Tucson in addition to that of LAPLACE. For example the Mars Phoenix Mission is based in Tucson, and local researchers are playing a key role in the Cassini−Huygens mission to Saturn and Titan. LAPLACE is exploring ways to take maximum advantage of the physical proximity of these researchers. In addition our astrobiology−related programs are evolving and expanding to reach graduate education, international collaborations and education and public outreach to high school teachers and non−science undergraduates.

Construction of Equipment and Development of Techniques

In module 1 we are in the design and construction phase of a laboratory Fourier Transform spectrometer to obtain high precision radio frequencies enabling us to search for organic molecules in interstellar clouds, pre−planetary disks and comets. Large parts for the spectrometer are on order and the Steward Observatory machine shop has begun to produce smaller elements. The instrument is expected to be in use by the end of the year.

In module 2 we are constructing an automated telescope for the study of solar type stars. The major items for this telescope, large optical steel tube assemblies, are nearing completion. Researchers will initiate observations by the end of this year.

In module 3, we have two construction projects. Close and Biller completed their first observations using simultaneous differential imaging in two spectral bands near 1.6 microns. The technique is able to suppress speckle noise by using a methane spectral feature that occurs in planetary (or faint brown dwarf) companions, but not in the light of the central star. The technique has enabled a very large improvement in primary to secondary contrast. A first survey of the youngest stars that might host bright giant planets has been made in Chile, and

data are being analyzed. The technique is now being used with the 6.5−meter MMT in Arizona to search for companions to nearby stars.

Freed and Hinz are constructing a second instrument, a 5−micron imager (Klio) for use with the infrared optimized adaptive optics system of the MMT. This instrument is nearing completion, and test observations are planned for Fall 2004.

Laboratory and Telescope Observations, and Development of Observation Plans

In module 1, graduate student Halfen's observations of 25 rotational transitions with the 12−m telescope at Arizona Radio Observatory have confirmed the identification of glycoaldehyde in the interstellar medium from which stars and planetary systems form. This detailed process is necessary for the identification of complex molecules, and it has served as a preparatory program for future surveys to find more complex molecules.

Graduate student Milam has observed formaldehyde in three new comets and HCO^+ in comet Hale Bopp. Some of the evidence suggests that mm−sized particles containing these molecules break off, and could be swept up by planets (Milam, Savage, Ziurys and Wyckoff, in press).

Werner and Judd are exploring the gas phase polymerization of formaldehyde to make more complex sugars in the laboratory. A series of experiments for necessary technique development are in progress.

In module 2, Meyer *et al* . have submitted the results of their first observations of disks around solar type stars observed with the Spitzer Space Telescope (SST). The results suggest that there is not a unique correlation between the age of the disk and the emission by its dust. Stochastic processes of asteroid collisions are one possible cause. Supporting work has been carried out in collaboration with graduate student Mamajek. They find that circumstellar disks in the terrestrial planet zone (0.1 to 10 AU) dissipate within 30 Myr (Mamajek *et al.* , in press). Meyer has also initiated a program to explore the relationship between stellar rotation and the presence or absence of circumstellar disks. Under the supervision of Hinz, Liu and collaborators have used the technique of nulling interferometry to resolve the circumstellar disk around the intermediate mass young star HD100546.

Najita (with Gorti, Hollenbach and Carr) has been awarded SST time to search for gas in circumstellar disks around very young stars. Najita, Strom (and Richter) have also been awarded observing time on the Infrared Telescope Facility (IRTF) on Mauna Kea to develop techniques for observing circumstellar atomic and molecular gas. In addition Najita was awarded observing time at the Keck telescope for detecting and characterizing circumstellar gas.

In module 3, using the Vatican Advanced Technology Telescope (VATT) at Mt. Graham International Observatory, the first observations have been made of earthshine in the near infrared and the data reduction will be part of Turnbull's Ph.D. thesis. This spectral region is potentially important for studying terrestrial

planets. It contains stronger water bands than the visible, and this could be significant for studying cold terrestrial planets. It also contains bands of carbon dioxide, from which a quantitative measure of abundance can be made, and the most easily observed band of methane, which is important for a Life Finder mission.

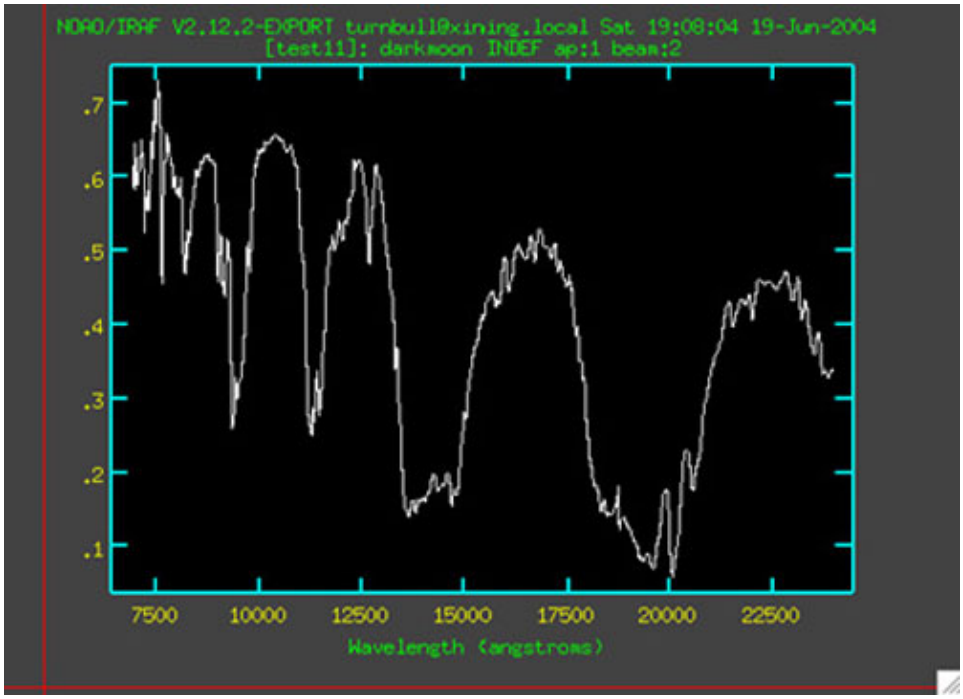

Figure 1: The near infrared albedo spectrum of the Earth obtained from earthshine measurements at the Vatican Advanced Technology Telescope at Mt. Graham International Observatory. From left to right the bands are: Oxygen A band 7600A, Water 8300A, Water 9400A, Water 11300A, Oxygen 12700A, Water 13800A, Water 18700A, Carbon dioxide 20000 and 20600A and Methane 22000A.

Theoretical Studies

In module 1, Adamowicz and Bednarz have started to use quantum mechanical calculations to investigate the processes leading to simple sugars. The first part of the project is to model stationary states and dynamical behavior of molecules and molecular ions, and the development of new algorithms and computer software is underway.

In module 2, Lunine has worked with Raymond and Quinn (University of Washington) to develop models of terrestrial planet formation, to explore the masses of the predicted planets, and the content of volatiles such as water. Studies of systems resembling the solar system typically yield one to four terrestrial planets, and they have a variety of water contents and eccentricities that seem determined by the giant planet characteristics. In planetary systems where a "roaster" Jovian planet had formed early, close to the star, they find that terrestrial planets can form with amounts of water similar to Earth, but formation of terrestrial planets is suppressed overall as the orbital radius of the

"roaster" moves outward from 0.1 AU.

Malhotra (in collaboration with Kring, Ito and R. Strom) has been investigating the nature of the Late Heavy Bombardment (LHB) of the Moon ~3.9 Gyr. They are exploring the possibility that a large catastrophic asteroid break−up event close to a gravitational resonance was responsible for the LHB. They are modeling in detail the dynamics of such a break−up event, calculating synthetic crater records from such an event, and confronting these with the observed crater records.

Malhotra and Moro−Martin are modeling the expected signatures of planets in the mass surface density distribution of debris disks in support of observational programs. They have examined the observational consequence of such signatures in the unresolved stellar spectral energy distribution, and their dependence on the planetary and debris parameters.

Malhotra has also been studying the stability of orbits of sub−jovian mass planets She has developed a simple secular stability criterion for two−planet systems that provides strong constraints on the orbital location of sub−jovian mass planets.

In module 3, Burrows, Sudarsky and collaborators are building on their successful models of isolated planets to predict the brightness and spectra of Jovian planets around other stars. These studies are closely coupled with the plans to observe these objects.

Turnbull has used data collected to help the Search for Extraterrestrial Intelligence (SETI) project to help design searches for emission from terrestrial planets. She has worked with the TPF Science Working group to develop a list of stars appropriate to possible TPF missions.

Meetings and astrobiology development

This has been a busy year in planning new activities, and a number of them have been international in scope. In January LAPLACE hosted the first *Graduate Student Astrobiology Conference* in Tucson, attended by about 60 students from approximately 40 different schools, including a number from foreign countries.

In April we held a two−day meeting with physical and life science researchers, assisted by Juan Mercado of the Spanish Astrobiology Institute. Prior to the meeting we made presentations to a number of departments in the UA's College of Science, and there was general enthusiasm for developing a much wider program than we currently have. The Planetary Science Institute (PSI) also sent a representative to the meeting, and we look forward to future collaborations with them. There was agreement for LAPLACE and life sciences to work together. As a first step the UA College of Science submitted a National Science Foundation *Integrative Graduate Education and Research Traineeship* (IGERT) grant proposal. This proposal focuses on the biochemical origins of life. Although they are not yet part of the LAPLACE team, UA life sciences researchers, including Nancy Moran, new member of the National Academy of

Sciences, are keenly interested in working with us.

LAPLACE will be participating in the Vatican Observatory Summer School (VOSS) on astrobiology in Castel Gandolfo, Italy, in the summer of 2005. This is a joint project of the Vatican Observatory (Corbally and Coyne) and faculty from the UA (Impey, Lunine and Woolf) and the University of Washington (Baross and Sullivan). We found the polycom system to be helpful in holding a planning meeting.

Figure 2: UA, Vatican and University of Washington researchers during an April 2004 planning meeting for the VOSS. Use of the NAI polycom system aids greatly in the communication among the far–flung collaborators. Woolf, Lunine, Impey and Corbally participated from the UA campus; Baross and Sullivan participated from the Washington campus.

Chris Impey of the UA Astronomy Department is Principal Investigator for a grant from the Templeton Foundation to explore the relationship between astrobiology and religious thought. The funds will bring in speakers in science and other areas from outside UA, and be used for course development. The Templeton team includes Lunine and Woolf from LAPLACE and professors from the Vatican Observatory and UA Departments of Biology, Judaic Studies, Art, Humanities and Education. It is a promising avenue for interdisciplinary outreach.

LAPLACE has also received its first private funds for astrobiology scholarships for graduate students. These will be distributed for the first time for the Fall 2004 semester.

Teaching

We have taught a number of courses in astrobiology at UA as well as throughout the community. UA typically enrolls 100–200 students per term in the advanced *Life in the Universe* course for nonscience majors. Tim Slater leads the Education and Public Outreach (EPO) group. EPO held two courses *Astrobiology for Teachers* in Fall 2003 and Spring 2004. In Spring 2004, Meyer and Woolf taught an astrobiology course to seventeen astronomy and planetary science graduate students. In the summer of 2004 the EPO group taught a master's level course for teachers. EPO held seven workshops for teachers in 2004.

These outreach efforts are part of an "advanced EPO" project in which our team is focused on exploring the conceptual problems encountered by students in astrobiology, and teaching at a higher level than commonly occurs in public outreach. We see this as an essential part of the process of developing broad based support for astrobiology.

Hiring of postdoctoral assistants

The hiring of postdoctoral assistants for this work began with receipt of funds in November 2003. In a few cases appropriate people were available, and they have already been hired. However in the majority of cases, the postdoctoral assistants are due to arrive at the start of the Fall 2004 semester. All available positions will be filled by year–end.

Project Report: An Astronomical Search for the Essential Ingredients for Life: Placing Our Habitable System in Context. Progress Report

Project Investigators:	***Ludwik Adamowicz , J. Roger Angel , Aldo Apponi , Michael Brown , Adam Burrows , Laird Close , Mark Giampapa , Eric Herbst , Philip Hinz , David Kring , Jonathan Lunine , Renu Malhotra , Michael Meyer , Joan Najita , Robin Polt , Edward Prather , Tim Slater , Stephen Strom , Neville Woolf , Lucy Ziurys***

Project Progress

Module 1: Building Blocks of Life

This module has carried out a variety of laboratory, theoretical, and observational studies centered on the possibility that the ribose in DNA/RNA had an interstellar origin. The following sections detail this progress.

Laboratory Spectroscopy of Simple Sugars

Aldo Apponi is currently in the design/construction phase of a new spectrometer: a Fourier transform microwave system, which will be used to measure the pure−rotational spectra of simple sugars. This spectrometer will have exceptional sensitivity in gas−phase studies of such pre−biotic molecules because it utilizes a supersonic molecular beam source, a high finesse Fabry−Perot filter cavity and ultra low noise amplifiers. The basic design is completed, and the University instrument shop has built the vacuum chamber. The pumping system and electronics are on order. The completed cell should be ready by July 2004 with initial tests in August 2004.

Figure 1: Larry Acedo and Aldo Apponi posing next to the newly constructed vacuum chamber in the University Research Instrumentation shop at the University of Arizona . When complete, the cell will house a sophisticated system of optics, electronics and cryogenic equipment that will be used to study molecules important to rudimentary life on Earth.

Observational Studies of Molecular Clouds and Comets

Graduate student DeWayne Halfen is completing a radio astronomical investigation of glycolaldehyde. Additional observations have been conducted at the Arizona Radio Observatory's (ARO's) 12−m telescope at Kitt Peak to confirm a few spectral lines in SgrB2N that may have arisen from image contamination in previous measurements. Thus far, 25 very favorable rotational transitions have been unambiguously confirmed. The column density of glycolaldehyde in SgrB2N is calculated to be N_{tot} ~10^{13} cm^{-2} . Success of this project indicates that more complicated sugars may be detectable in interstellar gas, provided the spectroscopy and quantum mechanics of the molecules are well understood.

Graduate student Stefanie Milam has conducted observations of comets Linear, Neat, and Bradfield. Formaldehyde, H_2 CO, the basic precursor to ribose−like sugars, has been detected in these objects. Other sugars may be present as well. Furthermore, because comets appear to routinely disintegrate and fragment as they approach the sun, millimeter−sized grain−like particles containing organics are ejected into interplanetary space and probably end up in planetary atmospheres. Further investigation of archived data suggests organic, grain−like precursors for species such as HCO^+ and HNC in comet Hale−Bopp. Recent analysis of data taken of this comet indicates a possible secondary source, believed to be organic−rich, volatile grains as seen in Figure 2 **.** These grains are easily fragmented to produce more common "cometary species" such as H_2CO and HCO^+ through photodestruction. (Milam, Savage,

Ziurys, and Wyckoff , *Ap. J* , in press).

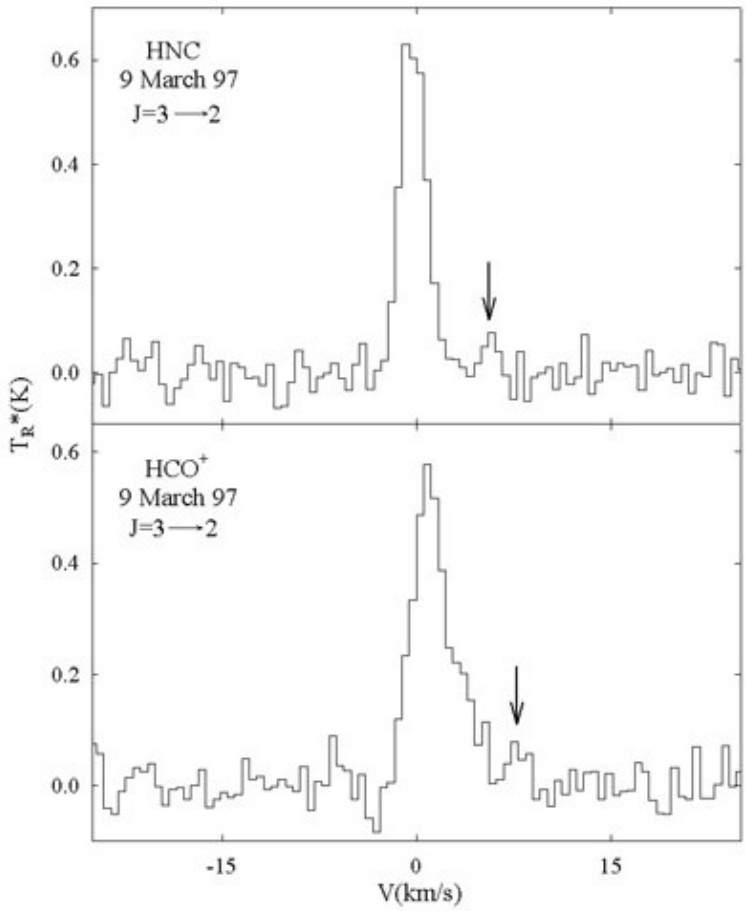

Figure 2: The J=3_2 transition of HCO^+ at 268 GHz and the J=3_2 line of HNC at 272 GHz detected towards comet Hale−Bopp, using the Arizona Radio Observatory 12 m telescope on March 9, 1997, with 500 kHz (0.55 km/s) resolution. A second velocity component appears to be present in both spectra, shifted by about 5 km/s from the main line, indicated by arrows. Recent analysis suggests the secondary components likely arise from volatile, organic grains.

Gas−Phase Laboratory Organic Chemistry

Graduate students Ben Werner and Matt Judd have begun lab experiments to test whether the gas−phase reactions of H_2CO can lead to simple sugars. Their first task is to devise a suitable source of gas phase H_2CO. They have discovered that they can get a good stream of relatively pure formaldehyde gas at 50°C from paraformaldehyde with catalysis by tosyl acid. (Higher temperatures lead to disproportionation to produce a variety of compounds.) They have trapped the stream in deuteriochloroform, and have analyzed the resulting mixture by proton nuclear magnetic resonance (NMR). They are

presently trying to measure the rate of trimerization to trioxane in deuteriochloroform, which is actually reasonably slow. Additionally, they are looking at ways to generate a gas phase stream of the 2−carbon sugar from aqueous solution.

Quantum Mechanical Calculations of Reactions Leading to Ribose

This part of the research concerns the use of quantum mechanical calculations and molecular dynamics (MD) simulations to investigate the possible processes and mechanisms involved in the reactions leading to interstellar formation of simple sugars, conducted by Ludwik Adamowicz and post doctoral fellow Eugeniusz Bednarz.

The first part of this project has been devoted to developing new, more accurate methods for modeling stationary states and dynamical behavior of H_2^+, H_2, H_3^+ , H_3 and their isotopomers. The reactions leading to simple sugars involve protenated species such as $H_3\ CO^+$, or $CHOCHOCH_2\ OH_2^+$. The development of new algorithms and computer software is under way, and we expect publications of the first series of results soon. The publications will concern isotopic effects (proton−deuteron exchange) in excited ro−vibrational spectra of the cation hydrogen systems. The study of small hydrogen clusters is a prerequisite to investigating ion−molecule reactions leading to protenated sugars.

Next, we will consider hydrogen/proton exchange between the hydrogen clusters and simple organic molecules leading to formation of organic cations in the gas phase (such as the mentioned above). The goal of the calculations will be to determine the lowest−energy pathways leading from the reactants to the products. This information will be supplied to the molecular dynamics simulation program to calculate reaction rates and equilibrium constants. Since the considered transformations involve small molecular systems, quantum effects may play important roles in accessibility of certain reaction channels. Also hydrogen/proton tunneling has to be taken into consideration, and the classical MD approach may become inadequate.

Highlights

- *Ziurys' group designed and began fabrication of a Fourier transform microwave system spectrometer.*
- *The group conclusively detected simple sugars and their precursors in interstellar gas and comets.*
- *Observations provided evidence of comet fragmentation involving simple organics.*

Module 2: Formation of Habitable Worlds

Najita was awarded time in cycle 1 on the Spitzer Space Telescope (SST) to carry out a program aimed at quantifying gas content in circumstellar disks surrounding stars with ages t ~ 10 Myr. The goal is to exploit the wavelength coverage afforded by SST to explore multiple diagnostics sensitive to gas located from the terrestrial planet through giant planet forming regions of disks.

Collaborators on the project are Gorti and Hollenbach (NASA Ames Research Center) and Carr (US Naval Research Laboratory).

Najita, Strom and collaborator Matt Richter (University of California, Irvine) were awarded time (for November 2004) on the NASA Infrared Telescope Facility to carry out a program aimed at defining optimal observing procedures for obtaining high resolution, ultra−high signal/noise spectra of molecular and atomic diagnostics of circumstellar gas.

Najita was awarded time (for November 2004) with the near−infrared cryogenic echelle spectrograph (NIRSPEC) on Keck II to carry out an ambitious program aimed at detecting circumstellar gas and characterizing its kinematics around stars spanning a range of ages from three to thirty Myr.

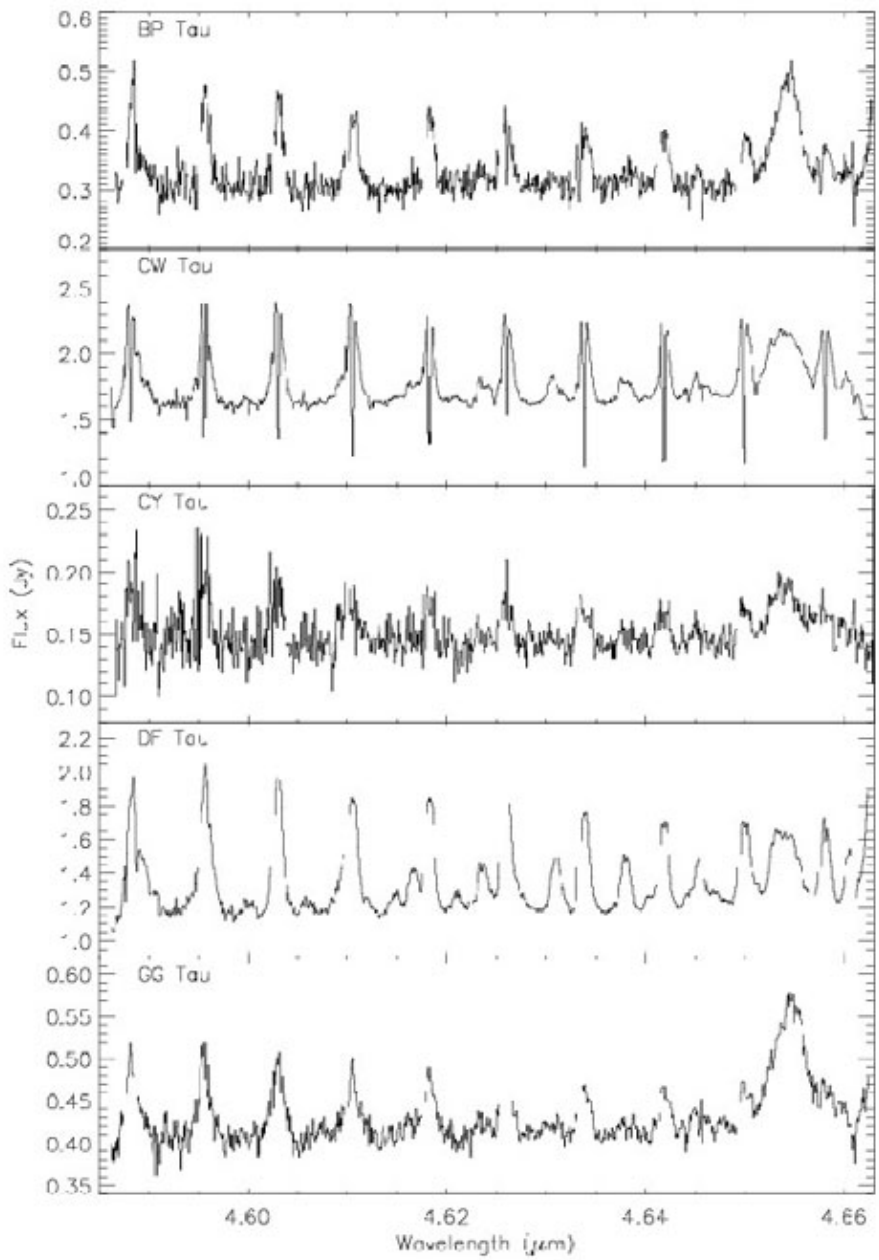

Figure 3: Example of typical spectra of CO fundamental spectra of T Tauri stars observed with NIRSPEC. Results suggest the utility of CO fundamental emission as a probe of disks at planet formation distances. Najita and team will continue such observations using NIRSPEC during this year's observing time.

Najita submitted a paper in collaboration with Glassgold and Igea on the thermochemical structure of optically thick disks.

Meyer continues to lead a Legacy Science Program utilizing data from the Spitzer Space Telescope (SST) entitled "Formation and Evolution of Planetary Systems" (FEPS). Members of the FEPS team involved in LAPLACE include Lunine, Malhotra, Meyer, Najita, and Strom. Initial results from FEPS will appear in a special issue of the Astrophysical Journal set for September. The

paper reports the detection of two debris disks, each with a prominent inner hole in the dust distribution that could be a signpost of planet formation. Through LAPLACE, Meyer and colleagues hope to: i) follow up interesting SST detections with high spatial and spectral resolution ground−based observations; and ii) work with colleagues in the University of Arizona (UA) Lunar and Planetary Lab and elsewhere within the NAI to understand the observed evolution in circumstellar disk properties around sun−like stars in the context of our own solar system evolution. Over 100 stars will be observed with SST in the summer of 2004 and many new results on the evolution of gas and dust disk properties are anticipated. Post−doctoral research associate Daniel Apai will join LAPLACE in September and is expected to play a key role in both areas. Meyer also plans to involve an undergraduate student in this work as part of his senior thesis through the Honors College . Two examples of the potential importance of ground−based observations to help interpret SST observations are the recent work of students Mamajek and Liu. As part of Mamajek's thesis, 10−micron observations were obtained with the Magellan 6.5−m telescope in Chile to characterize disk properties of 10−30 Myr old stars. In a paper to appear in the Astrophysical Journal, Mamajek et al. report that dust in the terrestrial planet zone around sun−like stars dissipates on timescales less than 30 Myr. Under the supervision of LAPLACE member Hinz, Liu *et al* . (*Astrophysical Journal* , submitted) resolved the thermal infrared (IR) emission from the disk surrounding the intermediate mass young star HD 100546 using the technique of nulling interferometry. Liu and collaborators have also recently constrained the amount and spatial distribution of thermal IR emission in the Vega debris disk system. Strom and colleagues continue to study the evolution of angular momentum around young sun−like stars and the connection to circumstellar accretion disks and planet formation. While disks play a central role in braking the expected increase in rotation speed of young stars as they contract in radius (conserving angular momentum), it is clear that other factors can also be important. For example, there appear to be differences in the evolution of specific angular momentum between high and low mass stars. Future work on the connection between the presence/absence of disks and rotation in younger protostars as well as older post−accretion stars (10−100 Myr) are underway utilizing ground−based observations as well as the SST.

Giampapa made significant progress in launching the program to monitor stellar activity in clusters spanning a range of ages. The National Optical Astronomy Observatories (NOAO) hired William Sherry as a postdoctoral fellow, and he will be in residence before 1 October 2004 . Hardware and software design and purchases for the photometric monitoring component of the program are well underway. Two proposals critical to spectroscopic monitoring were submitted: (1) WIYN 3.5−m/Hydra−−Long−Term Proposal: "The Evolution of Activity in Solar−Type Stars" (status: pending), and (2) WIYN 3.5−m/Hydra−−Standard Proposal: "Chromospheric Activity at Intermediate Ages" (status: pending). Two papers discussing the telescope hardware and data handling methods for the acquisition and reduction of photometric data are currently in preparation.

Lunine has worked with Raymond and Quinn (University of Washington team) on two papers about the origin of terrestrial planets. For the first paper (*Icarus,*

165), they conducted forty–four simulations of late stage planetary accretion, focusing on the delivery of volatiles (primarily water) to the terrestrial planets. They investigated volatile delivery as a function of Jupiter mass, position and eccentricity, the position of the snow line, and the density (in solids) of the solar nebula. In all simulations, they found that one to four terrestrial planets formed inside 2 astronomical units (AU). These planets vary in mass and volatile content. In the forty–four simulations the models formed forty–three planets between 0.8 and 1.5 AU, including 11 habitable planets between 0.9 and 1.1 AU. These planets range from dry worlds to “water worlds” with 100 + oceans of water (1 ocean = 1.5 × 1024 g), and the planets vary in mass between $0.23M_{Earth}$ and $3.85M_{Earth}$.

In the second paper, submitted to *Science* , they conducted simulations of terrestrial planet formation in the presence of "hot Jupiters," under the assumption of early orbital migration.
They showed that even under these circumstances, terrestrial planets similar to those in the Solar System can form, and can have water contents equal to or higher than the Earth's. For small orbital radii of hot Jupiters (e.g. 0.15, 0.25 AU) potentially habitable planets can form, but for semi–major axes of 0.5 AU or greater their formation is suppressed.

Figure 4: What might planets around stars look like? Lunine and collaborators' simulations of planet formation produce various results for solar system composition.

Malhotra, in collaboration with Kring, Ito and R. Strom, has been investigating the nature of the Late Heavy Bombardment (LHB) of the Moon, ~3.9 Gyr. This group is exploring the possibility that a large catastrophic asteroid break–up event close to a gravitational resonance was responsible for the LHB. They are modeling in detail the dynamics of such a break–up event, calculating synthetic crater records from such an event and confronting these with the observed crater records.

Malhotra and Moro−Martin are studying the expected signatures of planets in debris disks. They have examined the signatures of such features in unresolved stellar spectral energy distribution and their dependence on the planetary debris parameters. They have submitted two papers for publication.

Malhotra has also been studying the stability of orbits of sub−Jovian mass planets. She has developed a simple secular stability criterion for two−planet systems that provides strong constraints on the orbital location of sub−Jovian mass planets.

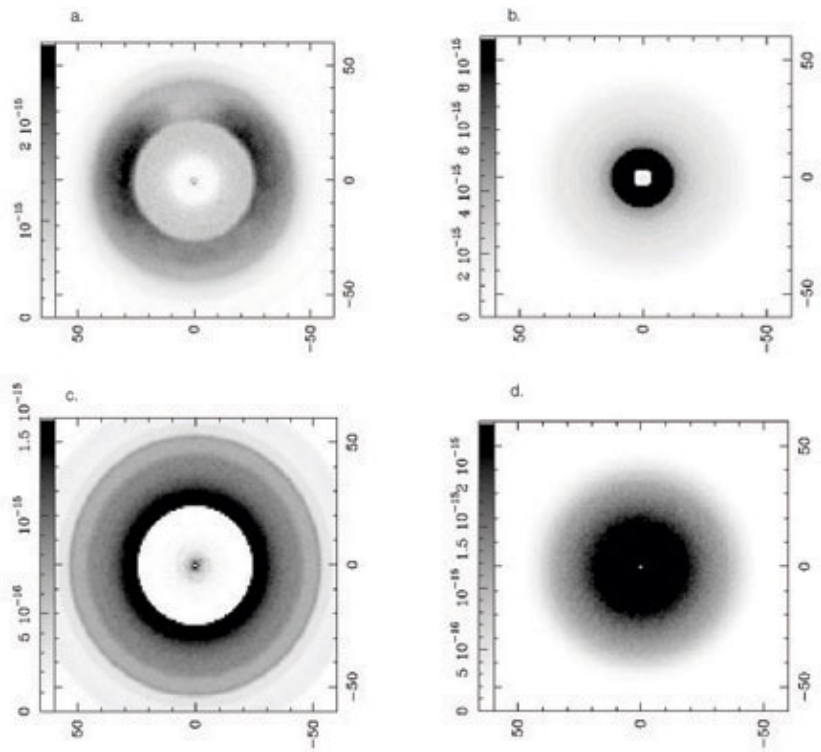

Figure 5: Simulations of dust disks with embedded planets. The figures show the brightness surface density distributions at 70 microns arising from systems with four different planetary configurations: a) Solar System planets; b) single Jupiter mass planet at 5 AU; c) single Jupiter mass planet at 30 AU; d) system with no planets. In all cases the dust−producing planetesimals are between 35 and 50 AU, similar to the Solar System Kuiper Belt.

Highlights

- *First results of the Spitzer Legacy program about young disks have been accepted for publication.*
- *Lunine and collaborators produced models for the origin of terrestrial planets.*
- *Giampapa and collaborators initiated construction of telescopes for monitoring solar−type stars in clusters.*
- *Malhotra and collaborators' models have supported observations of debris disks and planet formation.*

Module 3: Nature of Planetary Systems

The theoretical program has made rapid progress in the past year towards both modeling expected spectra of giant planets and implementing two distinct search strategies to carry out the first direct detection of these elusive objects. Burrows, Sudarsky and collaborators are building on their successful isolated models for substellar objects to predict brightness and spectra of objects down to planetary masses around other stars. The modeling has integrated stellar irradiation into the calculations, providing predictions for spectra of these objects from the visible into the thermal infrared.

Freed and Hinz are in the process of building an optimized 3–5 micron imager (called Klio) for use with the only thermal–IR optimized adaptive optics system on the 6.5–m MMT. This system will be optimized to detect older, cooler planets in the thermal infrared. First tests of this camera are planned for Fall 2004.

Close and Biller have successfully demonstrated a unique differential technique (Simultaneous Differential Imaging) to detect planets at 1.6 microns by taking advantage of their methane absorption, and have detected a brown dwarf of ~ $27M_{Jupiter}$. Observations have begun with the system on the 6.5–m MMT to characterize the prevalence of warm giant planets around nearby young stars.

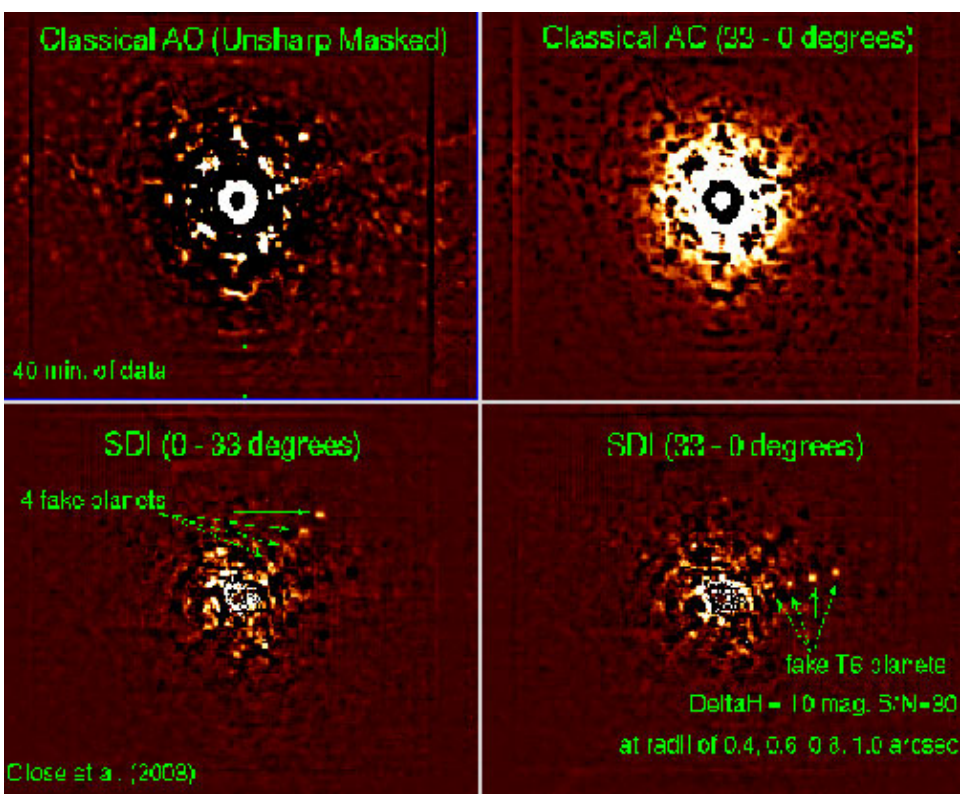

Figure 6: Simulations of Simultaneous Differential Imaging.

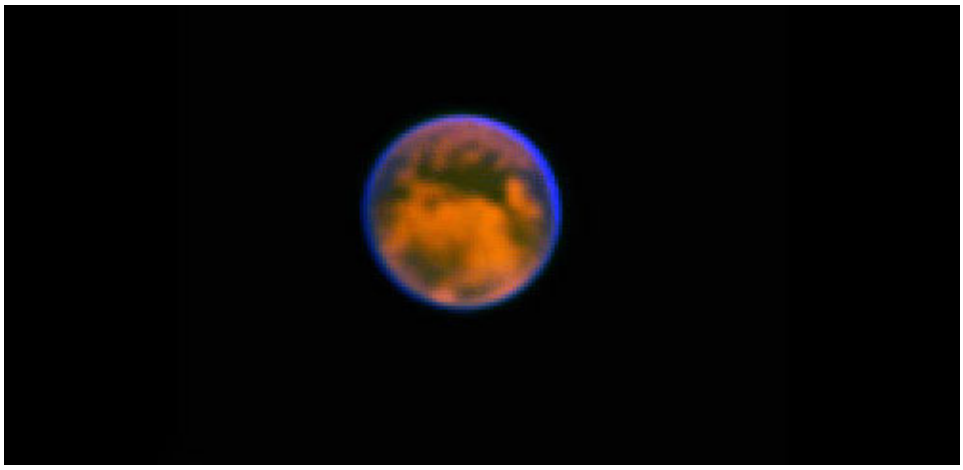

Figure 7: New images of unsurpassed clarity have been obtained with the European Southern Observatory (ESO) Very Large Telescope (VLT) of formations on the surface of Titan, the largest moon in the Saturnian system. They were made by an international research team of Markus Hartung, ESO; Laird Close, University of Arizona; Rainer Lenzen, Max−Planck Institut für Astronomie, Heidelberg, during recent commissioning observations with the "Simultaneous Differential Imager (SDI)", an exoplanet detection device, just installed at the NACO Adaptive Optics instrument. With the high−contrast SDI camera, it is possible to obtain extremely sharp images in three colors simultaneously. Although mainly conceived for exoplanet imaging, this device is also very useful for observations of objects with thick atmospheres in the solar system like Titan. Peering at the same time through a narrow, unobscured near−infrared spectral window in the dense methane atmosphere and an adjacent non−transparent waveband, images were obtained that are virtually uncontaminated by atmospheric components. They map the reflectivity of a large number of surface features in unprecedented detail.

Observations have been made of near infrared earthshine using the 1.8−m Vatican Advanced Technology Telescope (VATT) on Mt. Graham. These observations include one each made in summer and winter (mid−November). For the November observation, the humidity was sufficiently low that the lunar continuum could be clearly seen in the middle of the strong 1.4− and 1.8−micron water bands, despite the air mass of 2−3 times zenith. The spectrum has been measured from 0.7 microns to 2.4 microns. Clearly visible are the 1.27−micron band of oxygen, the CO_2 bands at 2.00 and 2.06 microns as well as near 1.6 microns, the methane band at 2.2 microns and the water bands at 0.94, 1.13, 1.38 and 1.89 microns. The 2.2−micron methane feature seems to be the most easily distinguishable methane feature in the spectrum of the Earth, and so is the most appropriate band for a LifeFinder study. The observations will be part of Margaret Turnbull's thesis, the UA's first astrobiology−oriented Ph.D. thesis.

It is potentially significant that all these features together with those previously reported in the visible earthshine can be seen from the ground at a dry site. We will be exploring the possibility of ground observations of terrestrial planets, particularly at the near IR wavelengths where currently planned Terrestrial Planet Finder (TPF) observations will be limited in angular resolution by the size of mirror that can be incorporated into a space mission. The many possible sites for performing a LifeFinder study will be compared.

Turnbull has developed lists of stars for the Search for Extraterrestrial Intelligence (SETI) program. She has used these same basic lists and information to develop star lists for the TPF missions, working with the TPF science working group. These lists will also be a part of her thesis.

Highlights

Burrows, Sudarsky and collaborators developed self–consistent models of irradiated giant planets that can guide ongoing searches for "other Jupiters."

Freed and Hinz developed an optimized 3–5 micron camera, called Klio, to detect older giant planets where they are predicted to be relatively bright.

Close and Biller successfully implemented a simultaneous differential imaging technique (SDI) to allow searches for young giant planets in the near infrared.

Woolf and collaborators observed near–infrared earthshine from Mt. Graham, Arizona.

Turnbull and collaborators developed star lists for TPF missions and for SETI.

Module 4 Advancement of Astrobiology

We have initiated our ***L*** ife ***a*** nd ***Pl*** anets ***A*** strobiology ***Ce*** nter, LAPLACE, and submitted a request to the Arizona Board of Regents for official designation as a UA Center. A UA undergraduate student, David DuPlessis, won the competition for a Center logo. DuPlessis also designed and implemented the LAPLACE website, http://www.laplace.arizona.edu.

Figure 8: LAPLACE Logo.

Because LAPLACE did not receive the first NAI funds until November 2003, we did not hold the proposed *2004 Winter School for Astrobiology* . Instead LAPLACE hosted the first *Astrobiology Graduate Student Conference* (ABGRADCON). Details about the conference are available at http://www.noao.edu/meetings/abgradcon/. The abstracts for this conference will be permanently available in the journal *Astrobiology* . For the short term they are available at http://skye.as.arizona.edu/~turnbull/ABGRADCON/GradCon2004.html , together with a list of seventy−five student contacts. The abstracts are also available through the LAPLACE website, http://www.laplace.arizona.edu .

The graduate conference was well attended with about sixty attendees from forty different institutions. There have been a number of follow−up activities. For example, the graduate students who participated in the conference established their own association and website, http://www.societyforthestudyofastrobiology.com/ .

LAPLACE polled the attendees to determine their preference for the nature of the future *Winter School* effort. The majority of responders indicated a preference for an approximately week−long session, either combined with a graduate student conference (on alternate years) or alone. In light of the experience of ABGRADCON and preferences, LAPLACE is refining its concept of the *Winter School* proposed to NAI to better serve the student population.

Interest in astrobiology at UA is increasing. In addition to ABGRADCON, the NAI−LAPLACE team had a two−day meeting with colleagues from UA life science departments and the Planetary Science Institute (PSI) in order to determine how to expand astrobiology activities in Tucson. Juan Mercader of the Spanish Astrobiology Institute attended, and was especially helpful in

organizing the meeting. One result of the meeting was the submission of a National Science Foundation *Integrative Graduate Education and Research Traineeship* (IGERT) grant proposal to develop life science participation in LAPLACE. UA biologists, Howard Ochman and Nancy Moran, led this effort with support by members of our NAI team. The UA College of Science inducted its first Galileo Circle Fellows in spring 2004. Included in the first four fellows were Jonathan Lunine (Planetary Sciences) and Neville Woolf (Astronomy) from our NAI–LAPLACE team. Additionally, Meyer and Woolf taught a three–unit, one semester graduate course, *Introduction to Astrobiology* , to seventeen students from three UA departments.

The Vatican Observatory Summer School (VOSS) in 2005 will be based on the theme of Astrobiology. Jonathan Lunine is the lead organizer. Staff will also include Woody Sullivan and John Baross of the University of Washington NAI team, Chris Impey and Neville Woolf of UA, and Chris Corbally and George Coyne of the Vatican Observatory.

Impey led a team that successfully obtained a grant from the Templeton Foundation, *Astrobiology and the Sacred: Implications of Life Beyond Earth.* The University of Arizona is one of two universities selected from 200 institutions worldwide to develop this dialogue. This program develops education in the field of astrobiology and has public discussions of the relationship between astrobiology and religion. The key speaker for the first year will be Francisco Ayala. LAPLACE will collaborate with the Templeton Foundation over the grant period to produce thoughtful and systematic reflection on the implications of the search for life. Such work will supplement the LAPLACE astronomical and biological research efforts.

LAPLACE received a five–year $50,000 private donation for its first astrobiology student scholarships. LAPLACE will use the funds to help graduate students at different points in their careers. The scheme is to provide book scholarships for first year students, travel scholarships for those in the middle of their work, and advanced scholarships to help students in their final years of obtaining their Ph.D.

Our Education and Public Outreach (EPO) program straddles the boundary between traditional public outreach, college non–major education and teacher education. In addition to holding seven workshops for teachers around the country, and two general astrobiology courses for pre–service teachers, it initiated a Master's level course at UA in the summer of 2004 for in–service teachers. We regard this extension of public outreach to undergraduates and teachers as essential for developing future astrobiologists as well as for developing a science–literate public. UA continues to enroll 100–200 students per term in the popular *Life in the Universe* advanced course for nonscience majors. LAPLACE team members play an active role in developing and teaching the course.

Highlights

- *UA will hold the first astrobiology–related Ph.D. defense in summer 2004.*

- *LAPLACE hosted ABGRADCON in January 2004.*
- *UA College of Science submitted an IGERT proposal to NSF.*
- *UA, University of Washington and the Vatican Observatory are planning the VOSS in astrobiology in 2005.*
- *UA College of Science selected Lunine and Woolf as Galileo Circle fellows.*
- *Templeton Foundation awarded a Templeton Research Lectures grant to UA.*
- *A private donor provided the first astrobiology scholarship funds.*
- *Meyer and Woolf taught the first astrobiology graduate course.*
- *EPO submitted six abstracts and one journal article to the Journal of College Science Teaching.*
- *EPO held two courses, Astrobiology for Teachers, in both the Fall of 2003 and Spring of 2004.*
- *EPO taught a Master's level course for teachers in the Summer of 2004.*
- *EPO held seven workshops for teachers around the US.*

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

EPO: University of Arizona

These are the Education and Public Outreach activities for the University of Arizona.

Great Explorations in Math and Science – Astrobiology

Professional development opportunity for K–12 teachers utilizing curricular materials from Lawrence Hall of Science Great Explorations in Math and Science (LHS GEMS). This is a full–day workshop within a series of workshops spanning the full spectrum of science. Teachers are able to receive college credit upon completion of a set of these workshops, of which this Astrobiology workshop is a part.

Milky Way Galaxy Workshop

One hour workshop and curriculum presentation on the size and scale of the Milky Way Galaxy.

Living the Polar Lifestyle – The Importance of Water for Life

One hour workshop and curricular materials presentation at the Arizona Science Teachers Association conference. The topic focused on the importance of water for life within the context of Astrobiology.

Relevance of Remote Sensing in Astrobiology

A one hour workshop providing content knowledge about remote sensing and its relevance to astrobiology. Curricular materials were also disseminated.

Science Communication Working Group

The purpose of the NAI Science Communication Group is to provide a forum for communicators who either work in or have an interest in astrobiology to exchange ideas and information and explore ways of sharing this with those who wish to communicate astrobiology more effectively. Ultimately, the group will strive to understand how elements of one part of the science communication spectrum might lead to innovative approaches in communicating astrobiology to public audiences. Emphasis will also be placed on improving specific arenas of science communication – for example in the scientist/ science journalist relationship. This knowledge will be disseminated through workshops and short courses at astrobiology–related meetings for a

range of audiences (for example, researchers, journalists or specific groups of experts), at standalone workshops (for example for university/research institution public information officers) and via an Internet site to provide information across the astrobiology community.

The group will also develop interdisciplinary approaches for the effective communication of astrobiology and will work closely with the NAI and NAI teams, when invited, to implement them – for example, contributing expert input and offering best practices for an education or communication project. It may also occasionally report on specific issues, suggesting solutions and a plan for implementation.

Astrobiology Public Lecture

Timothy Slater was invited to the University of Nebraska to give a public lecture on the background and current science of astrobiology.

Astrobiology Talk for High School Teachers

Tim Slater was invited to the University of Nebraska in Lincoln, NB to speak to high school teachers about teaching astrobiology.

Communicating Astrobiology to the Public Conference

Timothy Slater attended the "Learning How to Communicate Astrobiology to the Public" conference and brought results back to UofA scientists and EPO members.

International Optics Conference – Invited Talk

Timothy Slater was invited to give a talk to scientists and educators on the teaching and learning of integrated science.

Geological Society of America Meeting Workshop

Dr. Timothy Slater gave a talk on the testing and grading strategies for introductory science courses at this meeting in Seattle WA.

Templeton Foundation Grant Investigating Connection Between Astrobiology and Spirituality

Tim Slater, Chris Impey, and Richard Poss of the University of Arizona were awarded the Templeton Foundation Grant in February to investigate the relationship between astrobiology and spirituality.

National Science Teachers Association Evolving Earth workshop

One–hour workshop focusing on the integration of biology and geology utilizing a piece of curriculum from the Life in the Universe Lab Activities Manual.

Astrobiology Summer Course

Five−week summer course offered as a part of a Masters in Biology program at the University of Arizona. The Masters Program is designed for in−service teachers to obtain a Master's degree through the General Biology Program. Sponsored in part by the Howard Hughes Medical Institute. Guest lectures provided by local astronomers and biologists.

Sabbatical Astrobiology Collaboration

Professor of Biophysics arriving at the University of Arizona Life and Planets Astrobiology Center from Canada. He will be collaborating with the Conceptual Astronomy and Physics Education Research (CAPER) group to learn sound pedagogical teaching and research methods in the field of astrobiology. He will also be a lead instructor for the on−line astrobiology course co−sponsored by NAI.

Next Generation of Science Centers

Dr. Tim Slater was a panelist for a discussion on how astrobiology can be effectively communicated to the public.

Voyages Through Time (VTT) Collaboration

NAI EPO leads from University of Arizona attended a Voyages Through Time teacher training workshop to become acquainted with the curriculum. The leads will then be responsible for contributing to VTT dissemination efforts via workshops, short courses, and professional development experiences for teachers.

Natives, Africans, Asians, Latinos, & Allies (NALA) Workshop

Half day astrobiology workshop conducted at the Natives, Africans, Asians, Latinos, & Allies (NALA) Conference in South Dakota.

Journal of College Science Teaching

Article (now in press) about teaching an undergraduate science majors course in astrobiology about to appear in the Journal of College Science Teaching

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Mars GRS Curriculum Development Project

Curriculum development project focusing on the NASA "Follow the Water" theme. Curriculum related to Mars developed by a team of scientists, teachers, and curriculum developers at the Lunar and Planetary Sciences Lab in Tucson Arizona. Following development, workshops were provided for area teachers on the curricular materials.

On−Line Astrobiology for Teachers

This is an on−line course for middle and high school science teachers. The course topics cover the discovery of planetary systems around other stars, the nature of habitable zones around distant stars, the existence of life in extreme environments including the hydrothermal ecosystems of Yellowstone National Park, and the cryogenic ecosystems of Antarctica. These concepts serve as a foundation to study possible extraterrestrial ecosystems on objects like Mars and Europa. The teachers also investigate the methods used in the ongoing search for extra−terrestrial intelligence (SETI). The overarching theme of the course is to align the teaching of astrobiology concepts with the National Science Education Standards and the NASA Roadmap for Astrobiology Research. Sponsored by NASA Astrobiology Institute. Teachers develop strong pedagogical content knowledge in astrobiology.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

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Team Reports: University of California, Berkeley

University of California, Berkeley
Executive Summary
Principal Investigator: Jill Banfield

Biomars Report of Activities for the Period June 2003–June 2004.

Biomars members: Principal investigators: Jillian F. Banfield (PI). Co–investigators: Janice Bishop, Kristie Boering, Kevin Cuff, William Dietrich, David Emerson, George Luther III, Michael Manga, Eric Roden, Herb Their, Mark Kim (PARC). Coordinator: Javiera Cervini–Silva

BioMARS Education and Public Outreach (EPO) efforts . Kevin Cuff and Herb Thier (University of California at Bekeley and Lawrence Hall of Science)

Our efforts have focused on gathering information from local science educators, secondary school students, and BioMARS scientists that will ensure that resultant educational materials are unique, effective, and truly useful in both formal and informal educational settings locally and nationally. This process has included convening numerous focus group meetings at local high schools and Lawrence Hall of Science. At an early focus group meeting, which was used to gauge local student and teacher interest in proposed EPO activities, BioMARS project leader, Jill Banfield, made a presentation that provided an overview of the project's scientific aims, as well as the nature of her own project–related work. We have also worked on the development of hands–on instructional materials that provide opportunities for students to explore standards–based science concepts directly related to investigations that BioMARS PIs are engaged in (e.g. heat transfer and its relation to subsurface fluid transport), and enable students to develop a better overall understanding of the nature of science. These materials include inquiry–based activities that use the research of BioMARS' scientists to highlight and illuminate how important investigation design and detection systems are to BioMARS research in particular and, by extension, how these two elements are fundamental to all scientific research. Effectiveness of these activities has been assessed through a series of preliminary field tests with high and middle school students at local middle schools and community centers.

Spectroscopic Characterization of Martian Rocks Analogs. Janice L. Bishop (SETI Institute)

We acquired the NASA Langley ASD visible/near–infrared (VNIR) field

spectrometer and have tested it out on several rocks and minerals. Preliminary samples measured include a variety of sulfate minerals, acid mine drainage materials and some other Fe− and S−bearing samples. We are in the process of developing a library with this spectrometer for comparison of spectra collected in the field.

High quality reflectance spectra were measured at the NASA−supported Brown University Reflectance Experiment Lab (RELAB) of an acid mine drainage precipitate containing the minerals gypsum and ferrihydrite and a crystalline rock composed of the hydrated iron sulfate mineral rozenite that were collected at the Iron Mountain site in CA. These spectra were analyzed and compared with VNIR and mid−IR spectra of minerals and convolved to the spectral parameters of Martian Pathfinder, Pancam and mini−TES spectra. Emittance spectra and Mössbauer spectra were also measured of these samples by colleagues. Analyses of the Martian rocks and soil were preformed in comparison with these samples and it was shown that hydrated iron sulfate minerals such as the rozenite collected at Iron Mountain are consistent with many of the spectral and chemical properties of the global Martian dust observed currently at Gusev Crater and previously at the Pathfinder landing site. These results were reported at the Abscicon 2004 meeting (Bishop and Banfield, 2004) and a paper on this work is currently in progress.

Metal cycling, Microbes, and Organic Biomolecules. Jillian F. Banfield, William Dietrich, Michael Manga, Javiera Cervini−Silva (University of California at Berkeley), and Janice Bishop (SETI Institute). Organisms adapted to both acidic and neutral pH environments participate in iron and sulfur cycling. We have explored the role of extracellular polymers associated with neutrophilic iron−oxidizing bacteria in templating the crystallization of iron oxyhydroxide minerals with novel morphologies. Our results show that alginate−like organic threads accumulate a poorly crystalline precipitate and direct the growth of curved pseudo−single crystals of an unexpected structure, akaganeite, with very large aspect ratios (Chan et al.). These materials would not be expected in the absence of biological templates. At very low pH, we have studied the assembly of subsurface microbial communities sustained by iron oxidation. We have used culture−independent methods to investigate the abundance, distribution, and metabolism of an unexpected archaeal member that cannot be detected using typical PCR−based approaches. We have also explored the interactions between organic polymers and mineral surfaces and discovered new pathways for both depolymerization and polymerization of organic carbon compounds (Cervini−Silva and Banfield (in review); Cervini−Silva et al. (in review)).

Microbially−Mediated Sulfur and Iron Cycling . George Luther (University of Delaware), Jill Banfield (University of California at Berkeley), David Emerson (George Mason University) and Eric Roden (University of Alabama). With Dr. Banfield's group we have studied the mechanism of polythionate oxidation at low pH, which is facile with hydroxyl radicals formed on pyrite surfaces (Druschel et al, 2003). With Dr. Roden's group, we have investigated bacterial redox cycling at the oxic−anoxic interface with the neutrophilic Fe(II)−oxidizing bacterium strain TW2 and one paper is in press (Roden et al, 2004). With Dr. Emerson's group we have investigated the biotic oxidation rates of Fe(II) using

the isolate ES−1 obtained from the Fe(II) seep at Contrary Creek, VA. The biotic oxidation rate is significant under microaerobic conditions (< 20 µm O_2) and cannot be distinguished from the abiotic rate above 20 µm O_2. We have also discovered using our *in situ* solid−state voltammetric electrodes that FES_{aq} and $FeMnS_{aq}$ clusters are present in the environment (e.g., Fe(II) seeps), indicating that the sulfur cycle is intimately tied to the Fe cycle in fresh water environments. This and other Fe work were presented in Luther (2004) and Trouwborst et al (2004).

We are now designing a method with Dr. Emerson to use our electrodes to determine potential *in situ* Fe−oxidizing activities that can have broad applications in the field and in the lab. We plan further field research with the Biomars group and laboratory work exploring Fe cycling with microbial organisms with Drs. Emerson and Roden.

Neutrophilic Fe−oxidizers: Habitats, Distribution, and Physiology . David Emerson (George Mason University).

In addition to strains already in hand, we have begun new enrichment cultures from Fe mats located at the Loihi Seamount near Hawaii, the Eifuku Seamount near Guam, and the Soufriere hot spring system on the island of St. Lucia. This latter site is especially interesting because there are 50°C thermal springs there that show significant signs of microbial Fe−oxidation.

Melissa Floyd, a graduate student in the lab, has been developing a laboratory microcosm system that simulates conditions that occur in natural Fe−springs. The initial engineering challenge of maintaining suitable concentrations of Fe(II) under microaerobic conditions at neutral pH has nearly been met. This system will allow us to address questions about the physiology and molecular ecology under controlled conditions in the laboratory. Once the system is fully functional we intend to carry out model−testing experiments with the help of Dr. Roden.

Project Members : David Emerson (George Mason University), Ph.D, Co−Investigator, Research Scientist, ATCC; Robin Sutka, Ph.D, postdoctoral (through Sept. 2003), Melissa Floyd (current graduate student, George Mason Univ.), Cynthia Lydell (technician, ATCC, partial support from NAI)

Towards Isotopic Determinations on Martian Meteorites. Don DePaolo (University of California at Berkeley).

Work has begun on evaluating isotopic signatures of life and hydrological processes on Mars, with specific focus on Ca and Fe isotopes. For Ca isotopes there is a need to better constrain the equilibrium isotopic partitioning associated with inorganic processes to better assess evidence for organic fractionation. Two experiments are in progress. In one, calcite will be grown and equilibrated with dissolved carbonate in the laboratory at temperatures between about 10°C and 70°C (C and O isotopes will be measured as well to assess kinetic effects). The materials for this experiment are being assembled and the experiment design worked out. The second approach will be to use a natural terrestrial system where dissolved carbonate and solid calcite are expected to be in equilibrium. The system chosen is pore water in a deep−sea

sediment made up mostly of carbonate ooze. Samples have been obtained and analyses are in progress. A substantial effort is also underway to improve the precision of measurement of Δ^{44} Ca using a new multi−collector thermal infrared multispectral scanner (TIMS) instrument. We are collaborating with Will Dietrich and Michael Manga (below) to evaluate the origin of Martian channels by studying box canyons on the Snake River Plain. Samples have been collected and sample preparation has begun to establish the age of one canyon using cosmogenic He. In the coming year, the work already started will be continued, and in addition we will be working on Ca and Fe isotopes in volcanic hot and cold springs to characterize these environments, and making measurements on Martian meteorites.

Interaction between the geodynamic and hydrologic processes on Mars. Michael Manga. (University of California at Berkeley). We have developed experimental and numerical models for the evolution of mantle convection on Mars (Wenzel et al., Geophysical Research Letters, 2004). These models predict the spatial and temporal evolution of heat flow, which in turn are the critical boundary conditions for hydrothermal processes in the crust. We have also started to develop numerical models to study the hydrothermal processes that occur when magma is intruded into the cryosphere. We have used surface observations to better constrain the distribution and amount of water present in the Martian subsurface. We have shown that recent floods at Cerberus Fossae can be explained by discharge from aquifers (Manga, Geophysical Research Letters, 2004).We have also studied experimentally the mobility of granular mass flows in order to reevaluate the potential role of water in mass wasting on Mars. We find that unusually large run−out distances of granular flows can be explained only by the presence of interstitial fluids such as liquid water. Project members : Yoshiko Ogawa (postdoc: hydrothermal processes in the Martian crust), Bruno Cagnoli (postdoc: mobility of granular flow and the evidence for water on Mars), Mark Wenzel (graduate student: mantle convection on Mars), Veronika Soukhovitskaya (undergraduate: mobility of granular flow and the evidence for water on Mars), and collaborations with Curt Oldenburg at the Lawrence Berkeley National Laboratory (LBNL) on the numerical modeling.

Early Mars Atmosphere . For the atmospheric photochemistry experimental work exploring how the formation of aerosol in the atmosphere of early Mars may have had a dramatic influence on climate and habitability (Co−PI Boering), a more sensitive quadrupole mass spectrometer was purchased and incorporated into the existing experimental apparatus for studying the kinetics of formation and optical properties of atmospheric aerosols in the laboratory. Recent experimental results from this year were presented by graduate student Mate Adamkovics (supported by NAI funds) in a talk at NASA's Third Astrobiology Conference in April 2004 in which we found that particle formation by ultraviolet illumination can occur at considerably lower CH_4 −to− CO_2 ratios than predicted by photochemical models, a result that may mean that organic aerosols may have had a larger influence on the climate of early Earth and early Mars than previously estimated.

Project members : In addition to the continuing experimental work at UC Berkeley, collaborations are currently underway with R. Zare (Stanford) and G. Cooper (NASA Ames) to study the polycyclic aromatic hydrocarbon (PAH)

composition and the 13 C isotopic composition of the particles formed, respectively.

PUBLICATIONS

PEER−REVIEWED

Bishop, J.; Banfield, J.F. Spectroscopic Analysis of Fe− and S−bearing Materials for Remote Sensing of Biomarkers on Mars (in preparation).

C. S. Chan, G. De Stasio et al., “Microbial Polysaccharides Template Assembly of Nanocrystal Fibres,” *Science* , ***303*** , 1656, (2004).

Cervini−Silva J and Banfield, J.F. Coupled redox and dissolution reactions at surfaces of phosphate minerals can impact carbon dioxide and humic acid production in soils. *Environ. Sci. Technol.* (in review)

Cervini−Silva, J; Fowle, D.A.; Banfield, J.F. Biogenic dissolution of soil phosphate minerals. *Am. J. Sci.* Special Issue on Biogeochemistry (in review)

Druschel, G., D. Emerson, B. Glazer, C. Kraiya, R. Sutka and G. W. Luther, III. 2004. Environmental limits of the circumneutral iron−oxidizing bacterial isolate ES−1: Field, culture, and kinetic results from voltammetric analyses. *Geochimica Cosmochimica Acta* Vol. 68 (11S), p. A387.

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Abstracts

Bishop, J.L. & Banfield J.F. (2004). Spectroscopic Analysis of Fe− and S−bearing Materials for Remote Sensing of Biomarkers on Mars. *Astrobiology Conference* 2004 (p.86).

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Druschel, G., D. Emerson, B. Glazer, C. Kraiya, R. Sutka and G. W. Luther, III. Environmental limits of the circumneutral iron−oxidizing bacterial isolate ES−1: Field, culture, and kinetic results from voltammetric analyses, presented at the 2004 *Goldschmidt Conference* , Copenhagen, Denmark, June 9, 2004.

Druschel, G.K., D. Emerson, B. Glazer, C Kraiya, R. Sutka, and G.W. Luther. Defining the environmental limits of the circumneutral iron−oxidizing bacterial isolate ES−1: Field, culture, and kinetic results from voltammetric analyses. *Goldschmidt Conference* , 2004.

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Manga, M., and A. Sinton, Wax models of Europan tectonics, Workshop on Europa's icy shell: Past, present, and future, Lunar Planetary Institute [IS THIS CORRECT?] (LPI) contribution 1195, pages 46−47.

Trouwborst, R.E., G. Koch, G. Druschel, L. Shanks, G.W. Luther, III and B. Pierson. Hot spring microbial mats: A model for Precambrian Banded Iron Formations, presented at the NASA Astrobiology Science Conference, NASA Ames Research Center in Mountain View CA, March 30, 2004.

Sessions

Javiera Cervini−Silva:

Co−chair (with Jon Chorover, University of Arizona). Symposium on Molecular Biogeochemical Processes. American Geophysical Union. San Francisco, December 13−17, 2003.

Co−chair (with Hailiang Dong, Miami University). Symposium on Microbial Impacts on Clay Transformation and Reactivity. The Annual Meeting of The Clay Minerals Society. Richland, June 19−24, 2004.

Co−chair (with Stephan Kraemer (Eidgenössische Technische Hochschule Zürich (ETH−Zürich)) and James Fredrickson (William R. Wiley Environmental

Molecular Sciences Laboratory (EMSL)−Pacific Northwest National Laboratory (PPNL)) : Symposium on Interfacial Biogeochemical Processes. Goldschmidt Conference, Moscow, ID. June 2005.

EDITORIAL ACTIVITIES

Journal special issues

David Emerson has edited a special issue of Geomicrobiology Journal on Neutrophilic Fe−oxidizing Bacteria. This issue will appear in September 2004, and contains 5 articles that cover a wide range of topics related to neutrophilic Fe oxidizers.

Javiera Cervini−Silva is co−editing a special issue of Clays and Clay Minerals on Microbial Impacts on Clay Transformation and Reactivity. The issue will appear in February 2005 and contains 14 articles.

EPO: University of California, Berkeley

These are the Education and Public Outreach activities for the University of California, Berkeley.

BioMARS E/PO Efforts

Enhancing Public Understanding of Science By Highlighting BioMARS Scientific Investigations – BioMARS E/PO Efforts During 2004 Kevin Cuff and Herb Thier

INTRODUCTION Recent descriptions of activities of rovers on the surface of Mars have generated a high degree of public interest in the collection and analysis of data from the planet's surface. Our primary intention in designing and executing BioMARS E/PO efforts is to use this current interest to introduce and reinforce the public's understanding of science as an endeavor. This is especially important during a time period when public misunderstandings are widespread where the nature of science is concerned, despite science education reform efforts over the past decade (National Science Board, 2004).

Fundamental to effectively enhancing public understanding of the nature of science is the creation of mechanisms that foster the development of working understandings of the concepts of specification of the system(s) of interest, collection and analysis of evidence both directly and at a distance in those systems, and the processing of all data collected to identify what has and has not been learned to help inform future investigations. With this in mind, we have initiated the development of educational materials that use the research of BioMARS scientists to highlight and illuminate how science works. In particular, these materials have been designed to illustrate how important investigation design and detection systems are to BioMARS research in particular, and by extension how these two elements are fundamental to all scientific research.

BioMARS E/PO EFFORTS DURING 2004 Throughout the past project year BioMARS E/PO efforts have focused on: I) Gathering information from local science educators, secondary school students, and BioMARS scientists that will ensure that resultant educational materials are unique, effective, and truly useful in both formal and informal educational settings locally and nationally; and II) The development of inquiry–based instructional materials that enable students to develop a better overall understanding of the nature of science through hands–on explorations of standards–based science concepts directly relate to investigations that BioMARS PIs are engaged in (e.g. heat transfer

and its relation to subsurface fluid transport).

I) Information Gathering One key component of our information gathering process has been our participation in a series of informative meetings with secondary school science and mathematics teachers and coordinators, as well as middle and high school students in the Berkeley and Oakland Unified School Districts. The meetings consisted of presentations of our overall vision and rationale regarding intended BioMARS E/PO activities, followed by discussions of the merits and feasibilities of these activities. On the whole, these meetings provided valuable information that enabled us to establish a set of highly realistic and attainable goals that will guide our future efforts. Another important component in the information gathering process has included convening numerous focus group meetings at local high schools and UC Berkeley's Lawrence Hall of Science. At an early focus group meeting, which included the participation of middle and high school teachers, science coordinators, and students, as well as several experienced informal science educators, BioMARS project leader, Jill Banfield made a presentation that provided an overview of the project's scientific aims, as well as the nature of her own project−related work. This presentation served as the focal point for a discussion that centered on responses to, among others, the following focus questions:

? What aspect of the Mars−related research that has been described today are you personally interested in? What level of participation in such research would you be interested in?

? What is it about this research that you feel makes it suitable for incorporation in formal (classrooms) and/or informal (after school programs, including internship opportunities) educational settings?

? If you agree that developing understandings of the concepts of design and detection play a major role in building your or your students understanding of science as a process, how would you suggest we incorporate this into educational programs (both formal and informal)? INSTRUCTIONAL MATERIALS DEVELOPMENT A set of six inquiry−based activities have been developed, which provide opportunities for students to develop a better overall understanding of the nature of science. The activities comprise a series of hands−on explorations of standards−based science concepts that directly relate to research being conducted by BioMARS scientific PIs, such as heat transfer and its relation to subsurface fluid transport. In addition, the activities introduce and expose students to the processes associated with investigation design and detection systems. For example, in one activity students design a system that uses the energy associated with a rolling marble to move a stationary wooden block a certain distance. Then they use a set of common materials, including halved sections of PVC pipes, to test their designs. Later they apply their newly acquired understandings to meet the challenge of modifying their systems to accomplish slightly more difficult tasks. To gain a sense of how effective recently developed activities are in terms of student comprehension of key concepts, a series of preliminary field−tests were conducted with middle and high school students at local middle schools and community centers. These tests included the use of an evaluation instrument

designed to assess students' beliefs regarding how science is conducted. Preliminary analysis of data collected during these tests indicates trends toward changes in students' understanding of the nature of science as a result of their participation in activities developed thus far.

FUTURE E/PO EFFORTS In the coming year, we will continue developing and field−testing inquiry−based activities that use the research of BioMARS scientists to illustrate the importance of investigation design and detection systems to BioMARS research in particular and, by extension, how these two elements are fundamental to all scientific research. These activities eventually will be included in a set of materials we intend to create, which will comprise a unique educational resource that will positively impact how science is taught and learned in both formal and informal settings locally and nationally.

To help ensure that our efforts are truly useful and have broad impact, we intend to continue gathering information from educators, students, and scientists in the coming year. We will continue convening focus group meetings similar to those that occurred in 2004, which will include the participation of other BioMARS scientists, locally−based students, teachers, and science educators. These meetings will enable us to obtain extremely valuable feedback regarding our materials, as well as those being developed by other NAI−sponsored E/PO groups. In addition, we plan to engage in discussions with locally and nationally−based scientists and science educators that center on how we can best achieve our primary educational goal of developing materials that foster an improvement in public understanding of how science works.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

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Team Reports: University of California, Los Angeles

University of California, Los Angeles
Executive Summary
Principal Investigator: Edward Young

The UCLA astrobiology research program progressed on four fronts in the past nine months. These four fronts, or themes, are: 1) extrasolar planetary systems and the origins of organic molecules; 2) habitability of planets and their satellites; 3) Earth's early environment and life; and 4) evolution of biological complexity. Research completed as part of our first year of participation in the NASA Astrobiology Institute's third Cooperative Agreement has provided some answers pertaining to key questions in astrobiology, including: Is there evidence for life−sustaining water associated with rocky bodies in extrasolar planetary systems? Are terrestrial planets likely to be stable in the wide variety of planetary configurations observed around other stars? What controls the potential habitability of Jupiter's Galilean moons? What was the source of the bolide that collided with Earth in the late Eocene? When did life first appear on Earth? How can transition metal isotopes be used as tracers of biological processes? Can the biogenicity of ancient microfossils be established conclusively or not? How important was horizontal gene transfer for facilitating the evolution of early life on Earth? The many projects reported on in this annual report can be grouped according to the four themes described above. Some of the results of these studies are summarized below.

Extrasolar planetary systems: Several advances in our understanding of extrasolar planetary systems were made this past year. UCLA astronomers have placed limits on the mass of icy and rocky bodies resembling our own Kuiper belt objects (KBOs) that might exist around other stars. On a similar line of inquiry, UCLA astronomers have proposed a new method for detecting oceans on planets around other stars. The method relies on the fact that so−called main−sequence stars like our own become more luminous with time. This increase in luminosity can lead to evaporation of oceans on orbiting planets resembling Earth. The gaseous water released by this evaporation would leave a spectroscopic signal detectable as the water passes in front of the star. Our astronomers have also made progress in trying to understand the conditions that lead to the formation of the only known examples of extrasolar planets with masses comparable to Earth. The problem is intriguing because these Earth−mass planets orbit around a pulsar (PSR1257+12). The space around pulsars would not be the first places to search for planets as they are the remains of a giant explosion that destroyed a massive star. It appears that in this case the explosion may have also destroyed a companion star the

remains of which were left to form a protoplanetary disk around the remaining core. Understanding the ways that planets form in these rather bizarre circumstances would help us to understand whether or not we should be counting circumpulsar environs as potential sites for planets harboring life. Another potential environment for terrestrial−like planet formation might be within so−called second generation planetary systems formed after the merger of two stars. Our team has been granted observing time on the Spitzer Space Telescope to search for evidence for such oddball planetary systems.

Theoretical studies of the stability of a small Earth−like planet in the presence of a giant planet like those known to orbit other stars have been carried out this year. Results provide a "map" of orbital configurations that are stable with respect to the smaller planet.

The origin of organics: UCLA team members ordered parts for the UCLA First Light Infrared Test Experiment Camera (FLITECAM) instrument to carry out astrobiological research on the Stratospheric Observatory for Infrared Astronomy (SOFIA) (Figure 1). The fruits of this work should occur in 2006 and will allow detection in space of dust composed of organic compounds.

Habitability of planets and their satellites: Our team has moved forward with studies of the features of the icy moons of Jupiter that make these solar system bodies potential homes for primitive life. Focus has been placed on heat transport in the Galilean moons as this will control the state of water on these relatively wet bodies. Our most recent work on Europa's icy shell shows that tidal dissipation can cause melting of water ice only near the base of the ice layer, meaning that tides imparted by Jupiter are not the cause of some of the physiographic features that result from periodic melting of water ice seen on the surface of Europa.

A key feature of habitability is the presence of volatiles on a planet. Our team published this year results of a study showing that volatiles, comprising the atmospheres and even oceans, can be added to a planet by large impacts of volatile−bearing asteroids or comets. The study shows that retention of volatiles carried by the impacting body depends on the planet's gravity (escape velocity) and the speed and trajectory of the impactor. The investigators conclude that, contrary to the conclusions of some earlier studies, Earth could well have acquired its inventory of volatiles by such impacts.

Climate change on Mars is controlled by the tilt of the planet's axis of rotation, referred to as obliquity. UCLA scientists developed a computer model of the Martian obliquity history. Results obtained this past year indicate that deformation of the planet may play a key role in determining obliquity and therefore climactic change.

Earth's early environment and life: A key to understanding the history of life on Earth is developing reliable methods for identifying fossil microbes. Our team has begun construction of a new Raman imaging facility that will be used to help to resolve outstanding questions regarding the biogenicity of very old putative fossil microbes.

The partitioning of the stable isotopes of light elements can be used in a variety of ways to investigate links between the biosphere and lithosphere. In some cases isotope partitioning might be useful as a clue to the presence of biological activity (a biomarker). In other cases an isotopic signal can be used as a proxy for climate change that can be correlated with evolutionary changes. During this past year several new laboratories at UCLA have contributed to improved understanding of the variability of isotope ratios with application to the astrobiological sciences. Our team has shown for the first time that the process of transferring an electron can lead to partitioning of transition metal isotopes in ways that resemble the effects seen in biological systems. These findings raise the possibility that it is the electron transfer itself that results in a selectivity of one isotope over another when organisms utilize transition metals. Identification of the mechanism of biological isotope selectivity enhances the prospects for using such signals as biomarkers. In another study, we have completed in these past few months thousands of carbon and oxygen isotope analyses of a complete section of Cambrian limestone from Siberia that marks a pronounced excursion in Earth's carbon isotopic record closely related to a mass extinction event. This new isotopic record can be correlated with biostratigraphic zones to help resolve questions surrounding the causes of these enigmatic isotopic features in Earth history that appear to be associated with changes in biological diversity.

The "great oxidation event" during which free oxygen became plentiful in Earth's atmosphere is marked by a drastic reduction in the presence of mass independent fractionation (MIF) effects among the isotopes of sulfur. Our team has been examining the cause of the MIF effects in sulfur to better understand their links with the presence or absence of O_2 in a planetary atmosphere. Toward this end, SO_2 photodissociation experiments were performed this year demonstrating that the effects of broadband ultraviolet light are different from those effects obtained for narrow bands. These findings are particularly relevant since photolysis in atmospheres will result from broadband rather than narrowband exposure.

Impacts of comets and/or asteroids almost certainly play a fundamental role in the origin, evolution, and extinction of life. The influence of impacts on evolving life on Earth was most acute in the early history of our planet. Against this backdrop, members of the UCLA team carried out geochemical studies of sediments from several known impact and extinction horizons ranging in age from late Pliocene (2.4 million year old) through early Archean (3.5 billion years old). The sediments examined include those representing the greatest mass extinction events in Earth history. Among the most recent findings are that a late Eocene impactor came from the Main Asteroid belt, suggesting that an episode of numerous asteroid collisions in the asteroid belt ultimately lead to the Eocene impacts. The implications are clear; events in the asteroid belt may have had profound influence on the history of life on our planet.

Rocks from Akilia Island , Greenland , have been reported to contain evidence for extraordinarily ancient life on Earth (> 3.8 billion years old). The age and origin of these rocks have been the subject of much debate, however. Studies just completed by UCLA team members support a >3.8 billion year old age and a chemical sedimentary origin for the controversial Fe−rich quartz−pyroxene

rocks that contain the evidence for life. As an outgrowth of this controversy, our team members engaged in Akilia geology led an NAI–sponsored field trip to examine evidence for >3.8 Ga life on Earth. Seventeen field–trip participants traveled to west Greenland in June 2004 to visit key early life localities (Figure 2) and discuss their origin in the field and in sessions held in the capitol city of Nuuk .

Evolution of biological complexity: Genomics is providing a new window on the ways in which life evolves to greater levels of complexity. Members of the UCLA team made progress this year on the ways that horizontal gene transfer, by which organisms living in similar environments preferentially exchange genes, affected the progress of evolution on Earth. Their findings published this year indicate that prokaryotic genome innovation was accelerated by horizontal gene transfer by a factor of 10,000. These same workers reported this year their development of a new phylogenetic analysis tool that uses the presence or absence of genes to determine phylogenetic trees. The new method of conditioned reconstruction mitigates the polluting effects of horizontal gene transfer. In a separate genomic study, our team explored the origins of the process of microbial sulfate reduction and its potential as an important process on early Earth. Results show that sulfate reduction may be far more common among Archaea than previously assumed, making it more likely that microbial sulfate reduction was an important component of ancient Earth's geochemical cycles.

UCLA–sponsored astrobiologists have progressed on several fronts pertaining to ancient animal life this year. Microbial studies on early Cambrian fossils confirm that shifts in body symmetry occurred several times in animal evolution. Sense organs are a fundamental feature of animal life. Studies of the evolution of the developmental genetics of sensory and neural systems in basal animals continued this year. Our group reported work on the eye/sense organ developmental gene *sine oculis* from sponges, jellyfish, ctenophores and basal bilaterians, including flatworms and mollusks. The work demonstrates the presence and, in the case of jellyfish, expression of these sense organ related genes, providing critical insight into the evolution of sense organs. We continue to make progress in this area with recovery of other sense organ genes such as *optix* and *eyes* absent in basal animals. We have also been successful in the first stages of recovery of genes that we infer to be important in the evolution of the skeletons of Bilateria. This investigation of the developmental underpinnings of invertebrate skeletogenesis will ultimately allow us to integrate the fossil record of evolution.

Figure 1: A nearly−monochromated image of the planetary nebula NGC 7027. The image shows bright emission at a wavelength of 3.3 microns from polycyclic aromatic hydrocarbons (PAHs). The infrared picture was obtained using FLITECAM, the first−light near−infrared test camera for NASA's SOFIA , during ground−based trials at the University of California 's Lick Observatory. The instrument also has a new spectroscopic mode that allows the emission feature to be resolved. When SOFIA operations begin, the UCLA team will use FLITECAM to study the development and evolution of these carbon chain molecules in stellar environments.

Figure 2: Rocks showing possible evidence for early life on Earth 3.8 billion years ago, Akilia Island, west Greenland. The locality was visited during an NAI–sponsored field trip in June, 2004, led by UCLA team member Craig Manning.

Project Report: Habitability of Jupiter's Galilean Moons

Project Investigator:	***Gerald Schubert***

Project Progress

The following progress has been made in connection with establishing the viability of habitable environments in the solar system with emphasis on geodynamics:

1: ***Coupled orbital–rotational–viscoelastic dynamics of the Galilean satellites***
We have developed and tested a code to solve the complete orbital–rotational–viscoelastic dynamics of a deformable body. We have begun by investigating the behavior of rigid bodies, finding that this "well studied" problem was not well understood, and that existing studies were inconsistent with each other. A manuscript has been submitted to *Icarus* . The code for deformable bodies is completed, and has been cross–checked with a code based on a different approach.

2: ***Heat transport in tidally heated bodies***
The generation of heat by tidal dissipation is calculated from the solution of the equations of motion for a layered viscoelastic body, and this is coupled to parameterized heat transport equations. Work on Europa's icy shell has revealed that tidal dissipation cannot lead to melting near the surface of the shell, only near its base. These results were presented at "Workshop on Europa's Icy Shell" and at the Spring 2004 American Geophysical Union (AGU) conference.

3: ***Detection of tidal flexure on Europa by inSAR***
A feasibility study was carried out to determine if an orbiting spacecraft could detect the tidal flexing of fractures on Europa using ***inSAR*** . (Manuscript in Press)

4: ***Martian Obliquity History***
The evolution of the spin axis of Mars is controlled by its shape and by the history of its orbit around the Sun. We have developed a code to model the evolution of a deformable Mars and follow its obliquity through time. Results so far indicate that, for reasonable viscosities, deformation may be an important controlling factor in the history of Mars' obliquity.

5: ***Participation in the Jupiter Icy Moons Orbiter (JIMO) Science Definition Team***

William Moore served on the Science Definition Team for the Jupiter Icy Moons Orbiter, NASA's next mission to the moons of Jupiter.

Highlights

- Tidal heating does not lead to melting in icy shells, except near the bottom, and is therefore not a likely explanation for cryovolcanic features on the icy moons of Jupiter.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.2:*** Outer Solar System exploration

Project Report: Extraterrestrial Impact History on Earth

Project Investigator:	***Frank Kyte***

Project Progress

Field studies in the Barberton greenstone belt, South Africa , were conducted in June and July 2003 by Prof. Donald R. Lowe, Stanford University , and Prof. Gary Byerly, Louisiana State University , on 1) the Archean impact record, especially very large impacts; 2) Archean komatiitic volcanism; and 3) surface processes on the Archean Earth. In addition, Lowe and Byerly led a field conference for 29 invited international scientists June 23– July 2, 2003 , in the Barberton belt. This conference was sponsored by the NAI and partially supported by the UCLA NAI program. Among the key issues addressed during the conference were the relative roles of biological and abiotic (hydrothermal) processes in forming carbonaceous matter and siliceous sediments in the Barberton and similar early greenstone–belt sequences. Byerly has concentrated on: 1) refinement of field mapping, stratigraphy, and geochronology of the Barberton greenstone belt; and 2) examination of the Barberton ironstone pods, including field relations, mineralogy, and geochemistry. We have isolated zircons from several critical horizons, one a possible new impact layer, and one that will provide important constraints on the rates of deposition of black cherts. These samples should be dated this year using the Stanford Sensitive, High–Resolution Ion Microprobe (SHRIMP) facility. During the academic year, progress was made in writing and publishing the results of our environmental studies, and Mrs. Alexandra Krull Davatzes, a Stanford PhD student, began writing chapters in her thesis dealing with Archean impacts and impact processes. She has submitted one paper to Geology dealing with the condensation mechanics of rock vapor plumes formed by large meteorite impacts. Louisiana State University (LSU) PhD student Keena Kareem, is nearing completion of her work on these komatiites – several highlights are listed below. Two new LSU students are beginning work, including one that will focus on near–surface Archean alteration, especially carbonation of komatiites.

Frank T. Kyte, UCLA, has carried out analytical work on the geochemistry of sediments from several known impact and extinction horizons ranging in age from late Pliocene (2.4 Ma) through early Archean (3.5 Ga). This has included work on sediments from mass extinction events at the Permian–Triassic, Triassic–Jurassic, and Cretaceous–Tertiary boundaries. An important project

concluding this year has been characterization of impact deposits from one of the late Eocene impact events. Previous work on the late Eocene provided strong evidence of increased flux of interplanetary dust during the late Eocene, which might be caused by a comet shower from the Oort Cloud at the outer fringes of the solar system. Our latest work shows that the Cr−isotopic signature from a late Eocene impactor is consistent with a source from a main−belt asteroid compositionally similar to ordinary chondrites. We suggest that the increased dust flux might be related to numerous asteroid collisions following a major breakup event in the asteroid belt.

Highlights

- Studies of the thickest Archean spherule bed in the Barberton belt by Alexandra Krull Davatzes, PhD student at Stanford, shows that the impactor was about 40−50 km in diameter and the resulting rock vapor cloud evolved as it condensed, with more refractory, bolide−derived components tending to dominate the earliest condensates and more basaltic, target−derived components tending to dominate later condensates.
- Studies of the chromium isotope composition of iridium−rich impact spherules indicate that one impact in the late Eocene was likely by an asteroid disturbed from the main belt. This is generally inconsistent with earlier hypotheses that late Eocene impacts were caused by a comet shower.
- Ironstone pods, previously interpreted as sites of Archean seafloor hydrothermal vents, were reinterpreted by Lowe and Byerly as Modern subaerial vents. This work was discussed on the Nature website and will likely be controversial for some time. It has implications for the nature of Archean sedimentation, environments and early life.
- Keena Kareem's work on komatiites from the 3.3 Ga Weltevreden Formation shows them to be remarkably well preserved, with fresh olivine and melt inclusions. They also appear to have erupted at unusually high temperatures, nearly 1700C, and moderately high oxygen fugacities, above QFM. They are nearly chondritic in many respects, but oxygen and lithium isotopes suggest complexities that may provide interesting constraints on Archean tectonism and mantle recycling.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

Project Report: Extrasolar Planetary Systems and the Potential for Terrestrial Planets

Project Investigator:	***Brad Hansen***

Project Progress

Pulsar planet formation:

The planets orbiting the pulsar PSR1257+12 are the only known examples of extrasolar terrestrial mass planets. NAI–supported graduate student Thayne Currie has been modeling the evolution of protoplanetary disks in the circumpulsar environment. He has developed a numerical disk evolution code and is examining the evolution in the context of modern theories of protoplanetary disk evolution. Future work will describe the next stage of evolution, using the final gas disk profile to begin a simulation of the assembly of the final planets from smaller mass planetesimal bodies.

Comet clouds in Binary systems:

The interaction of planetesimals with giant planets leads to the ejection of smaller bodies from their original orbits and some are deposited into the Oort cloud, to return as comets. The size and extent of such a comet cloud depends on the strength of external perturbing forces that replace the effect of the giant planet perturbations. The presence of a close stellar companion results in much stronger perturbations than in the case of our solar system (in which Galactic tides are thought to play the dominant role). As such, binary systems may have much more compact comet clouds. We have begun a series of numerical simulations to quantitatively investigate this process. An observational consequence is the possibility of a greater number of comet–star impacts, which may explain anomalous atmospheric abundances in some stars, such as the DZ white dwarf stars. This project, in addition to other planetesimal evolution calculations, is being discussed with Steinn Sigurdsson, at fellow NAI institution Penn State .

Hot Jupiters

Some extrasolar Jovian planets are located very close to their parent stars and the resulting irradiation has a significant effect on their thermal balance and hydrostatic structure. At present, models for these objects are limited by the fact that most stellar/planetary models are one dimensional in nature, contrary

to the inherently two– or three–dimensional structure of these objects. I am collaborating with Sara Seager and James Cho (at fellow NAI institution Carnegie Institute of Washington (CIW)) to develop a realistic model for such objects. I am adapting my stellar evolution code to make full use of the two–dimensional information from Cho's surface flow calculations as outer boundary inputs. We expect to have the first fully operational applications of this code running by the end of the summer.

Spitzer Observations

In June I was awarded time on the Spitzer Infrared Space Telescope to perform a search for `Second generation planetary systems' around a sample of evolved stars. Our sample is drawn from a list of stars that are suspected to be the remnants of stellar mergers (two evolved stars spiraling together because of the radiation of gravitational waves). Such mergers are likely to be messy, leaving behind a remnant disk rich in heavy elements (since the stars are evolved stars composed primarily of Carbon and Oxygen). We intend to search for infrared radiation that results when such a disk is illuminated by the central star and reradiates that energy at lower temperatures. If such infrared excesses are indeed observed around these stars, it would indicate an entirely new environment for planet formation –– a newly formed disk composed of the ashes of old, burnt–out stars.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Spitzer	Research or Analysis Techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Astronomical viewing time granted to project researcher.

Cross Team Collaborations

Sara Seager and James Cho, Carnegie Institution of Washington's DTM; Steinn Sigurdsson, Penn State.

Project Report: Evolution of sensory and neural systems in basal animals

Project Investigator:	***David Jacobs***

Project Progress

We are making substantial progress in our objective to understand the assembly of animal body plans.

We have focused on the evolution of the developmental genetics of sensory and neural systems in basal animals. Our approach examining developmental genes in basal taxa has been effective. We recently published a paper on the eye/sense organ developmental gene *sine oculis* from sponges, jellyfish, ctenophores and basal bilaterians such as flatworms and mollusks. These data demonstrate the presence and, in the case of jellyfish, expression of these sense organ related genes, providing critical insight into the evolution of sense organs–––a fundamental aspect of the animal condition. The presence of these genes in sponges is at once intriguing and illuminating and will ultimately require new models of the evolution of genes and development at the base of the animal tree. We continue to make progress in this area with recovery of other sense organ genes such as *optix* and *eyes* absent in basal animals. We have also been successful in the first stages of recovery of genes that we infer to be important in the evolution of the skeletons of Bilateria. This investigation of the developmental underpinnings of invertebrate skeletogenesis will ultimately allow us to integrate the fossil record of evolution

Highlights

- These data demonstrate the presence and, in the case of jellyfish, expression of these sense organ related genes, providing critical insight into the evolution of sense organs–––a fundamental aspect of the animal condition.
- The presence of these genes in sponges is at once intriguing and illuminating and will ultimately require new models of the evolution of genes and development at the base of the animal tree.

Roadmap Objectives

- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.2:*** Foundations of complex life

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

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Project Report: Evolution of eukaryotes and the Cambrian Explosion

Project Investigator:	***Susannah Porter***

Project Progress

Collaborator Susannah Porter is involved in two projects sponsored by the UCLA lead team: one that focuses on the early fossil record of animals, and one that focuses on the paleoecology & taxonomy of the ~750 Ma Chuar and Uinta Mountain Groups. Porter has nearly completed a manuscript related to the first project, and will present the work at this coming year's Geological Society of America (see highlights below). Field studies in the Uinta Mountain Group were conducted both last summer (2003) and this past June, the latter with an undergraduate research student working in her lab. Samples from last season's fieldwork have been processed and light– and scanning electron microscopy of fossils is underway. Porter also submitted a review paper on Proterozoic eukaryotes and presented two invited talks on the same subject.

Highlights

- Microstructural studies on early Cambrian fossils confirm that the radially symmetric chancelloriids are closely related to the bilaterially symmetric halkieriids, supporting accumulating evidence that shifts in body symmetry occurred several times in animal evolution (e.g., Finnerty et al., 2004, *Science* , 304: 1335). Symmetry in animal body plans is thus not as conserved as previously thought.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life

Project Report: Electrochemical isotope effects with applications to stable isotope fractionation in transition metals

Project Investigators: ***Abby Kavner , Edward Young***

Project Progress

Our project to identify the underlying mechanisms of stable isotope fractionation in biological systems is moving forward. We have recently collected evidence that there is a charge−transfer contribution to kinetic stable isotope fractionation that should have significance for the biological fractionation of ^{56}Fe, ^{57} Fe, and ^{54} Fe and other transition metal isotopes. We performed a series of electroplating experiments that demonstrated a voltage−dependent isotope fractionation during reduction of Fe^{+2} to Fe metal, with magnitudes covering the range observed in natural biotic and abiotic systems. We have developed a theory, based on the fundamental theory for electron transfer developed previously by Marcus, that accounts for the observed voltage dependent fractionation. The theory is general and makes a broad−based series of predictions concerning stable isotope fractionation in a wide variety of charge−transfer reactions. Our results demonstrate a specific mechanistic origin of stable isotope fractionations in Fe during redox phenomena.

Armed with this new tool, we are now in position to use observed stable isotope fractionations as markers for the specific driving forces in charge−transfer reactions, including biologically mediated electron exchange reactions. In particular, the theory makes testable predictions about the isotope fractionation to be observed based on the ligands that surround a given transition metal during the electron−transfer processes. We are presently expanding our experiments to test these predictions.

Highlights

- We have established the first combined electrochemical/geochemical techniques to examine stable isotope fractionations due to charge−transfer processes, and have used this technique to establish voltage−dependent fractionation for Fe (manuscript in preparation).
- We have developed a theory that predicts stable isotope fractionation as a function of electron−transfer driving force. This theory is an extension of the Marcus theory to isotope specific reaction rates

(manuscript in preparation).

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Project Report: Early Earth's Atmosphere, Oceans and Life

Project Investigator:	***J. William Schopf***

Project Progress

Establishment of the biogenicity of ancient putative microscopic fossils, the challenging problem of unambiguously distinguishing true biologic remnants from nonbiologic look–alikes, is crucial both to understanding the early history of life on Earth and for detection and characterization of past life on other planets. To address this problem effectively, there is need for means to demonstrate in such objects a one–to–one correlation at a micron scale of distinctive "biological morphology" with assured "biological chemistry." By showing that individual putative "microfossils" are composed of carbonaceous matter, as would be expected of organically preserved microorganisms, such means would provide evidence supportive of a biogenic interpretation –– an interpretation that would seem all but irrefutable were the data to establish that the carbonaceous matter was unquestionably of biological origin. Our studies, carried out over the past year using laser–Raman imagery, provide a way to solve this problem. This work has already not only yielded new insight into the chemistry of the kerogen comprising individual ancient organic–walled microscopic fossils, but for the first time has provided means to "chemically map" the cellular structure of such fossils *in situ* , both in two and in three dimensions. To extend this work, a new state–of–the art Raman facility is being installed in my laboratories (supported by ~$500K of UCLA's "matching funds" for this NASA Astrobiology grant). Additionally, by use of confocal microscopy, we have just recently developed novel means to produce three–dimensional *optical* images of individual rock–embedded microscopic fossils (a problem heretofore widely assumed insoluble).

In sum, we are now prepared to produce optical and chemical images –– in both two and in three dimensions –– of individual rock–embedded ancient microorganisms. For the first time, distinctive "biological morphology" can be directly correlated with assured "biological chemistry at a micron scale in minute individual fossilized microorganisms."

Highlights

- New means have been devised to produce optical and chemical images –– in both two and in three dimensions –– of individual rock–embedded

ancient microscopic organisms.

Project Report: Dating Earliest Life from Akilia Island, Greenland

Project Investigators:	***T. Mark Harrison , Craig Manning***

Project Progress

New mapping, geochronology, and geochemistry of supracrustal rocks on Akilia Island, Greenland, support a >3800 Ma age and chemical sedimentary origin for controversial Fe−rich quartz−pyroxene rocks that have been reported to contain evidence for early life. Supracrustal lithologies comprise laterally continuous, mappable units of mafic amphibolite, ultramafics, and two Fe−rich quartz−pyroxene units. Map relations support the interpretation that quartz−pyroxene rocks were part of a predeformational volcano−sedimentary stratigraphy, but are inconsistent with alternative hypothesis of an origin as metasomatic veins. U−Pb ion−microprobe measurements of zircons indicate a minimum formation age of 3600 Ma for the quartz−pyroxene rock and a possible metasedimentary block in amphibolite gneisses. A >3800 Ma depositional age of Akilia supracrustals has previously been inferred based on controversial crosscutting relations involving orthogneiss in the high−strain portion of the supracrustals. We identified two new crosscutting metatonalites. Ion−microprobe measurements of zircon cores yielded 3746±11 Ma and 3835±31 Ma ages and Th/U zircon consistent with igneous growth in the bulk composition from which they were extracted. Low bulk Zr minimizes the possibility of zircon inheritance. Ion−microprobe depth−profiling study of a single zircon from the older orthogneiss yields an igneous core age of 3825±8 Ma, and shows an episode of zircon growth at 3731±10 Ma, which may have occurred during contact metamorphism at the time of emplacement of the second tonalitic sheet. These results support a >3825 Ma depositional age of the Akilia supracrustals. As an alternative to a chemical sedimentary origin for Fe−rich quartz−pyroxene rocks, it has been proposed that the pyroxene−rich bands are metasomatized ultramafic rocks and that quartz−rich bands are metamorphosed quartz veins. However, we find a large contrast in whole−rock d 18 O between the quartz−pyroxene rock (12.6 ‰) and adjacent metaigneous units (7−8 ‰) that argues against significant mass transfer. Moreover, immobile trace elements, Rare Earth Element (REE) patterns, S isotopes and PGE data are consistent only with an origin as hydrothermal deposits chemically sedimented in a volcanic/hydrothermal setting with minor, locally derived ultramafic and mafic detrital components. These results validate the interpretation that the quartz−pyroxene rock of the Akilia supracrustals is >3800 Ma metasediment.

Highlights

- New mapping and geochronology confirm >3.8 Ga origin of chemical sediment in west Greenland . Results are described in a paper submitted to American Journal of Science.
- Manning led a NAI–sponsored field trip to examine evidence for >3.8 Ga life on Earth. Seventeen field–trip participants traveled to west Greenland in June 2004 to visit key early life localities and discuss their origin in the field and in sessions held in the capitol city of Nuuk .

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere

Project Report: Whole genome comparisons and the Evolution of Methane and Sulfur Metabolisms

Project Investigator:	***Sorel Fitz–Gibbon***

Project Progress

Sorel Fitz–Gibbon collaborated with Todd Lowe (University of California Santa Cruz) on functional analysis of the hyperthermophilic crenarchaeon *Pyrobaculum aerophilum* using full–genome DNA microarrays. The analysis suggests that a set of key sulfur metabolism genes found in this organism function in the reductive direction, reducing sulfate, rather than the proposed alternative, sulfur species oxidation. Additionally, the demonstrated regulation of these genes in response to oxygen suggests that frameshift disruptions found for one key enzyme are due to recent events. This together with the report of a sulfate reduction phenotype in the crenarchaeon *Caldivirga maquilingensis* (Itoh et al, 1999) suggests that sulfate reduction may be far more common among the Crenarchaeota than previously assumed.

Sorel Fitz–Gibbon and Christopher House Pennsylvania State University (PSU) continued their collaboration using whole genome sequences to study phylogenetic relationships. Initial steps have been taken to include incomplete genome sequences into their analyses. This will allow perhaps hundreds of additional organisms to be represented, significantly increasing the diversity and depth of resolution of the resulting trees.

Highlights

- Regulation in response to oxygen of *Pyrobaculum aerophilum*'s divergent sulfate reduction genes leads to the suggestion that sulfate reduction may be far more common among the Crenarchaeota (and, more generally, the Archaea) than previously assumed.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems

Project Report: Significance of photochemistry in determining the inorganic and organic chemistry of protoplanetary materials

Project Investigators:	***James Lyons , Edward Young***

Project Progress

The goals of this project are to determine the origin of ^{16}O–poor water in the solar nebula, and to predict isotope anomalies in other nebular oxygen reservoirs (e.g., oxygen–containing organics) with an eye towards understanding the significance of photochemistry in determining the inorganic and organic chemistry of protoplanetary materials. James Lyons has converted an atmospheric chemistry model into a one–dimensional (1–D) solar nebula model, and has used the model to show that ^{16}O–poor water is produced in the nebula as a result of photodissociation of CO. These results have been submitted to the journal *Nature* (authors Lyons and Young), and, after receiving reviews, Lyons is presently making revisions and preparing the manuscript for resubmission. Lyons has presented these results at Lunar and Planetary Science Conference (LPSC) and Goldschmidt meetings during the past year.

Highlights

- A photochemical model of the solar nebula developed by Lyons and Young has shown that CO photodissociation can explain the origin of ^{16}O–poor water that is inferred to have been present in the nebula. This may explain the 30–year old conundrum of the oxygen isotope anomalies seen in calcium–aluminum inclusions (CAIs) in primitive meteorites.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Project Report: Photodissociation experiments elucidating the mechanism of anomalous sulfur isotope fractionation

Project Investigator:	***James Lyons***

Project Progress

This project involves collaborative work between James Lyons (UCLA) and James Farquhar at the University of Maryland (UMD). In this work SO_2 photodissociation experiments have been performed with the goal of elucidating the mechanism of anomalous fractionation in sulfur isotopes. Lyons visited UMD in July and November 2003 to participate in two sets of experiments. Results obtained thus far are different from some of the narrowband experiments reported by Farquhar et al. in 2001, and have been reported at Astrobiology Science Conference (AbSciCon) (March 2004) by Lyons et al., and by Wing et al. at Goldschmidt (June 2004). An initial paper describing experimental results is in preparation. Additional experiments are anticipated.

Highlights

- Broadband SO_2 photodissociation experiments yield elemental sulfur with different isotopic behavior than do narrowband experiments. This result is significant because in an actual atmosphere (either modern or Archean) broadband dissociation is expected.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere

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Project Report: Organic molecule detection using the Stratospheric Observatory for Infrared Astronomy

Project Investigator:	***Eric Becklin***

Project Progress

Team members ordered filters and GRISMS for the UCLA First Light Infrared Test Experiment Camera (FLITECAM) instrument to carry out Astrobiological research on the Stratospheric Observatory for Infrared Astronomy (SOFIA). The fruits of this work should occur in 2006 and will allow detection in space of dust composed of organic compounds.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

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Project Report: Orbital stability of terrestrial planets and asteroids

Project Investigator:	***Ferenc Varadi***

Project Progress

These advances were made in relation to establishing the effects of orbital dynamics on the prospects for habitability:

1. Searching for stable orbits for terrestrial planets in extrasolar planetary systems.
   In collaboration with the NAI team of the Carnegie Institution of Washington, we are carrying out a systematic search for stable orbital configurations in the gravitational three−body problem. We are looking for stable periodic orbits in resonances, which are centers of librations. We finished an exhaustive exploration of the 2:1 resonance in the restricted three−body problem, in which a small body is in resonance with a giant planet. We determined the regions of stability for a wide range of masses and eccentricities of the giant planet. Our visitor from France, J. Couetdic, revised the software to facilitate an automated search of all potentially important resonances. We are now preparing to implement the new software and to link the output to web pages in real time.
2. Long−term orbital simulations of the Solar System
   We have published our first paper on accurate, long−term simulations of the orbits of the planets.

Highlights

- There is now a very extensive map of stable orbits in the 2:1 orbital resonance.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets

Cross Team Collaborations

Collaboration with Alan Boss' group at the Carnegie Institution of Washington's DTM.

Project Report: Oceans and Kuiper Belts in Extrasolar Planetary Systems

Project Investigator:	***Michael Jura***

Project Progress

Our project on identifying asteroid belts and comets around other stars has moved forward on two fronts:

1) When a main sequence star evolves into a red giant and its Kuiper Belt objects

(KBOs) reach a temperature of ~170 K, the dust released during the rapid ice sublimation of these cometary bodies may lead to a detectable infrared excess at 25 microns, depending on the mass of the KBOs. Analysis of Infrared Astronomy Satellite (IRAS) data for 66 first–ascent red giants within 150 pc of the Sun provides an upper limit to the mass in KBOs at 45 AU orbital radius that is usually less than ~0.1 M(Earth). With improved infrared data, we may detect systems of KBOs around first–ascent red giants that are analogs to our solar system. (Jura, M. 2004, Astrophysical Journal, 603, 729. "Other Kuiper Belts")

2) The increase with time in the luminosity of a main–sequence star can eventually lead to substantial evaporation of the oceans on an orbiting terrestrial planet. Subsequently, the gas–phase H_2O in the planet's upper atmosphere can be photodissociated by stellar ultraviolet, and the resulting atomic hydrogen then may be lost in a wind. This gaseous envelope may pass in front of the host star and produce transient, detectable ultraviolet absorption in the Lyman lines in systems older than 1 Gyr. (Jura, M. 2004, Astrophysical Journal, 605, L65. "An Observational Signature of Evolved Oceans on Extrasolar Terrestrial Planets.")

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets

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Project Report: Impacts and the Evolution of Planetary Atmospheres

Project Investigator:	***William Newman***

Project Progress

Recent work has shown that large impacts (10 times the impactor mass and energy of a K/T–size event) may not erode planetary atmospheres. William Newman and colleagues consider the energetics of large bolide impacts on atmosphere–free planets in an attempt to determine whether these large impacts will contribute to or erode from the planet's volatile inventory. Their results show, for a wide range of impact speeds and for all but the most highly oblique impact angles, that volatile material will be added to the planet's inventory, especially if the planet has been depleted in volatiles as we assume Earth to be following the giant impact. For Venus, the situation is much the same as for Earth as it is for Mars, although for Mars the range of impact speeds is greatly reduced. Volatile retention depends primarily on the planet's escape velocity and the bolide's impact speed and angle of entry, with gravity being the truly dominant factor in these impacts. Following the giant impact, it is possible to acquire enough volatiles through impacts to account for the Earth's present–day inventory, without requiring significant degassing of surface volatiles and mantle outgassing, both of which seem unlikely following the giant impact. Results are described in Mischna, M.A. and Newman, W.I., "Atmospheric Accretion on Airless Planets: The Role of Oblique Impact Events," submitted to Planetary and Space Sciences, May 2004, 42 pages.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets

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Project Report: Genome Evolution and Innovation

Project Investigator:	***James Lake***

Project Progress

Progress has been good this year in the area of Genomic Studies. Six papers have been published in leading journals supported by the Astrobiology program. Two papers, described below, have been especially visible. As part of this work Prof. Jim Lake co–organized a special Genomics Section at the 2003 Gordon Conference on "The Origin of Life". He also helped Co–organize, with 5 others, the joint Astrobiology/Canadian Research Institute meeting held in Canada in April 2004. I also served as Co–chair of the EvoGenomics Focus group, with Blair Hedges (annual report has been submitted separately).

Horizontal Gene Transfer (HGT) Greatly Accelerates Genome Evolution and Innovation :

Through studies of whole genomes, we find that HGT is strongly influenced by genomic and environmental factors. Hence, organisms living in similar environments preferentially exchange genes with other organisms that have similar environmental parameters. As a result, we infer that HGT has accelerated prokaryotic genome innovation and evolution by a factor of about 10^4 . In practical terms, this means that the number of unique prokaryotic genes that would be "invented" in a ten thousand year period if HGT were absent can in fact be "invented" in a single year! (see Publication #3).

Conditioned Reconstruction: a method for deriving the genomic tree of life in the presence of horizontal gene transfer : Our lab has developed a new phylogenetic analysis tool that uses the presence and absence of genes to determine phylogenetic trees, just as sequence analyses use nucleotides. The method has two properties that make it unique: it is relatively unaffected by horizontal gene transfer, and it has the ability to detect "fusion" events in which a new genome is created by the fusion of the genomes of two existing organisms, hence it can detect endosymbiotic events in the evolution of life. (see Publication #1).

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

EPO: University of California, Los Angeles

These are the Education and Public Outreach activities for the University of California, Los Angeles.

Chicago 2004

Barbara Laval and Maria Rivera participated at the NASA Office of Space Science, Chicago 2004 conference "A Workshop to Foster Broader Participation in NASA Space Science Missions and Research Programs."

The conference goals were to reach out to minority scientists and share information on NASA's future space science missions and research programs, to include individuals from underrepresented colleges and universities and forge collaborations and build foundations of personal contacts, and broaden participation and establish common understanding and language.

The conference provided poster sessions, group discussions, and a tour to the Adler Planetarium.

NASA Tribal College and University Conference

Barbara Angel Spirit Wings Laval attended and participated in the NASA–Tribal College and University Conference – May 19–21, 2004, Pasadena, California, at the request of NAI Central's Karen Bradford and Krisstina Wilmoth. Ms. Laval presented the NASA Astrobiology Institute's Minority Insitution Research Sabbatical program, during session I – The NASA Opportunities for Research and Education.

Ms. laval also attended a closed session of the President's Roundtable. During this session ideas and needs were discussed and recommendations given to begin collaborations and extend participation with NASA missions and research programs.

Astrobiology Summer Science Experience for Teachers (ASSET)

Barbara Laval, UCLA's EPO Director, participated in the ASSET 2004 inaugural program. The program was interactive and content rich with presentations by leading astrobiology scientists. The scientists included Dr. Jill Tarter and Rocco Mancinelli from the SETI Institue, Dr. Nina Jablonski, California Academy of Sciences. Participants received hand–on experience with the Voyages Through Time curriculum. Field trips included the California

Academy of Science, Salts Flats, Wilcox High School and SETI Institute.

Participants attended scientific talks that addressed stellar evolution, formation of planetary systems and habitability, mechanisms of evolution, and SETI. Participants helped plan ASSET outreach activities, and polished leadership and presentation skills for conducting successful teacher workshops at their insitutions.

Palms Middle School Visit to UCLA

The Palms Middle School's four science classes held a science contest and the winners were rewarded with a visit to the NASA UCLA Center for Astrobiology in the Institute of Geophysics and Planetarey Physics.

Seventh grade Student Rodrigo Simas, president of the seventh grade leadership club at Palms Middle school, organized the visit with support from teacher Mr. Clairs. There were approximately 35 students who visited the center.

Upon arrival to UCLA, the students were given an hour–long private Planetarium show hosted by UCLA's Astronomy graduate student Ms. Karen Peterson. The students spent approximately one hour and fifteen minutes each with Dr. Abby Kavner, minerologist, Dr. Mark Webster, paleontologist, and Dr. Sorel Fitz–Gibbon, geneticist. Topping off the day, the students participated in a video conference with Dr. Bruce Runnegar, Director of the NASA Astrobiology Institute, Dr. David Morrison, NAI Lead scientist, and Ms. Estelle Dodson, Information Technologist. The students and Mr. Clairs were able to ask science and technology questions.

South Gate Middle School Visit

Barbara Llaval and Dr. Maria Rivera visited the South Gate Middle school in South Gate, California. Ms. Laval gave a general overview of Astrobiology and Dr. Rivera answered class questions pertaining to genomics. Ms. Buck, their science teacher, prepared the class by teaching the students basic genomic vocabulary.

Below are questions from the students in Ms. Bucks classes: GENETICS –

1. What would happen to a child if it doesn't get enough chromosomes from their parents will it be deformed or mentally ill? 2. How do genes pass from one generation to another? 3. Why is genetics so important? 4. Can genes die? What harm can happpen to DNA? 5. Do we get more traits from our fathers or mothers? 6. How come sometimes we don't inherit any traits? 7. What specific things do you have to look for to trace DNA? 8. Do aliens have DNA? 9. What are some traits that identify your heredity? 10. Can we be part Spanish since Spain conquered Mexico? 11. What are some traits to prove that we are part Spanish? Hair? Eyes? Skin? 12. Are the traits as same as the genes? 13. How do genes pass from one generation to another, do they change structure and traits?

CLONING 1. Is it possible in the future to successfully clone a human? 2. Who discovered the cloning process? 3. Was it by the cloning process that one celled organisms started? 4. If you could clone the entire jurassic age would you or would you not? 5. Could we clone a fossilized organism from another planet? 6. Is it possible to clone a fossilized, pre–historic animal and bring it back to life?

PERSONAL 1. Why did you get interested in genetics? 2. What brought you to the point that you wanted to learn genetics? 3. How often do you study for tests and how do you study? 4. What made you decide to study genetics? 5. Is it fun to study genetics? 6. How many years did it take? 7. Why are you interested in astrobiology? 8. What jobs can you get if you study Astrobiology? 9. What do you study in Astrobiology? DO you have to use a lot of Math? 10. Do you like the job/carreer and is it fun? 11. How long have you been studying this? How long does it take to get the position you have? 12. What do you plan on discovering?

ASTROBIOLOGY 1. What's going on on Mars? 2. What does the latest data mean? 3. What is astrobiology? 4. Do you know anything about the new planet Zetna? 5. Does space ever end? 6. Do aliens have DNA? 7. How can you study life so far away?

South Gate Middle School Visit (2)

Since the first visit to South Gate was a success, Ms. Buck asked if we would visit the class again. The topic for the second visit was Mars. Barbara Laval (UCLA) and Sheri Klug (Arizona State University) visited the class.

Mrs. Klug's job at Jet Propulsion Laboratory was manning the night shift of the MER mission's meridiani landing site. She discussed various aspects of Mars and Earth and answered sutdents' questions. She brought teacher packets for the teachers with materials and stickers for the students.

Society for the Advancement of Chicanos and Native Americans in Science (SACNAS)

Barbara Laval (UCLA) and Karen Bradford (NAI) attended and participated at the 2003 SACNAS conference – 30 Years at the Crossroads: Merging Disciplines & Advancing Diversity, Albuquerque, New Mexico.

The SACNAS National Conference is a professional scientific meeting that interweaves opportunities to share research, receive guidance, and develop professionally. Innovative conference activities consist of presentations of exemplary science research by top national scientists. The three–day meeting also included formal and informal mentoring sessions, inquiry–based training workshops for pre–college educators and cultural activities such as a Pow Wow.

NAI's Minority Institution Research Sabbatical – UCLA Presentations – Atlanta, Georgia

Barbara Laval (UCLA) and Karen Bradford(NAI) visited Atlanta University Center to present NAI Education and Public Outreach activities, and the Minority Institution Research Sabbatical (MIRS) program.

NAI MIRS Presentation/Discussion, NAI overview and MIRS Program and research with the NAI – Morehouse University. Mrs. Karen Bradford.

NAI MIRS Student Presentation, student research and activities as a result of the NAI MIRS program – La Tasha Taylor, Tennessee State University (TSU).

Attended Spelman College Science Day Activities.

Attended NAI Senior Scientist David Morrison's presentation and planetarium show – Fernbank Science Center.

NAI UCLA EPO Presentation – Atlanta University Center – Presentations and activities for grades 9 – 12, Barbara Laval (UCLA), Karen Bradford (NAI) and Todd Gary (TSU).

Sheri Klug from Arizona State University provided the Community Nights kit in support of our presentation.

Sally Ride Science Festival

Barbara Laval, Manager of the UCLA Center for Astrobiology, attended and participated at the UCLA Sally Ride Science Festival. Dr. Sally Ride, the first American woman astronaut to travel in space, invited 5th – 8th grade girls and interested adults to attend the festival at UCLA presented by the Sally Ride Science Club.

Sally Ride Science Club aims to make science, math, and technology accessible and fun for girls with natural curiosity. The Club works in collaboration with universities and colleges, girls and women's organizations, schools, and science and technology businesses.

There were two Discovery workshops and a Street Fair.

The NAI UCLA team invited the NAI Virtual Planetary Laboratory team to participate in this one day event.

The National Space Biomedical Research Institute – EPO Peer Review

UCLA's EPO Director, Barbara Laval, was invited to be a participant on an EPO Peer Review panel for the National Space Biomedical Research Institute (NSBRI). The NSBRI has recently released a Request for Proposals (RFP) to continue these Education and Public Outreach programs. The NSBRI is a NASA–funded entity comprised of 12 consortium member institutions, with Baylor College of Medicine serving as the lead institution. Its mission is to develop effective countermeasures to the deleterious effects on the human body of long–duration exposure to the lack of gravity in the space environment.

The Institute funds a portfolio of approximately 100 projects. This RFP includes calls for two different types of proposals, including K–16 curriculum and professional development programs, and a Space Life Sciences Graduate Program.

This E/PO panel took place on Thursday and Friday, August 26th and 27th in Houston, Texas.

Littleton High School Physics Class Project, Littleton, New Hampshire

Barbara Laval and Dr. Jonathan Aurnou participated in a videoconference with Mr. Bill Church's Littleton High School Physics Class on December 9, 2003.

Littleton High School Participants: Students: Ryan Haley, Joe Lahout, Eric Chase, Josh Ashey, Scott Letson, Phuong Thai, Zach Sar, Jon Hogan, Ian Nadeau, Joe Lis.

Staff and Faculty: mentor Arlene Soule, distance learning coordinator Regan Pride, and physics teacher William Church.

Summary: During the the 2002–2003 school year, Mr. William Church of Littleton High School received a grant from the Lemelson–MIT program to design a sidewalk heating system powered by alternative energy as part of his physics class. Such a project is of great practical interest in northern New Hampshire, where Littleton High is located. By the end of the school year Mr. Church and his class had designed working prototype of a system that utilized waste heat from the chimney the school's primary heat source. This past year their design was incorporated into the renovation of the high school's sidewalk.

During the 2003–2004 school year, a new group of students worked on devising experiments to measure the performance of the system. It was in the middle of designing these experiments that a videoconference was set up between the Littleton High School students and Professor Jonathan Aurnou (Earth & Space Sciences, UCLA). This video conference was carried out using the NASA Astrobiology Institute facilities at UCLA and allowed the students to access Prof. Aurnou's experience in planetary heat transfer processes. Dr. Aurnou and the students discussed thermal measurements in general, measurements specific to the sidewalk heating system, and how best to look for and interpret patterns in large data sets. Specifically, they benefited from the videoconference because they faced a question they had not considered before: "what is the proper data collection rate for the critical quantities that were being measured?" After the videoconference, the students worked to answer this question and as a result designed stronger experiments. In addition, the students enjoyed and benefited from talking with a professional scientist who utilizes the concepts they were currently learning in Mr. Church's physics class.

Future Videoconferences: During the 2004–2005 school year, yet another group of students will work on further improving the experiments the previous year's students created and in optimizing the sidewalk heating system. They will work to understand what was learned about the performance of the

sidewalk system from the previous year. Finally, they will conduct their own experiments and work to improve the system so that it is working at an optimal efficiency. Prof. Aurnou and Mr. Church plan to carry out another videoconference for this new group of budding young scientists.

NASA–National Association for the Advancement of Colored People (NAACP) Afro–Academic Cultural, Technological, and Scientific Olympics (ACT–SO) Science Competition

NASA Headquarters invited Barbara Laval to attend and participate as a NASA Judge for the 2004 NAACP ACT–SO Competion, held in Philadelphia, PA, July 7–10, 2004.

The Afro–Academic Cultural, Technological, and Scientific Olympics (ACT–SO) ia a major youth initiative of the NAACP.

ACT–SO is a learning experience and an opportunity for youth to be mentored and coached by community leaders, scientists, artists, writers, and musicians. ACT–SO involves volunteers, coaches, mentors, and judges on the local and national levels. Each of these individuals serve as role models and play an important role in their personal and professional development.

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NASA ASTROBIOLOGY INSTITUTE
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Team Reports: University of Colorado, Boulder

University of Colorado, Boulder
Executive Summary
Principal Investigator: Bruce Jakosky

The University of Colorado Center for Astrobiology brings together researchers who focus on scientific issues related to the origin and history of life here on Earth, the potential for life to exist elsewhere in our solar system, and the distribution of planets around other stars and their potential habitability. The participants in our effort span the range of scientific disciplines that comprise astrobiology and, by coming together in an academic and intellectual environment, provide a breadth of expertise that provides cross–cutting scientific leadership. Our efforts include research in the various sub–disciplines of astrobiology, teaching of undergraduate students, graduate students, and post–doctoral researchers both in the individual sub–disciplines and across all of astrobiology, and outreach to the broader university and public communities. Together, they add up to a vibrant program in astrobiology that reaches out across a substantial fraction of the university intellectual landscape. Here, we describe the components of our astrobiology program emphasizing, in order, the research, teaching, and outreach activities.

Research program in astrobiology. Our research efforts can be divided up into several themes:

1. *The origin and evolution of life on Earth.* Topics here include issues related to the origin of life and the genetic, the evolution of biochemical functions, the earliest recorded history of the Earth and of life on it, microbial diversity and life in extreme environments, and major evolutionary events in life's history.

   Under Prof. Michael Yarus' leadership, we are continuing our investigation into the smallest number of RNA molecules that can yield active RNA structures, now using experimental rather than theoretical approaches. Other related work has yielded interesting results, now being prepared for publication. These related experiments determine the number of consecutive randomized nucleotides required to isolate the simplest isoleucine binding RNA by selection. This work shows that unexpectedly short RNAs are best, the binding activity being most easily isolated with 26 consecutive random nucleotides. This is much shorter than expected, and in particular, the fact that adding nucleotides (to make longer starting sequences) is not helpful (but instead

somewhat inhibitory) is particularly hard to explain. What seems to be implied is that there is an unanticipated potent difficulty inhibiting the search for RNA active sites in longer starting sequences.

In an effort that involves collaboration between biochemistry (from Prof. Shelley Copley) and philosophy (from Prof. Carol Cleland), we have been exploring the potential for the existence of a “shadow biosphere” that consists of microbes that are not descended from life as we know it and that does not use the same biochemical structures and strategies to support metabolism, growth, and reproduction. Such a biosphere might exist in parallel to the standard life, but be undetectable by techniques that detect the standard biochemical molecules. Today, 99.9 % of microbes in the environment cannot be cultured, suggesting that there are a tremendous number of organisms about which we know essentially nothing.

Studying the ancient Earth and its biosphere is difficult because of the paucity of samples. Prof. Stephen Mojzsis and his group have been searching out samples and analyzing them. Their work on mass−independent fractionation of sulfur isotopes in ancient sediments provided data that: (i) places limits on the geochemical record of the transformation of the surface zone to an oxygen−rich environment between 2.5 and 2.3 billion years ago, possibly at the expense of methane; and (ii) described a means to investigate traces of early microbial metabolisms that utilized sulfur as an oxidant and provided data proposing the appearance of this metabolic style early in the Archean. In addition, research on Th/U coupled with the geochronology of zircons has traced the metamorphic transition from amphibolite to the granulite facies that dominates the geological history of all rocks that are more than 3.7 billion years old. This allows us to describe the metamorphic history of the oldest terranes and better glean clues concerning the habitability of the early Earth.

In the area of microbial diversity, projects continue to revolve around development and use of rRNA−based molecular methods to study the microbial constituents of ecosystems in extreme environments without the requirement for cultivation of the organisms. Some properties of organisms can be inferred from the phylogenetic results, and the sequences can be used to design hybridization probes to visualize organisms and their interactions in the environment. Recent results include: (i) Studies of Guerrero Negro hypersaline microbial mats showed that Green Non−sulfur bacteria, not cyanobacteria, dominate hypersaline microbial mats; this has impact on expected mechanisms of carbon fixation, isotope fractionation, and other geochemical parameters. (ii) The ongoing Guerrero Negro studies have discovered and identified by sequence more than 7000 novel microbes, some only distantly related to known organisms; the number of bacterial kingdoms was expanded from about 60 to about 80 in this study! (iii) The newly discovered acidic Yellowstone endolithic community is an entirely novel biome with relevance to the possibility of life on Mars and to the search for past life there.

Based on DNA sequence identity, Prof. William Friedman and his group have identified the symbiotic fungi associated with early land plants throughout their life cycle. These symbiotic fungi represent an ancient lineage of fungi that are known to form essential symbiotic fungal associations with most extant plants. The co−evolution of this ancient symbiotic fungal association throughout land plants potentially facilitated the evolution of the current complexity of terrestrial life. We have compared the fungal symbionts in the subterranean life cycle phases of early land plants to the fungal symbionts present in neighboring photosynthetic plants. These data suggest that the underground life cycle phases in these early plant lineages obtain carbon through a fungal network. Recent research suggests organisms that survive catastrophic impacts typically have an underground component such as a spore, or seed. Thus, a long−lived subterranean life cycle phase in early land plant lineages may have increased ability to avoid extinction following an asteroid impact by obtaining carbon through a fungal network.

2. *The origin and evolution of habitable planets.* Topics within our program relate to the habitability of planets, both in our solar system and beyond.

   At Mars, Prof. Bruce Jakosky and collaborators are exploring the geochemical energy that can support metabolism via chemical weathering at low temperatures on Mars. Such low−temperature environments may be widespread, based on recent discoveries and analyses pertaining to Martian gullies, sub−freezing liquid water, crater lakes, and depositional environments. Our results will be used to determine which types of geological environments are most suitable for supporting Martian organisms, and what the availability of energy as a resource is. To answer these questions, we have been using three different geochemical reaction modeling programs (EQ3/6, PHREEQC, and Geochemist's Workbench); these simulate the mixing of water with various host rock compositions based on Martian meteorites, to determine geochemical weathering pathways, and to estimate available energy that can support metabolism. This approach will allow us to determine the conditions that have optimal geochemical energy available to organisms.

   An issue being explored by Prof. Robert Pappalardo that is crucial to understanding the potential habitability of Europa is whether the satellite's level of internal activity has remained relatively constant, has waned through time, or is cyclical with periods of greater and lesser activity, each of which represents a physically plausible scenario. If Europa's level of internal activity is high today, its potential to harbor life is significantly greater than if the satellite's internal heat sources have dwindled over time (or if they cyclically diminish to negligible levels). To explore this, we have implemented a quantitative method of temporally ordering Europa's geological features based on their cross−cutting relationships as mapped within Geographic Information Systems software. It allows us to group lineaments that have indistinguishable

positions in the stratigraphic order. These lineaments can be treated as roughly contemporaneous, and used to investigate the changes in orientation and origin of the surface stresses through time. As a test case, this method has been applied to the lineaments of the Conamara Chaos region. We find that there are some intersecting lineaments that were either truly contemporaneous, or were re−activated after their initial formation.

Prof. Brian Toon and his group are exploring the factors controlling climate on terrestrial planets and their implications for planetary habitability. Some of the specific results from the year include: (i) Experimental studies show, as had been predicted in some theoretical studies, that the production rate of aerosols declines as the abundance of CO_2 relative to methane increases in simulated ancient terrestrial atmospheres. (ii) Additional experimental studies show that polycyclic aromatic hydrocarbons and terpene related compounds can form in Titan's atmosphere, with the unexpected result that the type of organic compounds formed shifts for CH_4 to N_2 ratios close to those in Titan's current atmosphere. (iii) A study of the escape of H_2 from the atmospheres of extrasolar planets and from the early Earth explains the observed structure of one extrasolar planetary atmosphere, and shows that planets can evaporate in the inner solar system. The terrestrial work points to hydrogen rich atmospheres with hydrogen partial pressures above 1 bar on early Earth.

Although Dr. Tom McCollom's funding as an NAI team member does not begin until this year, initial research on his project has already begun. The goal of the research is to develop numerical models of chemosynthetic−based ecosystems on Earth that will provide insights into possible analog environments on the early Earth, Mars and Europa. Towards this end, numerical models of serpentinization of ultramafic rocks and their potential to support chemolithoautotrophic microbes has been initiated. While it is too early in this research to draw specific conclusions, the initial results suggest that H_2−based microbial communities living on ultramafic rocks in the subsurface should be much more productive by several orders of magnitude than those based on basaltic or granitic rocks.

Prof. John Bally is investigating how planets are born. In what type of environment, and under what conditions do most stars (and associated planetary systems) form? How do grains and gas in proto−planetary systems evolve from interstellar properties to solid bodies? His group has been using the world's largest telescopes (such as the Keck 10m and Gemini 8m telescopes) to search for answers at wavelengths between 0.5 and 20 microns. They have found evidence for proto−planetary disks in the Carina nebula, which is a much harsher environment for star and planet formation than the comparable Orion nebula. They also used the Gemini−South 8m telescope to obtain thermal infrared images, sensitive to the presence of 100 to 500 Kelvin dust, of young stars embedded in the Orion nebula. These data show that most of Orion's "naked" young stars (in Hubble Space Telescope

images) nonetheless are surrounded by warm dust. His group also has found that ultraviolet (UV) radiation can actually enhance the onset of gravitational instabilities in disks, leading to “triggered” planetesimal formation. They are developing a numerical model to study the combined effects of UV−induced photo−ablation and other processes, to understand the onset of self−gravitational condensation into planetesimals.

3. *Societal and philosophical issues in astrobiology.* The major task in this theme is being carried out by Prof. Carol Cleland from the Philosophy Dept. at CU, and is described above.

4. *Astrobiotechnology development.* We are providing national leadership in development of technology for use in astrobiology flight missions. The major tasks to date have involved formation of an Astrobiotechnology Focus Group (reported on separately) and its sponsorship of the upcoming workshop on Mars Astrobiology Science and Technology. That workshop will address needs for Mars flight missions beyond the 2009 Mars Science Laboratory, and will instigate development of concepts and instruments.

Teaching program in astrobiology. Each of the CU Co−Investigators involves undergraduate students, graduate students, and/or post−doctoral researchers in their laboratories and groups. In addition, we offer: (i) An undergraduate course in “Extraterrestrial Life” that has been offered every semester for seven years, has typically 75 students enrolled each semester, is taught by one of the Co−Investigators (and has been taught by Jakosky, Bally, Pappalardo, and Mojzsis, for example), and uses the textbook co−authored by PI Jakosky (“Life in the Universe”, by Bennett, Shostak, and Jakosky). (ii) An undergraduate course in “Alien Cultures: Astrobiology, Science, and Society” discusses the societal and philosophical issues in astrobiology with senior undergraduate science majors. (iii) A graduate course in “Astrobiology”, aimed at students in both the physical and biological sciences, provides a broad training across the discipline. (iv) A graduate course in “Philosophy of Astrobiology” brings together students from both the sciences and astrobiology. (v) A graduate certificate in Astrobiology demonstrates training across the disciplines.

Outreach program in astrobiology. A central part of our program involves outreach beyond the astrobiology researchers on campus. Our program this year is substantially expanded from in previous years, and activities this year included: (i) A public symposium on Mars, tied to the Mars Exploration Rover missions; (ii) A traveling public symposium to take the excitement of astrobiology to schools catering to under−represented minorities, with visits this year to Ft. Lewis College and Hampton University; (iii) Open houses to get the public excited about the Mars missions, attracting a total of approximately 700 to the two Mars landings; and (iv) A science journalism workshop, aimed at providing in−depth training on the astrobiological relevance and significance of the Mars rover missions, run pre−landing and attended by about sixteen main−stream journalists.

Project Report: Divergence of protein families to provide novel function

Project Investigator:	***Shelley Copley***

Project Progress

The search for other forms of life motivates many aspects of the NASA Astrobiology program, including efforts to define life, to identify habitable planets, to understand the conditions conducive to the evolution of life, and to understand how life evolved on Earth. An idea that has not received serious consideration is the possibility that another life form might exist here on Earth. Carol Cleland and I have been exploring the possibility of a “shadow biosphere” consisting of microbes that are not descended from the last common ancestor of life as we know it and that do not use the same biochemical structures and strategies to support metabolism, growth, and reproduction. Although we have no evidence that a shadow biosphere exists, it must be recognized that we do not have the tools to detect it. We cannot culture 99.9% of the microbes in environmental samples; thus, there are many organisms about which we know nothing. Furthermore, molecular techniques such as rDNA amplification can only detect organisms that contain DNA as we know it. There are many examples in biology of convergent evolution – enzymes with the same function have arisen from different progenitors, and the eyes of insects and mammals originated independently. There are many solutions to any biological problem, and it is unlikely that the solutions reached by life as we know it are unique. Thus, it is possible that another form of microbial life emerged in parallel to life as we know it. This possibility warrants attention from NASA because Earth is not only clearly suitable for the evolution of life, but it is much more accessible than Mars, Europa, or extra–solar planets.

An additional effort related to astrobiology will begin in June. I will be spending five weeks at the Santa Fe Institute collaborating with Dr. Harold Morowitz. We will be searching for mechanisms by which the very slow reactions required to produce the building blocks of macromolecules might have been catalyzed under pre–biotic conditions.

Highlights

- The possibility that a shadow biosphere consisting of microbial life unlike life as we know exists and is not detectable with currently available technologies should not be dismissed.

- A new collaboration with Dr. Harold Morowitz to explore the origins of metabolism under pre−biotic conditions will begin in June 2004.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	life definition	Co−Investigator

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Project Report: Molecular survey of extremophile microbial diversity in hypersaline ecosystems

Project Investigator:	***Norman Pace***

Project Progress

Projects continue to revolve around the development and use of rRNA–based molecular methods to study the microbial constituents of ecosystems in extreme environments without the requirement for cultivation of the organisms. This cultivation–independent approach to ecosystems analysis is essential rather than classic methods because most microbes, >99%, are not cultured using standard techniques. With the molecular methods, rRNA genes are cloned directly from environmental DNA, and then sequenced to gain a phylogenetic snapshot of the organisms represented by the cloned genes. Some properties of organisms can be inferred from the phylogenetic results, and the sequences can be used to design hybridization probes to visualize organisms and their interactions in the environment. Recent results in NAI sponsored studies include:

1. Antarctic and Colorado endolithic communities. Primary productivity in rocks occurs through the action of endolithic microbial communities, photosynthesis–driven communities in the outer few cm of any rock surface exposed to light. These communities so far have only received limited study, only with classic microscopy and culture techniques. Ongoing rRNA gene analyses of Antarctic and Rocky Mountain endolithic communities have revealed many novel kinds of organisms, some closely related to described organisms, but others very different. A particularly noteworthy discovery this past year has been a highly acidic (pH 1) endolith community in a sinter field at Yellowstone. Molecular analyses showed the main community consists of cells of *Cyanidium caldarum*, a eukaryotic alga, embedded in a dense mesh of previously unknown *Mycobacterium* spp. The communities fossilize readily, encouraging their consideration as a target in the search for life on Mars. (Manuscript submitted to Science.)
2. Yellowstone high–temperature settings: This laboratory has for many years studied thermophilic ecosystems at Yellowstone and elsewhere. Current activities continue to explore the makeup of properties of communities that, during the past year, we have shown to depend on metabolism of hydrogen as an energy source. (Manuscript in preparation for PNAS.)

3. Hypersaline ecosystems: We are engaged in extensive analysis of the microbial composition of Guerrero Negro hypersaline mats, in concert with geochemical and other biological studies of the NAI Ecogenomics group. Particularly noteworthy at this stage is the finding, based on rRNA gene abundance, that so−called Green Nonsulfur Bacteria, not cyanoacteria, are the dominant species. This poses many hypotheses and new questions.

Overall, we are making excellent progress and this work is scientifically conspicuous. Additionally, the PI participates in numerous astrobiology−related public and institutional activities, for instance participation as a plenary speaker at the 2004 NAI Annual Meeting.

Highlights

- We have shown by phylogenetic, geochemical and thermodynamic measurements and modeling that Yellowstone and probably other geothermal ecosystems depend on hydrogen as energy source.
- Studies of Guerrero Negro hypersaline microbial mats showed that Green Nonsulfur Bacteria, not Cyanobacteria, dominate hypersaline microbial mats. This has impact on expected mechanisms of carbon fixation, isotope fractionation and other geochemical parameters.
- The ongoing Guerrero Negro studies have discovered and identified by sequence >7000 novel microbes, some only distantly related to known organisms. The number of bacterial kingdoms was expanded from about 60 to about 80 in the study. (This is major!)
- The newly discovered acidic Yellowstone endolithic community is an entirely novel biome with relevance to the possibility of life on Mars and to the search for past life there.

Roadmap Objectives

- ***Objective No. 3.4:*** Origins of cellularity and protobiological systems
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Project Report: Origin of multicellularity and complex land–based ecosystem

Project Investigator:	***William Friedman***

Project Progress

During the 2003–2004 year significant progress has been made characterizing fungal symbionts in early land plants. Nearly all land plants have a mutualistic fungal symbiosis: the plant host gains access to essential mineral nutrients through the fungus and the fungal symbiont acquires fixed carbon from the plant. However, the evolution of the mycorrhizal association over the nearly 500 million–year course of land plant history has rarely been studied. We are characterizing the fungal symbionts in early lineages of land plants that have a life cycle where one phase is above ground and photosynthetic and another phase is completely underground. This subterranean phase in these poorly understood plants is completely dependent on a set of fungal symbionts to provide a source of organic carbon. Based on our analysis, this type of plant life cycle involving a subterranean phase (that may last up to 15 years) may be relatively ancient among land plants. Recent research suggests organisms that survive catastrophic impacts typically have an underground component such as a spore, or seed. Thus, a long–lived subterranean life cycle phase in early land plant lineages may have increased ability to avoid extinction following an asteroid impact. For example, these lineages have survived the P–T, and K–T impacts.

Although the presence of fungal symbionts in early plant lineages has been known for many years, this is the first study to determine the fungal symbionts in early land plant lineages using DNA sequence identity. To date, the fungal symbionts throughout the life cycle in early land plant lineages (*Psilotales* and *Ophioglossales*) have been identified as glomalean fungi using DNA sequence data. A collecting trip to Ecuador in May 2004 gathered samples of lycopods (another early plant lineage) that are currently being studied. In addition to studying the fungal symbionts within early land plants, we have started to identify the fungal symbionts in neighboring plants within the community to place our data in a larger ecological and evolutionary framework. Based on DNA sequence data, subterranean phases of the life cycle in these early land plant lineages obtain fixed carbon through an extensive fungal network connected to photosynthetic neighboring plants. The fungi that form symbiotic associations with the underground phases of the life cycle in early land plant lineages represent a specific sub–sample of the total fungal diversity present in

the above ground phase and the photosynthetic neighboring plants. By elucidating the evolutionary patterns of the fungal symbionts throughout the life cycle of these early land plant lineages, we have begun to shed light on the coevolution of fungi and land plants.

Highlights

- Based on DNA sequence identity, we have identified the symbiotic fungi associated with early land plants throughout their life cycle. These symbiotic fungi represent an ancient lineage of fungi that are known to form essential symbiotic fungal associations with most extant plants. The coevolution of this ancient symbiotic fungal association throughout land plants potentially facilitated the evolution of the current complexity of terrestrial life.
- We have compared the fungal symbionts in the subterranean life cycle phases of early land plants to the fungal symbionts present in neighboring photosynthetic plants. These data suggest that the underground life cycle phases in these early plant lineages obtain carbon through a fungal network. Recent research suggests organisms that survive catastrophic impacts typically have an underground component such as a spore, or seed. Thus, a long–lived subterranean life cycle phase in early land plant lineages may have increased ability to avoid extinction following an asteroid impact by obtaining carbon through a fungal network.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems

Project Report: Biogeochemical cycling and resources on Mars

Project Investigator:	***Bruce Jakosky***

Project Progress

We are exploring the geochemical energy that can support metabolism via chemical weathering at low temperatures on Mars. Such low–temperature environments may be widespread, based on recent discoveries and analyses pertaining to Martian gullies, sub–freezing liquid water, crater lakes, and depositional environments. Our results will be used to determine which types of geological environments are most suitable for supporting Martian organisms, and what the availability of energy as a resource is. To answer these questions, we have been using three different geochemical reaction modeling programs (EQ3/6, PHREEQC, and Geochemist's Workbench). All three programs have been used to simulate the mixing of water with various host rock compositions based on Martian meteorites, to determine geochemical weathering pathways, and to estimate available energy that can support metabolism. Currently, we are using Geochemist's Workbench to determine various weathering products and estimate available energy based on Gibb's free energy, and have looked at three different reactions (the weathering of fayalite, ferrosillite, and magnetite) as an initial approach to the problem. For these three reactions, we have varied the temperature (0–25 degrees C), and looked at a range of H_2 fugacities to determine which temperature and fugacity will produce the most energy. This allows us to determine the conditions that have optimal geochemical energy available to organisms.

In the near future, we will develop a reaction matrix that will include a wider range of possible reactants and products for Mars based on terrestrial analogs and what is known about Martian mineralogy.

Highlights

- We are exploring the energy available to support metabolism of potential Martian organisms in aqueous environments at ambient conditions on Mars. Such environments might be widespread on Mars, given recent discoveries and analyses (including the Mars rover discovery of depositional environments).
- We anticipate obtaining results shortly that will be applicable to planning of future Mars exploration missions, determination of Martian

habitability, and the search for life on Mars.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Mars Global Surveyor	Science Team Member
1	Mars Odyssey	Science Team Member
2	Mars Science Laboratory	Planning Support
2	Astrobiology Field Laboratory	Planning Support

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Jakosky is involved in oversight of the study group that is defining the AFL mission.

Project Report: Geochemical–Microbe Interactions in Chemolithoautotrophic Communities on Earth

Project Investigator:	***Tom McCollom***

Project Progress

Although Dr. McCollom's funding as an NAI team member does not begin until Fall '04, initial research on the project has already begun. The goal of the research is to develop numerical models of chemosynthetic–based ecosystems on Earth that will provide insights into possible analog environments on the early Earth, Mars and Europa. Towards this end, numerical models of serpentinization of ultramafic rocks and their potential to support chemolithoautotrophic microbes has been initiated. While it is too early in this research to draw specific conclusions, the initial results suggest that H_2–based microbial communities living on ultramafic rocks in the subsurface should be much more productive by several orders of magnitude than those based on basaltic or granitic rocks.

Project Report: Geological Evolution and Habitability of Europa

Project Investigator:	***Robert Pappalardo***

Project Progress

An issue crucial to understanding the potential habitability of Europa is whether the satellite's level of internal activity has remained relatively constant, has waned through time, or is cyclical with periods of greater and lesser activity, all of which represent physically plausible scenarios. If Europa's level of internal activity is high today, its potential to harbor life is significantly greater than if the satellite's internal heat sources have dwindled over time (or if they cyclically diminish to negligible levels). The record of the satellite's geology, specifically its structures (ridges and bands) is key to unraveling this issue and is the focus of the proposed study. We have implemented a quantitative method of temporally ordering Europa's geological features based on their cross–cutting relationships as mapped within Geographic Information Systems software. It allows us to group lineaments that have indistinguishable positions in the stratigraphic order. These lineaments can be treated as roughly contemporaneous, and used to investigate the changes in orientation and origin of the surface stresses through time. We can investigate both their gross changes in lineament orientation and the match between their detailed orientations and modeled stress fields resulting from the tidal potential created by Jupiter's gravity. As a test case, this method has been applied to the lineaments of the Conamara Chaos region. We find that there are some intersecting lineaments that were either truly contemporaneous or were re–activated after their initial formation. We are currently implementing a tool for quantitatively testing the match between mapped lineaments and possible surface stress fields.

Highlights

- With the goal of understanding Europa's level of internal activity through time, we are mapping lineaments on Europa, determining a quantitative stratigraphic ordering, and comparing this stratigraphy to candidate stress mechanisms. We have implemented a quantitative method of temporally ordering geological features on Europa based on their cross–cutting relationships as mapped within Geographic Information Systems software. As a test case, this method is currently being applied to the lineaments of the Conamara Chaos region.

Project Report: Laboratory Studies of the Origins of an RNA World

Project Investigator:	***Michael Yarus***

Project Progress

We are continuing our investigation into the smallest number of RNA molecules that can yield active RNA structures, now using experimental rather than theoretical approaches. This work is not ready for a detailed report yet. However, other related work has yielded interesting results, now being prepared for publication. These related experiments determine the number of consecutive randomized nucleotides required to isolate the simplest isoleucine binding RNA by selection. Interestingly, this work shows that unexpectedly short RNA molecules are best, the binding activity being most easily isolated with 26 consecutive random nucleotides. This is much shorter than expected, and in particular, the fact that added nucleotides (to make longer starting sequences) is not helpful (but instead somewhat inhibitory) is particularly hard to explain. What seems to be implied is that there is an unanticipated potent difficulty inhibiting the search for RNA active sites in longer starting sequences.

Highlights

- Short RNA sequences, like those that may have been available to an RNA world with rudimentary RNA synthetic ability, are surprisingly the most competent sequences available for finding RNA binding sites and ribozymes.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules

Project Report: Origins of planetary systems

Project Investigator:	***John Bally***

Project Progress

How are planets born? In what type of environment, and under what conditions do most stars (and associated planetary systems) form? How do grains and gas in proto–planetary systems evolve from interstellar properties to solid bodies? I have been using the world's largest telescopes (such as the Keck 10m and Gemini 8m telescopes) to search for answers at wavelengths between 0.5 and 20 µm.

Most stars form in rich clusters that include massive stars where ultraviolet (UV) radiation and close passages of sibling stars pose hazards to proto–planetary disks. However, these hazards predominantly impact the outer parts of circumstellar environments; the inner 10 Astronomical Unit regions can survive for 10s of millions of years. Henry Throop (SWRI) and I are finding that UV radiation fields may actually stimulate planetesimal formation. While radiation and dynamical processes can rapidly strip away outer disks, exposure to UV may promote condensation of solid bodies in the planetary zone. UV preferentially removes light gases and small grains; large particles become concentrated in the disk mid–plane and can rapidly evolve toward gravitational instabilities.

Some aspects of planet formation and disk evolution require precision photometry with small telescopes. I started a program to monitor variations to select a sample of young stars with nearly edge–on disks whose gas and grain properties can be further probed by UV, visual, and near–infrared spectroscopy.

Highlights

- We have found evidence for proto–planetary disks in the Carina nebula similar to those in the Orion nebula. However, Carina has nearly 100 times the radiation field of Orion and is thus a much harsher environment for star and planet formation. We have been awarded Hubble Space Telescope and Spitzer Space Telescope time to follow up our preliminary work with ground–based telescopes.

- We used the Gemini−South 8m telescope to obtain thermal infrared images, sensitive to the presence of 100 to 500 Kelvin dust, of young stars embedded in the Orion nebula. These data show that most of Orion's "naked" young stars – those NOT showing evidence for large disks or "proplyds" traits in Hubble Space Telescope images – are surrounded by warm dust, presumably in a compact circumstellar disk in the planet−forming zone.
- We used high−resolution spectroscopy of atomic hydrogen lines emitted by Orion's "naked" stars to confirm the existence of compact inner disks. The Apache Point Observatory 3.5 m spectra, and our Fabry−Perot data cubes show emission features consistent with Keplerian disks directly illuminated by ionizing radiation from Orion's massive stars. The emitting gas appears to be bound by gravity to the circumstellar disk.
- To explore disk survival in intense UV radiation fields, I generated an analytic model for the evolution of a highly idealized disk. This model confirms that disk mass loss declines as a strong function of disk outer radius. The inner−planet−forming portions of disks can outlive the massive stars providing external illumination.
- Henry Throop (South West Research Institute) and I have found that UV radiation can actually enhance the onset of gravitational instabilities in disks, leading to "triggered" planetesimal formation. We are developing a numerical model based on Henry's PhD thesis to study the combined effects of UV−induced photo−ablation, grain growth, sedimentation of large particles towards the disk mid−plane, radial drift of these particles due to the "headwind" of thermally supported gas, accumulation of large particles near gaps, and the onset of self−gravitational condensation into planetesimals.
- A new initiative uses a network of small telescopes to continuously monitor the light variations of young stars to find rare objects in which our line−of−sight skims along the disk surface. One goal of this program is to select objects for further study at UV wavelengths (to measure composition and grain properties) before the Hubble Space Telescope dies, effectively preventing such measurements for a decade or more. Additional goals are accurate calibration of large−telescope data, the search for protostellar eruptions and flares associated with accretion, and identification of complete samples of young stars in selected regions. A commercial CCD camera, a computer controlled mounting, and an existing C−14 telescope are being used for this study. The camera, mounting, and software are identical to the 16−inch "VYSOS" telescopes being deployed by my collaborators Bo Reipurth and Rolf Chini for sites in Hawaii and Chile.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets

Project Report: Re−tracing Steps Towards a Habitable World: The Biogeochemical Evolution of Sulfur on the Early Earth.

Project Investigator:	***Stephen Mojzsis***

Project Progress

**Mass−independent isotope effects in sedimentary rocks by ion microprobe analysis.*

We and our NAI collaborators at UCLA have reported on a new high−resolution technique using the UCLA Cameca ims1270 ion microprobe in multicollection mode to investigate mass−independent (”^{33}S) sulfur isotope variability in a variety of Precambrian sediments including the oldest known rocks of sedimentary origin (*Mojzsis et al.* (2003) *Geochim. Cosmochim. Acta: 67(9), 1635−1658*). We have now moved beyond the feasibility stage and are actively engaged in measuring hundreds of samples spanning the “Great Oxygenation Event” between ~2.47 and 2.33 Ga that irreversibly oxidized the surface zone of the planet.

**Discrimination between preservation of original igneous zircon populations and inherited grains.*

We described a method whereby the chemistry of a complex metamorphic rock coupled with U/Th ratios in zircon from the same rock permits direct assessment of zircon “inheritance” vs. true igneous ages. The technique has been used to resolve outstanding problems in the genesis of lower crustal rocks that stabilize the continents (*Mojzsis et al.* (2003) *J. Geol. 111(4), 407−425*) as well as overcome the long−standing problem of interpreting primary “igneous” ages from overprinted “metamorphic” ages in the oldest rocks. This new methodology is being extended to samples of described pre−3.7 Ga rocks worldwide (Acasta gneisses, Canada; Manfred Complex, Australia; etc.)

Highlights

- Our work on mass−independent fractionation of sulfur isotopes in ancient sediments contributed data that (i) place limits on the geochemical record of the transformation of the surface zone to an oxygen−rich environment between 2.5 and 2.3 billion years ago,

possibly at the expense of methane (*Mojzsis, S.J.* (2003) *Nature 425 (6955), 249–251 doi:10.1038/425249a*); (ii) described a means to investigate traces of early microbial metabolisms that utilized sulfur as an oxidant and provided data proposing the appearance of this metabolic style in the early Archean; and (iii) formulated a novel way of identifying a sedimentary origin of rocks in highly metamorphosed terranes transcending different interpretations of conventional trace element arguments.

- Research on Th/U coupled with geochronology of zircon has traced the metamorphic transition from amphibolite to the granulite facies that dominates the geologic history of all rocks that are more than 3.7 billion years old. The importance of these studies rests in our new ability to deconvolve complex metamorphic overprinting on original igneous crystallization ages. We can now describe the metamorphic history of the oldest terranes and better glean clues concerning the habitability of the early Earth.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Field Expeditions

Field Trip Name: Jack Hills

Start Date: June 2003	***End Date:*** July 2003
Continent: Australia	***Country:*** Australia
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Narryer Gneiss Complex	***Keywords:***

Description of Work: Western Australia: (June–July, 2003) fieldwork in the Jack Hills region of the Narryer Gneiss Complex to investigate further occurences of the oldest known terrestrial materials (pre–4.0 billion year old zircons) and the North Pole region, Pilbara craton (with Dr. M. Van Kranendonk) to study the oldest well– preserved sediments.

Members Involved:

Field Trip Name: NAI field workshop

Start Date: July 2003	***End Date:*** July 2003
Continent:	***Country:***
State/Province:	***Nearest City/Town:***
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Barberton Greenston Belt	***Keywords:***

Description of Work: South Africa: *July, 2003) graduate student Dominic Papineau participated in the NAI field workshop to the Barberton Greenston Belt.

Members Involved:

Project Report: The Historical Character of Astrobiology and Circumventing the Problem of Defining "Life"

Project Investigator:	***Carol Cleland***

Project Progress

I continued investigating the question of how to search for extraterrestrial life in the absence of a definition of 'life'; in previous work, I concluded that it is a mistake for scientists to try to define "life". Because we lack a general theory of living systems it is unlikely that scientists will recognize genuinely strange life for what it is if they come across it. Recognizing strange life presupposes an adequately general theory of life, and formulating the latter requires systematically searching for what Thomas Kuhn called "anomalies." Anomalies are physical systems that resemble terrestrial life in provocative ways and yet are neither clearly living nor clearly non–living. The recognition of strange life thus begins with the verification and exploration of anomalies as grist for the theoretical mill. Verification presupposes the identification and use of trustworthy terrestrial biosignatures to help distinguish genuine anomalies from uninteresting false positives and false negatives arising from unanticipated interfering conditions; this represents an application of my previous work on historical science. The exploration of anomalies requires that anomalies become a focus of research—something sought out and pursued—rather than dismissed on speculative theoretical grounds (that inevitably reflect our pre–existing theoretical conceptions of life). The basic idea is to push beyond the boundaries of life as we know it.

My investigations into this area are currently two pronged. I am pursuing (with biochemist Shelley Copley) the possibility that Earth is home to strange microbial life that has hitherto not been recognized because our techniques for identifying microbial life are based too closely on the biochemistry and molecular biology of familiar terrestrial life. I am also beginning work on the question of how to search for and recognize potentially fruitful anomalies to our current concept of life. This is related but not identical to the question of designing suites of biosignatures for detecting extraterrestrial life; it differs from it insofar as the search is not for biology per se but for physical systems that are provocatively similar to and yet also different from familiar life.

Highlights

- When it comes to genuinely strange extraterrestrial life, it is not at all clear that we will recognize it if we see it. Our capacities to recognize life are constrained by our current beliefs about life, and these in turn are based upon our limited experience with familiar terrestrial life.
- The search for genuinely strange extraterrestrial life begins with the verification and exploration of anomalies, physical systems that resemble terrestrial life in provocative ways and yet are neither clearly living nor clearly non–living. It is only through the discovery of anomalies that we will be able to push beyond the boundaries of life as we know it on Earth.

Roadmap Objectives

- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3	life definition	Co–Investigator

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Project Report: The impact of atmospheric particles on life

Project Investigator:	***Owen Toon***

Project Progress

During the past year the group made progress in a number of areas. Melissa Trainer, a student in Maggie Tolbert's group, completed two sets of experimental studies related to the formation of aerosols in the early atmosphere of Earth and the current atmosphere of Titan. As had been predicted in some theoretical studies we found that the production rate of aerosols declines as the abundance of CO_2 relative to methane increases in simulated terrestrial atmospheres. This paper has been submitted to the journal Astrobiology. We also found that PAHs and terpene related compounds can be formed in Titan's atmosphere, with the unexpected result that the type of organic compounds formed shifts for CH_4 to N_2 ratios close to those in Titan's current atmosphere. This work has been submitted to the special issue of GRL on predictions for Cassini. Jen Heldmann graduated from the University of Colorado and moved to NASA Ames. She recently published a paper in Icarus related to gulley formation on Mars. Her work shows that the gullies are likely related to underground liquid water reservoirs and probably were formed under current Martian climate conditions. They represent the most likely place to find life on Mars in our opinion. Tian Feng has completed a study of the escape of H_2 from extrasolar planets and from the early Earth. We have submitted the extrasolar planet work to the Astrophysical Journal. It explains the observed structure of one extrasolar planetary atmosphere, and shows that planets can evaporate in the inner solar system. The terrestrial work points to hydrogen rich atmospheres with hydrogen partial pressures above 1 bar on early Earth. Brian Toon working with a group of paleontologists examined the evidence for survival at the KT boundary. In a paper in Geological Society of American Bulletin they showed that the initial in–fall of debris broiled all unprotected creatures alive within hours. Hence only those sheltered in holes or water survived. Alex Pavlov has submitted a paper to Nature showing that passage of the Earth through an intergalactic dust cloud would have plunged the Earth into a snowball state.

Several students, Melissa Trainer, Dan Curtis, Jen Heldmann, Teresa Segura, Kaj Williams, and Atilla Elteto, continued in the NASA Graduate Student Researchers Program (GSRP), or won new fellowships in that very competitive program. Maggie Tolbert was elected to the National Academy of Sciences.

Highlights

- Melissa Trainer, a student in Maggie Tolbert's group, completed experimental studies showing, as had been predicted in some theoretical studies, that the production rate of aerosols declines as the abundance of CO_2 relative to methane increases in simulated ancient terrestrial atmospheres.
- Melissa Trainer, a student in Maggie Tolbert's group, completed experimental studies showing that PAHs and terpene related compounds can be formed in Titan's atmosphere, with the unexpected result that the type of organic compounds formed shifts for CH_4 to N_2 ratios close to those in Titan's current atmosphere.
- Jen Heldmann showed that the gullies on Mars are likely related to underground liquid water reservoirs and probably were formed under current Martian climate conditions. They represent the most likely place to find life on Mars in our opinion.
- Tian Feng completed a study of the escape of H_2 from extrasolar planets and from the early Earth. The work explains the observed structure of one extrasolar planetary atmosphere, and shows that planets can evaporate in the inner solar system. The terrestrial work points to hydrogen rich atmospheres with hydrogen partial pressures above 1 bar on early Earth.
- Brian Toon working with a group of paleontologists examined the evidence for survival at the KT boundary. They showed that the initial in−fall of debris broiled all unprotected creatures alive within hours. Hence only those sheltered in holes or water survived.
- Alex Pavlov has submitted a paper to Nature showing that passage of the Earth through an intergalactic dust cloud would have plunged the Earth into a snowball state.
- Maggie Tolbert was elected to the National Academy of Sciences.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

EPO: University of Colorado, Boulder

These are the Education and Public Outreach activities for the University of Colorado, Boulder.

Journalist Professional Development Workshop on Mars

In December of 2003, the University of Colorado's Center for Astrobiology, the Laboratory for Atmospheric and Space Physics, and Center for Environmental Journalism joined together to host a 2–day workshop for journalists on Mars System Science and the MER landings. The workshop was funded as part of the Center for Astrobiology's E/PO efforts for the NASA Astrobiology Institute and served as a trial balloon for professional development of media professionals. We had twenty participants from across the country, primarily from the ranks of elite print media, along with eight scientists and educators from University of Colorado (CU), the Jet Propulsion Laboratory (JPL), and NASA Ames Research Center. Participants filled out pre– and post–workshop questionnaires designed to tailor the program to their needs and to determine how successfully their goals were met. During the workshop, participants heard lectures by a variety of Mars experts on Mars geological history, the MER missions and their scientific context, and the history of Mars exploration and plans for the future. In addition, there were roundtable discussions on the role of journalists in science education for the general public and how to increase the quality of communication between scientists and journalists. Feedback from the post–workshop surveys indicated that the journalists not only felt that the workshop was a worthwhile use of their time, but that it had impacted the quality of their writing as the MER missions continue. Many, including several regional journalists, commented that the workshop provided a level of background information that would help them for years to come not just for their writing on the MER missions. Several commented that this type of professional development, more common in other areas of science, was largely missing in space sciences. At the same time, participants pointed to the notion that this kind of workshop should not be sponsored by NASA directly but rather through universities or museums to retain objectivity, balance, and credibility within the community.

Public Symposia

In 2003–2004, three scientists from the CUB team visited Hampton University for a 2–day public symposium targeting undergraduates interested in astrobiology. In addition, we held a public symposium here at CU–Boulder in February that targeted the general public.

Public Talks, Interviews, Books and Popular Articles

PUBLIC TALKS: Bruce Jakosky 29 Aug, "Life on Mars?" CU Fiske Planetarium, "Mars Madness" symposium, Mars opposition. Bruce Jakosky 21 Nov, "Life elsewhere in the Solar System?" astrobiology outreach symposium, Hampton Univ., Hampton, VA. Bruce Jakosky 13 Dec, "Mars exploration and the potential for life elsewhere," CU Mars Science Journalist Workshop, CU. Bruce Jakosky 24 Jan 04, "The Spirit mission to Mars," LASP Open House for the Opportunity landing, LSTB. Bruce Jakosky 12 Feb 04, Convenor and moderator, Public Symposium on "Mars Exploration Rover Results and the Future of Space Exploration," CU. Bruce Jakosky 4 Mar 04, "Astrobiology, science, and religion," Phi Beta Kappa Foundation annual banquet, Denver. Bruce Jakosky 8 Mar 04, "Life Elsewhere: The role of science and religion in society," University of Arkansas, Barringer lecture. Bruce Jakosky 12 Mar 04, "The Mars Exploration Rover missions and the search for water on Mars," Boulder Rotary Club. Bruce Jakosky 20 May 04, "Mars rover results, liquid water, and the potential for life," Colorado Scientific Society, Golden. John Bally June 4 public presentation at Fiske Planetarium "Birth of Stars and Planets." John Bally April 2 public talk at the Denver Astronomical Society on the DU campus "Formation of Massive Stars."

Bob Pappalardo "The Search for Europa's Ocean" for Colorado Springs Astronomical Society (May 25, 2004).

Bob Pappalardo "The Search for Europa's Ocean" for the Longmont Astronomical Society (June 17, 2004).

Tom McCollom gave talks on the MER landing sites at each of the Mars Landing Open Houses at LASP in January.

PUBLICATIONS:

Mojzsis, S.J. (2004) Life in the first billion years: Journal of High School Science (Canada) 3 (1), 46–51. Public service/outreach activity for high school science students in Canada and USA.

Mojzsis, S.J. (2004) Atmosphere evolution, In Encyclopedia of Geology, edited by R. Selley, R. Cocks and J. Youngquist: Academic Press, London (in press). Long book chapter, meant for a general science readership.

Mojzsis, S.J. (2003) Probing early atmospheres: Nature 425 (6955), 249–251 doi:10.1038/425249a. Nature News and Views article.

Mojzsis, S.J. (2003) The Early Earth: Physical, Chemical and Biological Development: Eos Trans. Amer. Geophys. Union 88 (36), 358. Book review.

Pappalardo, R. (2004) Jupiter's Water Worlds. Astronomy, v. 32(7), 34–71.

John Bally, (2004) Astronomy, v. 32(7), 34–71.

OTHER MEDIA:

In 2003–2004, Bruce Jakosky gave media interviews related to Mars, astrobiology, NASA programs.

In 2004, Steve Mojzsis was involved in two NOVA television specials in cooperation with WGBH (Boston) public television and Channel 4 in the UK that highlight his work and that of colleagues in Astrobiology. These programs have already aired in the UK. Anticipated US airdate: Fall 2004.

In 2003, Steve Mojzsis gave numerous radio, magazine and newspaper interviews regarding ongoing controversies surrounding the earliest evidence of life on Earth as chemical or morphological fossils (e.g. Simpson, S. (2003). Questioning the oldest signs of life: Scientific American April issue.

OTHER E/PO ACTIVITIES: Bruce Jakosky convened "Frontiers of Mars Exploration: Geology, climate, and life," AAAS meeting, Denver. Bruce Jakosky organized and lectured in the NAI Insight Course in Planetary Science, 30 July to 4 August, 2003, Flagstaff.

Undergraduate Course

"Extraterrestrial Life" is an undergraduate course cross–listed in Geological Sciences and Astronomy.

Publications: University of Colorado, Boulder

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Des Marais, D.J., Allamandola, L. J., Benner, S. A., Boss, A. P., Cronin, J. R., Deamer, D., Falkowski, P. G., Farmer, J. D., Hedges, S. B., Jakosky, B. M., Knoll, A. H., Liskowsky, D. R., Meadows, V. S., Meyer, M. A., Pilcher, C. B., Nealson, K. H., Spormann, A. M., Trent, J. D., Turner, W. W., Woolf, N. J. & Yorke, H. W. (2003). The NASA Astrobiology Roadmap. *Astrobiology*, 3: 219–235.

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Harris, J.K., Kelley, S.T., Spiegelman, G.B. & Pace, N.R. (2003). The genetic core of the universal ancestor. *Genome Research*, 13: 407–412.

Heldmann, J.L. & Mellon, M.T. (2003). Observations of martian gullies and constraints on potential formation mechanisms. *Icarus*, 168: 285–304.

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Jakosky, B.M. (2003). Astrobiology as a science: A scientist's view of exploration and historical science [Abstract]. AAAS (American Academy of Arts & Sciences) Workshop on Origin of Life, Washington, DC.

Jakosky, B.M. & CoBabe–Ammann, E. (2004). Educating and informing the public in astrobiology through educating and informing science journalists [Abstract]. AbSciCon 2004, NASA Ames Research Center, Moffett Field, CA. International Journal of Astrobiology, Supplement 1 (March): 92.

Jakosky, B.M. & Mellon, M.T. (2004). Mars ground ice: Stability at the present epoch at low and mid latitudes and implications for astrobiology [Abstract]. AbSciCon 2004, NASA Ames Research Center, Moffett Field, CA. International Journal of Astrobiology, Supplement 1 (March): 83.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

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Team Reports: University of Hawaii, Manoa

University of Hawaii, Manoa
Executive Summary
Principal Investigator: Karen Meech

Water is the medium in which the chemistry of all life on Earth takes place. Water is the habitat in which life first emerged and in which all of it still thrives. Water has modified Earth's geology and climate to a degree that has allowed life to persist to the present epoch. We propose to create a research and education framework that links the biological, chemical, geological, and astronomical sciences to better understand the origin, history, distribution, and role of water as it relates to life in the universe. We focus on scenarios involving the sources and distribution of water in planetary systems and the delivery and incorporation of water into rocky planets that orbit within the “habitable zones” of their parent stars. Our framework will include and connect research on major aspects of planetary water—in effect we aim to understand the terms of a “watery Drake equation” (Figure 1). Sub–themes of our research include the following:

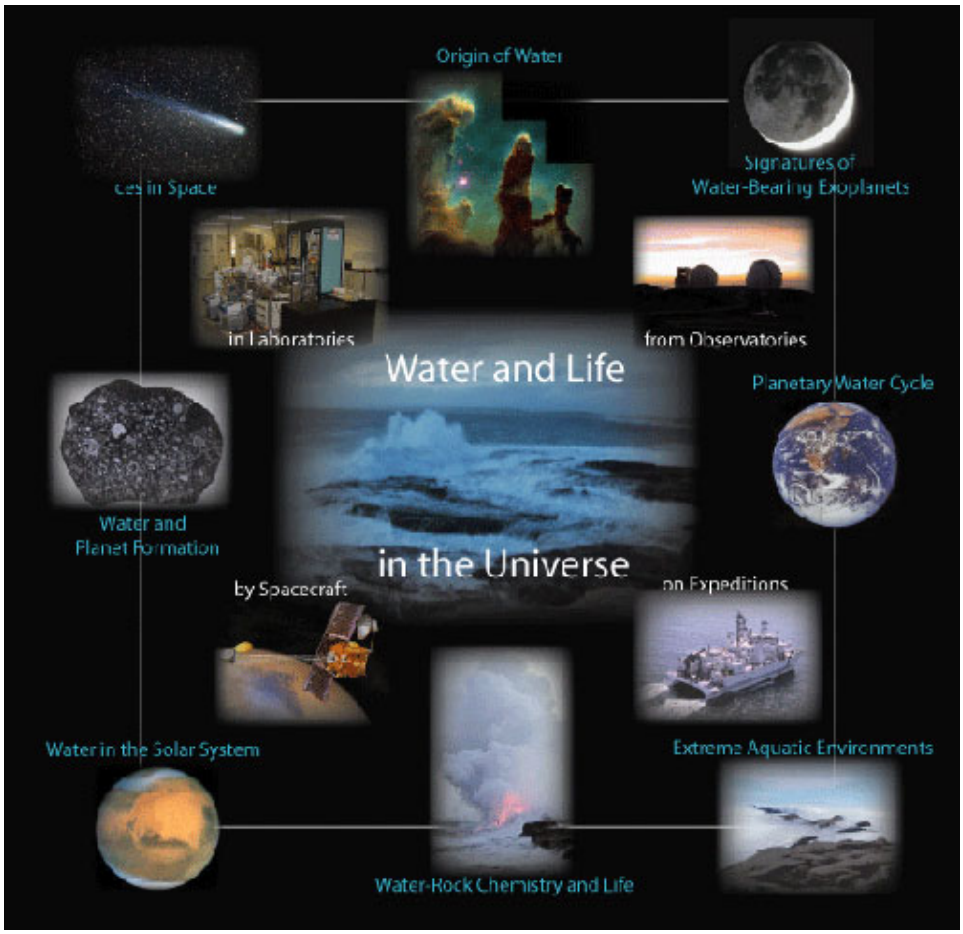

Figure 1. The Watery Drake Equation.

• Water is formed in the interstellar medium and in the denser molecular clouds that give rise to star–forming regions. Differences in elemental abundance, gas–phase chemistry, and grain chemistry will result in measurable variation in the abundance of water in those regions. Our team will use the powerful new sub–millimeter and infrared facilities on Mauna Kea to quantify the presence of water ice in the interstellar clouds, and to characterize and understand the environments where water exists in space (such as circumstellar disks).

• Comet ices preserve a chemical record of this precursor interstellar material, and detailed remote measurements of the isotopes of hydrogen in these icy bodies has shown that comets contributed some, but not all of the water to the Earth's oceans. Comets are also rich in the organic materials that are essential for life on Earth. Team members will investigate the inventory of both organics and ices in these small outer solar system denizens, specifically the comets, Centaurs, and Kuiper Belt objects.

• Because of the high abundance of water ice in the interstellar medium, water has played a vital role in physical and chemical processes that have lead to the formation of astrobiologically important molecules. University of Hawaii (UH) NAI team members will perform cutting–edge laboratory chemistry experiments to address, for the very first time, the important questions of how the basic life ingredients can be formed abiotically in extraterrestrial environments such as

molecular clouds, and the crucial role that water has played in their formation, and to understand the physical processes, as well as understanding the physics of complex molecule trapping, and formation on interstellar water−rich grain mantles and planetary ices.

• UH NAI team members will also use lab equipment to study the minerals in meteorites that formed as a result of interaction with liquid water early in the solar system. These minerals preserve a record of aqueous activity in their parent bodies that provides information about the abundance and distribution of water in the primordial solar nebula.

• The meteorites record the incorporation of water into silicate material in the primordial Solar System as an early step in its eventual inclusion in larger bodies, including planets. The cosmochemical record in meteorites shows that a large range of water abundance existed in the early Solar System, perhaps as a result of removal of water from the warm interior of the primordial nebula.

• Mars is the planet most resembling Earth; it contains unambiguous evidence for the activity of past and present water, and is probably the most likely to host or have hosted extant or extinct life. Studies of the history and action of water on Mars are thus of great importance in this regard. Our studies will model the hydrothermal and low−temperature alteration of crustal minerals and rocks by water, and team members will combine this with data from Earth observations and recent Mars missions to assess the Mars water inventory and its habitability.

• Water has been involved in life since its first appearance on the early Earth. The leading theories of the origin of life invoke prebiotic chemistry in low−temperature aqueous solutions, supplied with prebiotic molecules by atmospheric chemistry, or in the hydrothermal brines produced by high−temperature water−rock interactions. The first three billion years of the drama of life on this planet was played out entirely in aquatic environments. Water is also involved in geochemical reactions that maintain surface conditions permissive of life. The presence of water significantly alters the properties of minerals in Earth's crust and mantle, something crucial to the operation of plate tectonics. These geologic processes, in turn, drive many of the biogeochemical cycles important to Earth's habitability. Our team will investigate the water−rock chemistry in the deep oceans and its relation to habitats for life. The reaction between silicate rocks and water, particularly at high temperature (e.g., at submarine hot springs near mid−ocean ridges), produces aqueous fluids and altered mineral surfaces whose thermodynamic disequilibria are potential energy sources for life.

• Besides water, life also requires a source of carbon and nutrients, and an environment that is conducive to the propagation of genetic information. Many aquatic environments on Earth are challenging or “extreme” from the point of view of these other requirements. By studying these we can better understand what may limit the origin and persistence of life in aquatic habitats elsewhere in the universe. These extreme environments include lava−water interfaces in the Hawaii Volcanoes park as the magma from Kilaeua flows into the ocean, as well as steam geysers, high altitude lakes (such as lake Waiau on Mauna Kea),

and field work in volcanically active Iceland. We will focus here on a comparative study of microbial biodiversity and metabolic activity in these extreme aquatic habitats.

• We will develop an integrated model of planetary water and its early history on Earth−like planets, which can be used to explore the time−evolution of water on the early Earth, as well as Earth−size planets whose space environment or composition differ from Earth's. Extraterrestrial aquatic environments may be far more extreme than most encountered on Earth. Water inventories and cycles in Earth−sized planets around other stars may be quite different from our own. Planetary water abundance may be a very sensitive function of the chemistry in the planet−forming nebula, the water abundance in that nebula, the presence of giant planets and factors such as ultraviolet radiation from the central star.

• Finally, we will develop concepts and prototype hardware for instruments that could be used to detect and characterize life on other planetary bodies.

• By developing and testing models, and exploring the outcomes of alternative scenarios, we seek to determine what controls the abundance and distribution of water and hypothetical aqueous habitats in other planetary systems. This research will directly support the NASA search for past or present life on Mars and efforts (such as the NASA Terrestrial Planet Finder) to directly detect and characterize Earth−sized exoplanets.

Accomplishments

We are halfway through our first year, and most of our work can be characterized as getting set up. Nevertheless, we do have some initial science accomplishments.

Infrastructure set up

• The proposed framework of our research will support a group of postdoctoral scholars who will carry out independent, interdisciplinary research spanning two or more of the investigators' (or affiliated investigators') research specialties. Considerable effort was made this year in the recruitment of eight postdoctoral fellows; two additional fellows will be recruited next year. The postdocs arrived between June and October, and the others will arrive over the summer.

• We have negotiated with the University and acquired ~1800 sq. ft. of centrally located campus space for our postdoctoral “Water Hole” (office area and meeting facilities). Major renovations on the room are complete, and the procurement has begun for carpeting, furniture, and computer equipment.

• We have established an NAI Visiting Faculty Scholars Program, including acquiring and furnishing a visiting faculty apartment within walking distance of the University of Hawaii Campus . As part of the program we have established an NAI Visiting Faculty Scholar Committee and guidelines for its operation, and have received our first visitor under this program, Akiva Bar−Nun from the Tel

Aviv University ; he is actively working with several of our team members.

• We commissioned and calibrated a novel ultra high vacuum surface scattering machine in the chemistry department to investigate the formation of astrobiologically important molecules in the interstellar medium and in our solar system.

• Leveraged against the UH NAI grant, we have obtained NASA and DOD funding that use UH−NAI grant personnel to design, construct, and test a prototype laboratory miniature instrument for direct mass spectral analysis of liquids. We have built an initial laboratory prototype and demonstrated ionization at low vacuum (~3 Torr).

• We have also obtained National Science Foundation (NSF) funding that leverage UH−NAI grant personnel to design, construct, and test a prototype instrument for contamination−free sampling of basement rock fluids from deep−sea boreholes.

Science Results

- Cryogenic experiments, in collaboration with colleagues in Israel, with amorphous gas−laden water ice samples show that pre−perihelion activity in comets at large distances may be explained by the annealing (re−organization of the crystal structure) of the water ice which allows the trapped gases to escape.
- We have conducted experiments using the newly commissioned UH ultra high vacuum surface scattering machine, on the formation of two C_2H_4O isomers and nitrous oxide in interstellar ices, and have 3 papers in progress.
- The discovery and subsequent follow up of a discovery of a major accretion event and flare up in a young circumstellar disk has lead to the development of a new model for the onset of these events. This has important implications for short−lived heating events in early solar systems that might contribute to chondrule formation and aqueous alteration of early solar system material.
- Inorganic generation of hydrogen gas during hydration of mantle rock may fuel microbial life on other planets, as it does on Earth. This process has been demonstrated in serpentinite mud volcanoes in the Mariana forearc, on the floor of the Western Pacific Ocean, where it supports a community of Archaea.

New Collaborations and Initiatives

• Co−I Binsted has established a collaboration with NAI Ames member C. McKay, and they have submitted a major NASA equipment proposal to develop an innovative new sensor network andto deploy it in the arctic for hydrology research.

Mission Involvement

• UH NAI Principal Investigator K. Meech is a co−Investigator on NASA's Deep Impact mission. In addition to coordinating science observations of the comet target, 9P/Temple 1 with the goals of our comet/water investigations, we are planning a large UH−NAI lead outreach effort at the time of the mission. This will include teacher workshops leading up to the date of Encounter (July 4, 2005) and observing with the Faulkes Telescope facility on Maui . Two new graduate students have joined the UH NAI group to work on Deep Impact and Astrobiology−related projects.

• Co−I Toby Owen is heavily involved with the Cassini Saturn mission.

Education/Public Outreach Activities

K−12 Programs :

• Alii Summer Teacher Workshop – The first Astrobiology Laboratory Institute for Instructors was held June 14−18, 2004 . This was a collaboration with 2 NAI teams, SETI and Indiana−Princeton−Tennessee Astrobiology Initiative (IPTAI). Over 50% of the UH NAI team scientists contributed lectures, laboratory tours, and hands on activites to this program.

• Deep Impact and the Faulkes Telescope Facility – Development of a teacher−training program to utilize the 2−m Faulkes telescope on the summit of Haleakala, Maui , is underway. Workshops for Spring, 2005, are planned to prepare teachers so that they can utilize this resource (a research−grade telescope dedicated to outreach) to contribute to the Deep Impact mission encounter during July, 2005. This will also be the initiation of a more in−depth Faulkes teacher−training program. This telescope will be available for general use in October, 2004.

• Student Programs – Ten Hawaiian teachers and two from the mainland, trained in 2003, spent the fall, 2003, and spring, 2004, mentoring 59 students for astrobiology research projects. Of these students, 50% entered their projects in school science fairs, and 17% were recommended for State Fair (three projects receiving awards). One project was recommended for the Intel International Fair.

Public Outreach

• Hawaii Volcanoes Park – We are beginning a collaboration with the NASA Ames NAI EPO team, which has fostered a partnership with Yellowstone National Park . We intend to replicate this activity in the Hawaii Volcanoes National Park . Contact has been made with park staff, and plans are underway to collaborate with a PI at the Berkeley Space Sciences Lab to get an EPO grant from NASA for this project.

• Astrobiology Traveling Exhibit – We are collaborating with the NAI Carnegie team for loan of this traveling exhibit. This will be displayed from January−April, 2005, on all islands, with Aloha Airlines donating inter−island freight. We will plan science activities and lectures with our team members on each island.

Graduate Programs

• Astrobiology Winter School – We are collaborating with the University of Arizona (UAZ) NAI team to offer an Astrobiology Winter School for approximately 40 graduate students annually each January. The school will be offered in alternate years in Hawaii and Tucson . Both UH and UAZ are developing “boards” to plan the winter school content each year, and we will exchange two scientists to be on each other's boards. The first Winter school will be held for two weeks in Hawaii during January, 2005, with the theme of “Water in Space and on Earth.” The instructors will be UH NAI team scientists and collaborators.

• Astrobiology Seminar Series – We have set up an astrobiology seminar series, a one−credit seminar for UH graduate students and advanced undergraduates, to be offered in the Fall, 2004. All UH NAI team co−Is and postdocs will be participating.

Other Collaborative Efforts

• Star and Planet Formation Day – UH NAI Co−I B. Reipurth organized a scientific symposium at the Institute for Astronomy as part of our NAI activities on February 26, 2004 . Many of the local NAI team members and collaborators participated. The program is included in the table below.

09:30	Colin Aspin	Near−IR Spectroscopy of Herbig−Haro Energy Sources
09:50	Tracy Beck	Variations in Obscuration toward T Tau South
10:10	Crystal Brogan	W51B/W51C: Shock Triggered Star Formation?
10:30	Chris Davis	Near−infrared IFU Spectroscopy of Star Forming Regions at UKIRT
10:50	Eric Gaidos	Age−dating of Stars and Planetary Systems using Giant Planets
11:10		Coffee Break
11:30	Masa Hayashi	Subaru Disk and Planet Searches
11:50	George Herbig	NGC 1579 and LkHa−101
12:10	Klaus Hodapp	The Earliest Stages of Star Formation in NGC 1333
12:30	Martin Houde	The Orientation of the Magnetic Field in Molecular Clouds
12:50	Robert Jedicke	Space Weathering on Asteroids
13:10		Lunch
14:00	David Jewitt	CO in Cometary Precursors
14:20	Ralf Kaiser	Formation of Astrobiologically Important Molecules in Extraterrestrial Ices
14:40	Michael Liu	Brown Dwarf Disks in the Mid−Infrared
15:00	Karen Meech	The Deep Impact Mission
15:20	Gerald Moriarty−Schieven	A Complete Survey of Star Formation in L1551
15:40		Coffee Break

16:00	Tae−Soo Pyo	Spectroscopic Study of [FeII] Outflows with High Angular Resolution
16:20	Bo Reipurth	Companions to FU Orionis Objects
16:40	Ed Scott	Dust in the Protosolar Disk: Clues from Matrices of Primitive Meteorites
17:00	Alan Tokunaga	Infrared Spectroscopy and Imaging of KH15D
17:20	Jonathan Williams	SMA Observations of the Orion Proplyds

- The 2004 Bioastronomy Meeting – UH NAI Team members and collaborators have played a major role in the set up of the Bioastronomy 2004 meeting. UH NAI lead, Meech, is President of Commission 51 (Bioastronomy) of the International Astronomical Union, and it was her proposal that the meeting be held in Iceland. UH NAI Collaborator Thorsteinn Thorsteinsson was contacted and agreed to chair the local organizing committee with Meech as one of the members. UH NAI members Meech, Gaidos, and collaborators Ehrenfreund and Thorsteinsson are on the Science organizing committee. Meech has done all the fund−raising for the meeting, including securing NAI sponsorship.
- The development of two 16−inch telescopes, one for Hawaii and one for Cerro Tololo Observatory in Chile, has begun in order to do all−sky monitoring of star forming regions to create temporal catalogs of the variability of young stars.
- We have undertaken a collaboration with Lowell Observatory colleagues in order to gain access to some telescope time for our UH NAI research and outreach programs. To this end we have been developing an intelligent scheduler for automated scheduling of the telescope driven by requests. The Lowell 31−inch telescope observing database has been upgraded. An interface to interact with the database has been created, and an intelligent scheduler developed and nearly fully debugged. Anticipated completion is expected during summer, 2004. The complete system will be used for scheduling astronomical observations, both for research and outreach.

Project Report: Autonomous Sensor Networks for Hydrology Research

Project Investigator:	***Kimberly Binsted***

Project Progress

Co−I Kim Binsted has started a collaboration with Chris McKay (Ames NAI team) by submitting a proposal to develop a system of autonomous sensor networks in the Arctic for hydrology research. Autonomous sensor networks are desirable for conducting research on Earth, and essential on other planets. In remote locations with extreme environments, it is expensive and often hazardous to retrieve data manually. Because distance limits opportunities for fixing problems, the network must be robust, and conduct self−repair, if possible, or carry out damage−limiting strategies, if not. Canada 's High Arctic is a useful analog for conditions on Mars and Europa, both in the scientific questions posed by its ecosystems, and in the technological challenges involved in gathering data there. We propose to build an autonomous sensor network in the Expedition Fiord region of Axel Heiberg Island, to conduct hydrological research relevant to astrobiology, and to advance the state of the sensor network technology. The overall objectives are:

- To augment existing sensor network protocols in order to support efficient, robust, and autonomous data collection and transmission in extreme environments.
- To deploy an autonomous sensor network in the Expedition Fiord region of the Arctic .
- To collect and analyze data on the growth and movement of ice in this hydrologically important region.
- To evaluate the performance of the sensor network, both with regards to its performance in the Arctic environment, and the potential for deployment of similar technology elsewhere in the solar system.
- To give high school and college students access to this near real time data, so they can observe, and participate in, the research effort.

Highlights

- Co−I Binsted has established a collaboration with NAI Ames member C. McKay, and they have submitted a major NASA equipment proposal to develop an innovative new sensor network and to deploy it in the Arctic for hydrology research.

Roadmap Objectives

- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Cross Team Collaborations

NASA Ames Team – Chris McKay. Collaboration is just beginning.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: University of Hawaii, Manoa

Project Report: UH NAI Visiting Faculty Scholars Program

Project Investigator:	***Karen Meech***

Project Progress

The University of Hawaii (UH)–NAI has established a Visiting Faculty Scholars program that brings external collaborators to work with local researchers. The program will inject a breadth of innovative ideas to the UH–NAI, and strengthen our interdisciplinary research. We have secured a two–bedroom apartment in the University of Hawaii Faculty housing complex across the street from the Institute for Astronomy (IfA) to host our visitors up to three months each year. The director of the Institute for Astronomy has agreed to pay for the other 75% of the year for IfA visitors to make this apartment a viable resource. Further, the IfA has contributed $4,000 toward furnishing the facility. The facility was set up during June, 2004, and our first visitor, Akiva Bar–Nun, has arrived from Tel–Aviv University for a period of two months. Already, there has been considerable interaction among team members with our first visitor. In addition, we have established a visitor committee (NAI team members: Gaidos, Kaiser, and Reipurth), and the IfA has established a visitor committee, and a policy document has been set up regarding criteria for use of the visiting faculty facility. Our team is now entertaining proposals for additional visitors. The committee will meet quarterly, and review applications consisting of a short proposal and a curriculum vitae.

Figure 1. Master bedroom in the UH NAI / IfA Faculty visitor facility

Figure 2. Second bedroom in the UH NAI / IfA Faculty visitor facility

Figure 3. Dining room area in the UH NAI / IfA Faculty visitor facility.

Figure 4. Kitchen in the UH NAI / IfA Faculty visitor facility

Highlights

- We have acquired and furnished a visiting faculty apartment within walking distance of the University of Hawaii Campus.
- We have established an NAI Visiting Faculty Scholar Committee, along with guidelines for its operation in cooperation with the UH Institute for Astronomy.
- We have received our first long–term visitor under this program, Akiva Bar–Nun, here from Tel–Aviv University in Israel – sponsored in part by the UH NAI and in part by his home institution. He is here working with Meech, Owen, and Gaidos.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Project Report: Subglacial Sampling in Iceland

Project Investigator: ***Eric Gaidos***

Project Progress

University of Hawaii (UH) NAI–funded preparations for July field work at several sites in Iceland are underway. These activities will be coordinated with the 2004 Bioastronomy meeting in Reykjavik . The goal is to collect glacial melt water, sediment, and sub–aerial lake samples that will serve as the additional basis for a second hot–water drilling program to sample subglacial lakes in Iceland in 2005. The results of the first expedition, which is the first report of a viable subglacial lake (microbial) community, are in press in *Astrobiology* and will be presented as a poster at the Bioastronomy meeting. The July, 2004, field work will be conducted with Thorsteinn Thorsteinsson, UH NAI collaborator, and concentrate on sampling glacial streams and emerging glacial sediments at the northern and western margin of the Vatnajokull ice cap. We will also reconnoiter the geothermal area of Kverkfjoll, one of three proposed drilling sites for investigating subglacial water bodies. Finally, we plan to sample a large number of Icelandic subaerial lakes to construct a geochemical and microbial database with which to compare current and future subglacial data. Preparations at UH have included purchase of a moderate–volume centrifuge for microbiology work and various sampling supplies (e.g., pumps, filters).

Ms. Mary Miller (U.S. Army and Embry–Riddle University) is working as a volunteer in the Gaidos lab on isolating cyanobacteria from calcareous mats in a Mount Saint Helens hot spring. Miller participated in the sampling field work in September, 2003, and fulfilled her independent project requirement for her degree at Embry–Riddle. She presented preliminary results at the March, 2004, general Astrobiolgy meeting at NASA Ames. She is currently investigating aspects of co–culturing different cyanobacteria.

Mr. Nick Moskovitz, a graduate student at the Institute for Astronomy, will be working with Gaidos starting in the fall of 2004, on projects involving the extreme ultraviolet spectra of young stars, and light curve signatures of habitable planets.

Figure 1. Grimsvotn subglacial volcano on the Vatnajokull ice cap. Photo courtesy of Oddur Sigurdsson.

Highlights

- UH NAI–funded preparations for July field work at several sites in Iceland are underway to collect glacial melt water, sediment, and sub–aerial lake samples which will serve as the basis for a hot–water drilling program in Iceland in 2005.
- A program of student involvement in UH NAI research projects has begun, and students Mary Miller and Nick Moskovitz are working on projects involving culturing cyanobacteria and the light curves of habitable planets, respectively.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Field Expeditions

Field Trip Name: Iceland Subglacial Sampling

Start Date: July 17, 2004	***End Date:*** July 24, 2004
Continent: Iceland	***Country:*** Iceland
State/Province:	***Nearest City/Town:*** Vik
Latitude: 64.65 N	***Longitude:*** 16.72 W
Name of site(cave, mine, e.g.): Glacier	***Keywords:*** glacier, meltwater, microbial database

Description of Work: We will concentrate on sampling glacial streams and emerging glacial sediments at the northern and western margin of the Vatnajokull ice cap. We will also reconnoiter the geothermal area of Kverkfjoll, one of three proposed drilling sites for investigating subglacial water bodies.

Members Involved:
Thorsteinn Thorsteinsson
Eric Gaidos

Project Report: Post Doc Recruitment – Water and its Relation to Life in the Universe

Project Investigator:	***Karen Meech***

Project Progress

Our research framework design involves supporting a group of postdoctoral scholars who will carry out independent, interdisciplinary research spanning two or more of the investigator's research specialities. The postdocs will share a common office environment, the “Water Hole,” in an innovative means of fostering interdisciplinary collaborations. Our first recruitment began in August, 2003; our first batch of offers went out this spring, and a group of eight talented postdocs arrived during July through September 2004. The postdocs and their research, as it relates to our group program, are described below.

Andrew Boal – Ph.D., University of Massachusetts (2002), organic chemistry. Currently: Postdoc at Sandia National Laboratories. Andrew will be investigating biomolecular structure and function in extreme aqueous environments. He will be looking at potential designs of molecules that could predate present biomolecules, to develop a picture of those that might have existed in Earth's early oceans with implications for possible biomolecules on extrasolar planets.

Mark Brown – Ph.D., University of Tasmania (2000), molecular phylogeny of polar sea ice microbial communities. Currently: Postdoc at Wrigley Institute of Environmental Studies. Mark will investigate prokaryotic and eukaryotic microbial biogeography in the extreme environments of cold lake ecosystems. This work will have impacts on understanding of biodiversity, evolution, and ecosystem structures.

Lysa Chizmadia – Ph.D., University of New Mexico (2004), Geochemistry. Lysa will investigate the chemistry and isotopic composition of aqueously altered chondritic meteorites to understand the timing and physico–chemical conditions of aqueous alteration in asteriods. This will help clarify how and when water was accreted into asteroids and planets.

Audrey Delsanti – Ph.D., Observatoire de Paris–Meudon (2004), physical properties of Kuiper Belt objects (KBOs). Currently teaching astronomy to high school teachers. Audrey proposes to investigate the inventory, distribution, and state of water and organic molecules in minor bodies in the outer solar system

(comets, KBOs, and icy satellites), using the facilities on Mauna Kea , combined with chemical lab work.

Brian Glazer – Ph.D., University of Delaware (2004), investigation of microbial community structure and function in relation to geochemical redox gradients. Brian will be conducting research on microbial communities showing that the phylogenetic, physiological, and biochemical diversity will reflect environmental geochemistry. Brian will apply his approaches to address the origin of life on earth and its early succession.

Nader Haghighipour – Ph.D., University of Missouri (1999), planetary dynamics. Currently working as a postdoc with Alan Boss at the Carnegie Institution of Washington. Nader will be doing a theoretical investigation of the delivery of water to the terrestrial planets as influenced by the planet formation process and dynamical evolution of the system. Nader will also investigate planet formation in dynamically complex systems, focusing on the formation of life−harboring planets.

Norbert Schorghofer – Ph.D., University of Chicago (1998), physics. Currently working as a postdoc with Oded Aharonson at the California Institute of Technology. Norbert will investigate water ice on Mars, in part through theoretical investigations and by using Mars Orbiter data. Mapping the appearance and disappearance of water and carbon dioxide frost, Norbert will investigate the seasonal and inter−annual variations in the water cycle, and will investigate the stability of water at equatorial latitudes.

Weijun Zheng – Ph.D., Johns Hopkins University (2004), chemistry. Weijun will investigate the role of water in the formation of biologically important sugars in hostile extraterrestrial environments in the interstellar medium. Weijun will conduct laboratory investigations on the effects of charged particle processing of interstellar ices.

Highlights

- We have conducted our first postdoctoral recruitment, and have eight talented postdocs starting in the period July−September 2004.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
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- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Project Report: Miniature Mass Spectrometer Development

Project Investigator:	***F. Scott Anderson***

Project Progress

The NAI has allowed us to collaborate with Steven Smith at the Jet Propulsion Laboratory to expand development of a miniature mass–spectrometer that is well suited for measuring liquid water directly. The mass spectrometer is <5' in size (Fig. 1), is optimized for detecting heavy organic molecules (50–500K Da), can withstand ballistic emplacement (currently demonstrated to 1200g), operates at pressures as high as several Torr (consistent, for example, with surface pressures on Mars), and has simple electronics. These traits make the instrument uniquely relevant for astrobiology applications such as the detection of key organic biomarkers derived from cellular components as well as geochemical environmental characterization on wet or icy bodies throughout the solar system. The ionizer uses a modified electrospray introduced directly to vacuum (Fig. 2), and the spectrometer itself performs as a momentum filter using rotating radio frequency (RF) fields applied to four poles. The ion spray characteristics are currently undergoing extensive characterization in our laboratory test stand (Fig. 3), developed in part through support of the NAI. We have leveraged NAI funding with both NASA Mars Instrument Development (MIDP) and Department of Defense (DOD) Measurement and Signals Intelligence (MASINT) funds. To date we have acquired the test stand, built the vacuum system, built the electrospray ionizer and mass spectrometer, and have begun testing electrospray under a range of high voltage and vacuum regimes. We will present our initial results at the BioAstronomy Conference this year. We anticipate that we will complete characterization of the electrospray ionizer during the first year of effort, and that in year two we will characterize the momentum filter. In later years we plan to test this system in lacustrine and icy environments.

Figure 1. Prototype mass spectrometer, including four aiming elements, four RF elements, and a faraday cup analyzer. Length is ~ 4".

Figure 2. The electrospray to vacuum ionizer. The charged spray is generated from a electrical element inside of the spray needle visible here. Needle length ~1".

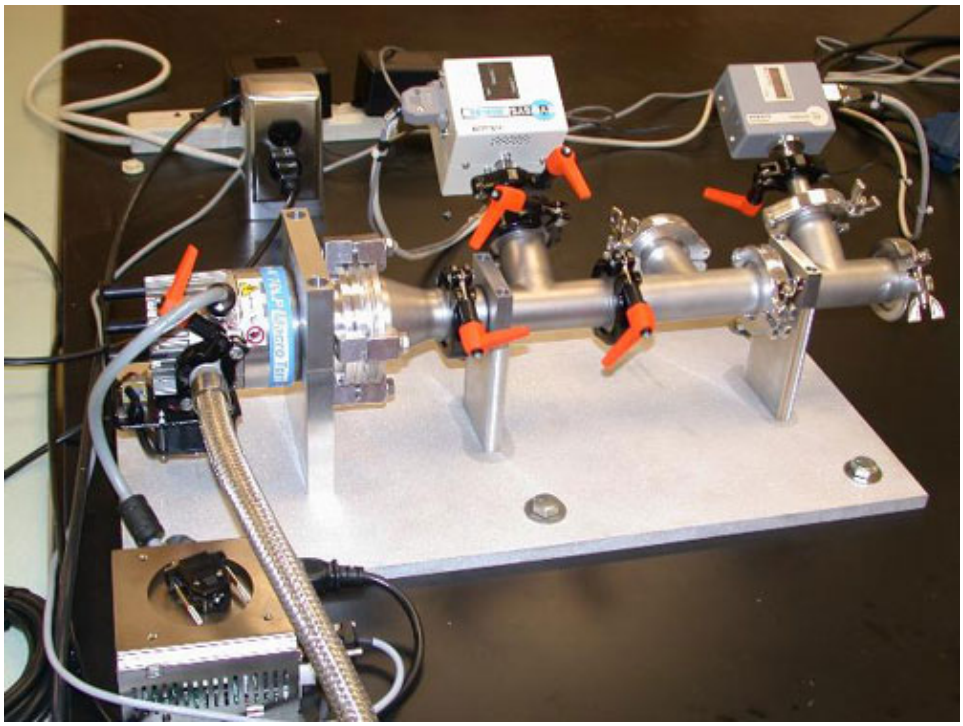


Figure 3. Laboratory vacuum system and test stand designed to accommodate the electrospray ionizer and mass spectrometer. The Mass Spectrometer (Figure 2) fits entirely in the rightmost "T", and the electrospray ionizer attached to the right end of the rightmost "T". The system can attain and accurately measure vacuum from 760 Torr to 10−7 Torr.

Highlights

- Obtained NASA and DOD funding that leverage UH−NAI grant personnel to design, construct, and test a prototype laboratory instrument for direct mass spectral analysis of liquids.
- Built initial laboratory prototype and demonstrated ionization at low vacuum (~3 Torr).
- Initial design presented at BioAst, 2004.

Roadmap Objectives

- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Project Report: Extraterrestrial Ice Laboratory Experiments

Project Investigator:	***Ralf Kaiser***

Project Progress

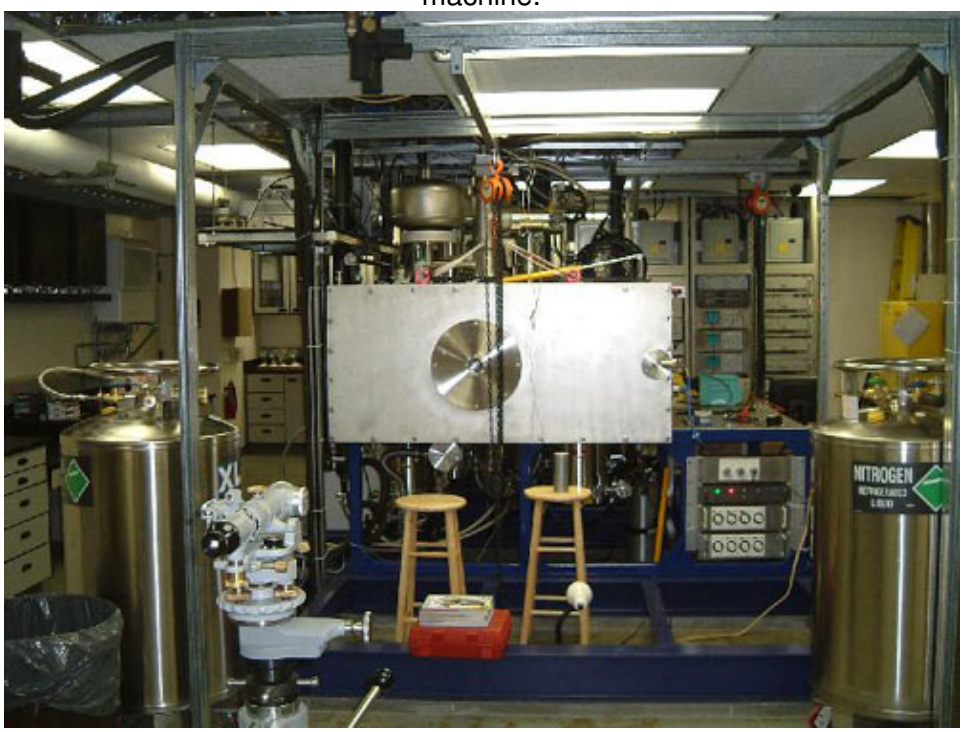
We commissioned and calibrated a novel ultra high vacuum surface scattering machine to investigate the formation of astrobiologically important molecules in the interstellar medium, and in our solar system. We are simulating the effects of cosmic radiation on interstellar grains in the interstellar medium to produce new chemical species. Thus, the basic premise of our experimental set–up is to mimic the conditions these grains will be under as realistically as possible.

This machine consists of a stainless steel cylinder; a 12" CF flange serves as the lid of the chamber and holds a centered, differentially pumped feedthrough. This construction enables an attached closed cycle helium refrigerator, and the target to rotate horizontally 360°.Gases are deposited on a cold finger made of a silver mono crystal attached to the 10K cold head. The temperature of the crystal is precisely controllable within a range of 10–350K, mimicking the temperatures expected in the interstellar medium. A magnetically suspended turbomolecular pump backed by an oil free scroll pump is mounted at the bottom of the chamber; this setup generates absolutely oil–free ultra high vacua; so far vacua down to 8×10^{-11} torr have been reached. Gas mixtures are prepared in a mixing chamber. The mixture is introduced via a gas deposition system into the main chamber. A linear transfer mechanism brings the capillary array a few millimeters from the cooled sample substrate. Homogeneous condensation of the mixture provides ice layers of defined crystal structures and reproducible known thickness down to a few tens of nanometers without contamination.

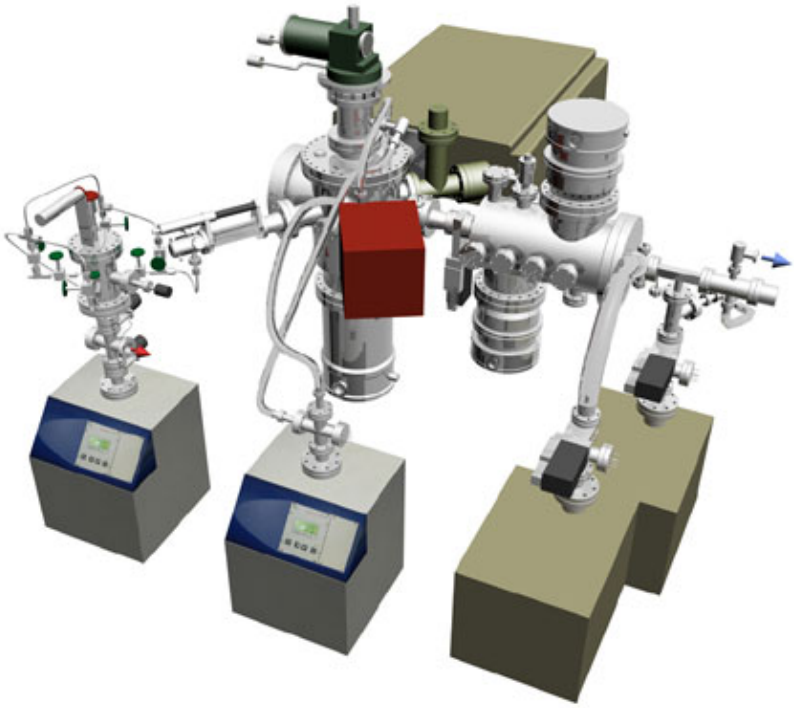
This experimental setup provides reproducible experimental conditions necessary to extract mechanisms leading to the formation of molecules in the solid state upon charged particles, atomic, and photon interaction with extraterrestrial ices. With this machine, electron and ion beams of well–defined kinetic energy and composition can be generated. The modular design of the sources makes it feasible to also incorporate a tunable ultraviolet (UV) photon source in future experiments. During the experiments, after the gas has been deposited to the silver target, the target can be rotated so that an Fourier transform infrared (FTIR) spectrometer can monitor the chemical modifications of the target *in situ* by an FTIR spectrometer in the spectral region of 6000–500

cm^{-1} via absorption–reflection–absorption. Gas species can also be detected via the quadrupole mass spectrometer during an experiment. The sensitivity of this is enhanced by a factor of 100 compared to currently operating machines worldwide.

Assembly of the University of Hawaii NAI Ultra High Vacuum surface scattering machine.



The University of Hawaii NAI Ultra High Vacuum surface scattering machine.



Schmatic of the University of Hawaii NAI Ultra High Vacuum surface scattering machine.

Highlights

- We commissioned and calibrated a novel ultra high vacuum surface scattering machine to investigate the formation of astrobiologically important molecules in the interstellar medium, and in our solar system.
- We have conducted experiments on the formation of two C_2H_4O isomers and nitrous oxide in interstellar ices, and have three papers in progress.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Project Report: Development of an Intelligent Telescope Scheduler

Project Investigator:	***Kimberly Binsted***

Project Progress

Co−I K. Binsted has been working with University of Hawaii (UH) undergraduate and graduate students to develop a scheduler for the Lowell observatory 31−inch telescope which is being used in a collaborative UH−NAI research and educational outreach program. Specifically, we need to develop robust software that can take teacher and student−requested observations and intelligently schedule these requests with a minimum of human intervention. The work schedule of these telescopes is basically created according to customers' observation requests. It is concerned by a lot of external factors, such as the movement of clouds and the positions of stars. With the amount of observation work increasing, creating a reasonable and efficient observation schedule becomes more difficult. The currently existing scheduling engine is not adequate to handle a large number of jobs. We have designed and created a more powerful scheduling engine to replace the current one. Inspired by the applications of artificial intelligence in many science fields, we choose to use the Genetic Algorithms, which have already been successfully applied to many scheduling problems, as the basis of the new engine. We have worked out the basic framework of the new algorithm and have already implemented it as a program and have obtained some good results. The program works quickly and the results look reasonable and good. The program has included augmenting the Lowell Observatory observation database, writing an interface to the system, and developing the scheduler.

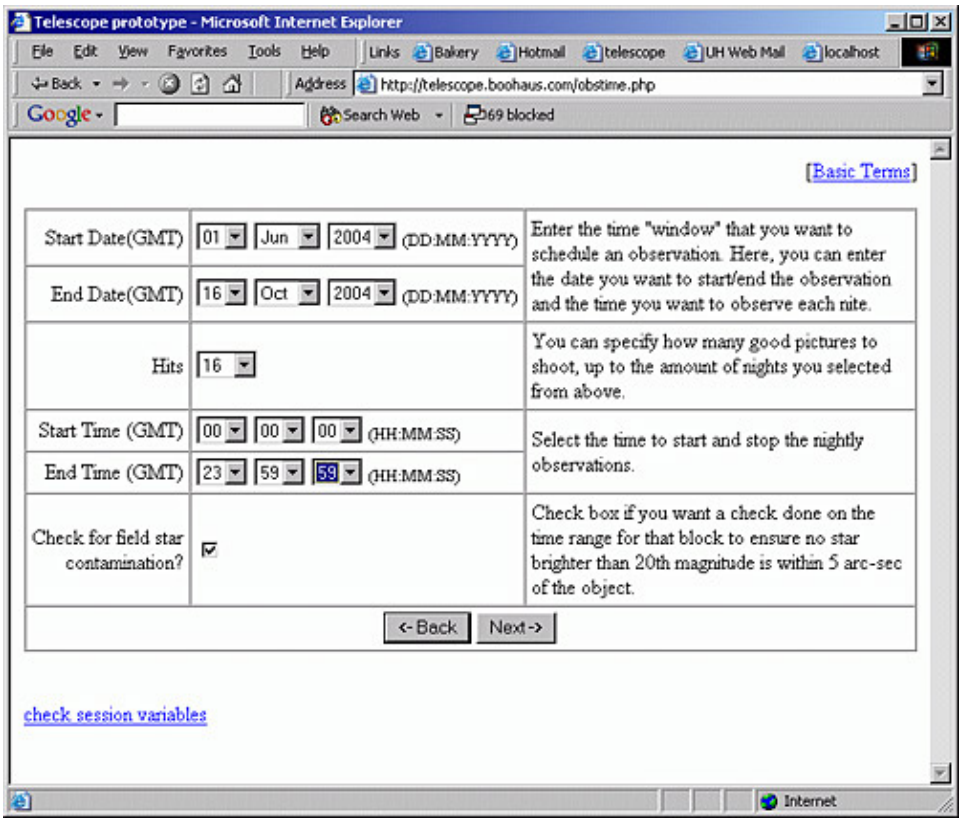


Figure 1. Screen shot of the intelligent scheduler interface for the Lowell Observatory 31 inch telescope.

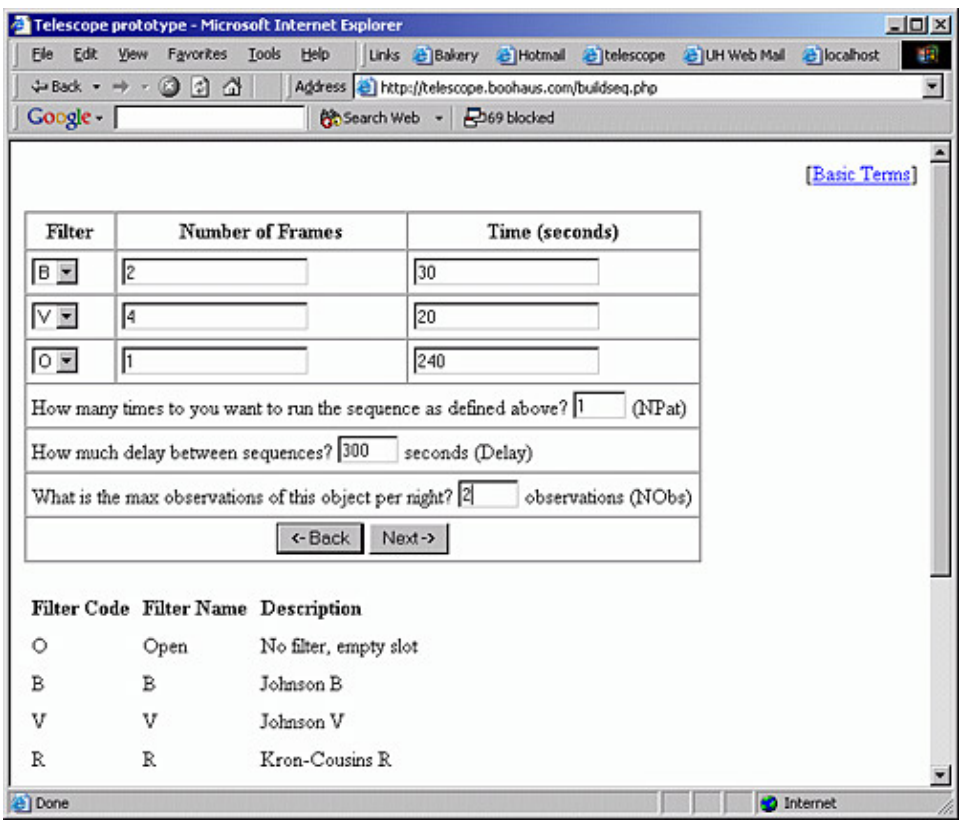


Figure 2. Screen shot of the intelligent scheduler interface for the Lowell Observatory 31 inch telescope.

Highlights

- The Lowell 31−inch−telescope observing database has been upgraded. An interface to interact with the database has been created, and an intelligent scheduler developed and nearly fully debugged. Anticipated completion is expected during summer, 2004. The complete system will be used for scheduling astronomical observations, both for research and outreach.

Project Report: Cometary Water and Volatile Abundances

Project Investigator:	***Karen Meech***

Project Progress

NAI team member Meech, and postdoc Pittichova, have been collaborating with Akiva Bar–Nun and Gila Notesco (University of Tel–Aviv), to understand the role of water ice in the activity of comets on their inbound orbital trajectories at large heliocentric distances. A thorough understanding of cometary activity is closely coupled with knowledge about the formation of comets, the physical and chemical structure in the nucleus, and its subsequent evolution, and this has implications for delivery of volatiles and organics to the terrestrial planets. The traditional view that sublimation of water–ice is the driver of activity in comets is changing considerably as observations with new telescope facilities are showing that comets are often active at very large distances from the sun, where the ambient temperatures are much lower than the sublimation temperature of water–ice. Thermal models have been able to explain some of the activity post–perihelion, due to slow transport of the heat from perihelion into the interior, however activity at large distances before the comet is heated has been difficult to explain. Work carried out on amorphous, gas–laden ice samples suggests that the cause of distant cometary activity is from gas release during annealing processes in the water ice between 35 and 120K. The experimental set up involves flowing different mixtures of gases onto a cryogenically cooled plate at 50K in a pumped chamber at 10^{-8} torr, forming 5– to 200–micron–thick ice layers. The ice deposition plate is then heated while monitoring the emanation of trapped gases, water vapor and ejected ice grains. The experiments show that the gases trapped in the amorphous ice during its formation are partly released from the ice during its annealing as it warms up. A paper is in progress describing this work.

Highlights

- Cryogenic experiments with amorphous gas–laden water ice samples show that pre–perihelion activity in comets at large distances may be explained by the annealing (reorganization of the crystal structure) of the water ice which allows the trapped gases to escape.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Project Report: Young Stellar Activity & Early Solar System Heating

Project Investigator:	***Bo Reipurth***

Project Progress

Bo Reipurth has been working on eruptive events in young Solar−like stars, the so called FUor and EXor eruptions. Observations of the prototype eruptive variable, FU Orionis itself, with the 8m Subaru telescope at Mauna Kea, has revealed that a nearby star is in fact a physical companion with characteristics similar to the T Tauri stars. Reipurth and co−worker Colin Aspin of the Gemini Observatory have proposed a new model for the onset of FUor eruptions, in which the disruption of a small multiple protostellar system leads to the formation of a binary star and triggering of large−scale disk instabilities. Such events are important not only for the growth it provides to the young star, but also for processes of irradiation of disk material, which may give clues to the short−lived intense heating events that affected chondrites and aqueous alteration products in the early solar system. As luck would have it, a major accretion event in a young star was discovered in January, 2004, by amateur astronomer Jay McNeil in the constellation Orion, and confirmed by University of Hawaii (UH) NAI associates K. Meech and J. Pittichova. This is the first major eruptive event since 1970, and it triggered a wealth of new observations around the world. Reipurth and Aspin's observations at the Mauna Kea observatory confirmed that McNeil's nebula is the result of a major eruptive event in a newborn star at the base of the nebula (see figure). The event represents a major flare−up in a circumstellar disk, reminiscent of events when our own Solar system was young.

The fact that McNeil's nebula was discovered by an amateur indicates that the community of professional astronomers do not have a sufficient capability to monitor the sky, and Reipurth has therefore embarked on an ambitious project, constructing two 16−inch fully automated telescopes, one to be located at the Haleakala Observatory in Hawaii for the northern sky, and the other at Cerro Tololo in Chile for the southern sky. These telescopes will monitor all of the nearest star forming regions, producing a vast catalogue of observations of temporal phenomena in the evolution of young stars as they approach adulthood.

Figure 1. In January 2004 amateur astronomer Jay McNeil discovered a new nebula in the constellation Orion. Observations at the Mauna Kea observatory showed that the nebula is the result of a major eruptive event in a newborn star at the base of the nebula. The event represents a major flare−up in a circumstellar disk, which eventually may turn into a planetary system. Such events are important for studies of irradiation of meteorites when our own Solar system was young. The figure, courtesy the Gemini Observatories, shows McNeil's nebula observed with the 8m Gemini telescope on Mauna Kea.

Highlights

- The discovery and subsequent follow up of a discovery of a major accretion event and flare up in a young circumstellar disk has lead to the development of a new model for the onset of these events. This has important implications for short−lived heating events in early solar systems that might contribute to chondrule formation and aqueous alteration of early solar system material.
- The development of two 16−inch telescopes, one for Hawaii and one for Cerro Tololo Interamerican Observatory in Chile, has begun in order to do all−sky monitoring of star forming regions to create temporal catalogs of the variability of young stars.

Roadmap Objectives

- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts

Project Report: Water–Rock Chemistry and Habitats for Life

Project Investigator:	***James Cowen***

Project Progress

An exciting development related to this NAI project is the funding of a grant to design, construct, and test a prototype instrument for contamination–free sampling of basement rock fluids from deep–sea boreholes. The new University of Hawaii (UH) NAI grant was instrumental in acquiring National Science Foundation (NSF) funds by allowing us to leverage personnel and new expertise assembled through the NAI grant; new NAI–UH post–doc Brian Glazer was recruited in part to help advance this and related projects.

Low temperature hydrothermal ocean fluids (<100° C) circulate everywhere within the porous and permeable volcanic rocks of the upper ocean basement and are subjected to continuous water–rock reactions, providing temperature and chemical gradients, and redox disequilibria that form plausible habitats for a variety of microbial communities. However, this potentially important subseafloor basement rock–fluid biosphere is virtually unexplored and its existence remains controversial. Since most mid–ocean ridge (MOR) flank and ocean basin crusts are buried under thick, impermeable layers of sediment, the fluids circulating within the underlying ocean crust are usually inaccessible for direct studies. Circulation obviation retrofit kit (CORK) observatories affixed to ocean drilling program (ODP) boreholes offer an unprecedented opportunity to study biogeochemical properties and microbial diversity in circulating fluids aging ocean basement. Our target ODP boreholes are drilled through sediments and penetrate into the underlying basaltic crust. They are sheathed by impervious steel liners, designed to prevent direct contribution from sediment pore water; thus fluid exiting the borehole is derived directly from the basaltic crust. A down–hole sampler should substantially overcome concerns of the cumulative contamination of the ascending fluids from chemical and biological processes associated with current borehole casings and possible infiltration of sediment pore waters through any joint leaks.

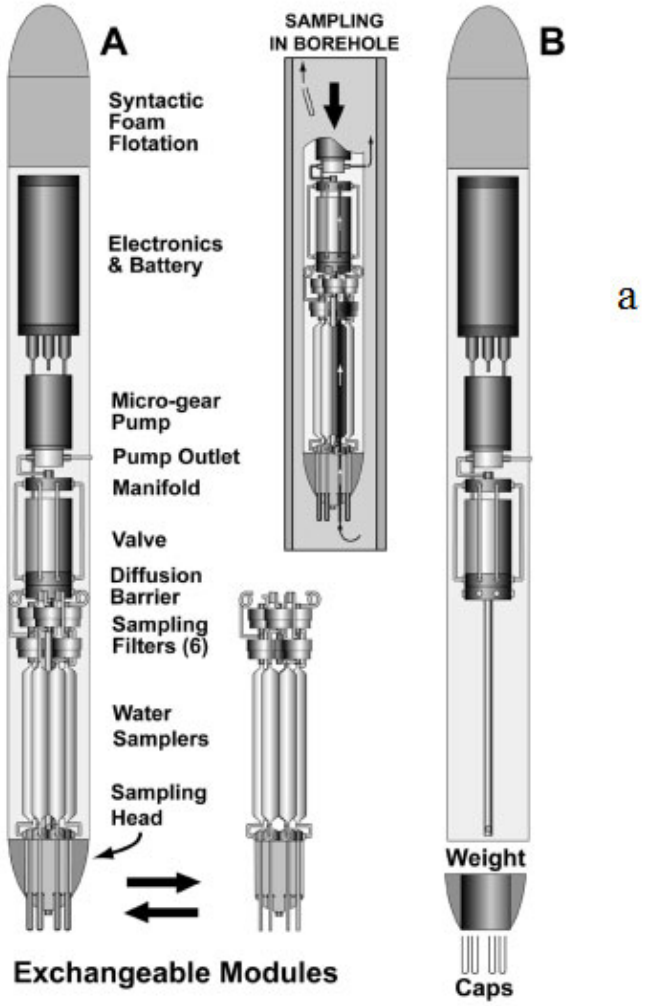


Figure 1. Proposed Downhole Sampler.

Figure 1. Concept drawing of ODP borehole downhole sampler currently under design for construction and deployment (hopefully summer/fall 2005). Drawing by Craig Taylor.

Highlights

- Obtained NSF funding that leverage UH–NAI grant personnel to design, construct, and test a prototype instrument for contamination–free sampling of basement rock fluids from deep–sea boreholes.
- Recruited post–doc Dr. Brian Glazer in part to participate in deep ocean basement microbial geochemical studies.

Roadmap Objectives

- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems

Field Expeditions

Field Trip Name: Borehole–in situ sampling	
Start Date: proposed: 7 or 8/2005	***End Date:***
Continent: NE Pacific Ocean	***Country:*** USA
State/Province: Juan de Fuca Ridge Flanks	***Nearest City/Town:*** Astoria, Oregon
Latitude: 47o 45.8'	***Longitude:*** 127o 45.6'
Name of site(cave, mine, e.g.): ODP Borehole (TBD)	***Keywords:*** basement microbiology, Ocean Drilling Program
Description of Work: Expedition will be to test the in situ, downhole sampler for uncontaminated sampling of geochemical and microbiological parameters of deep ocean basement fluids. This sampler will provide the foundation of extensive future studies.	
Members Involved: Brian Glazer James Cowen	

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: University of Hawaii, Manoa

Project Report: University of Hawaii Facilities Infrastructure

Project Investigators:	***Eric Gaidos , Rolf–Peter Kudritzki , Karen Meech***

Project Progress

The University of Hawaii, as part of its cost–sharing commitment to the NAI, agreed to provide space on campus for our proposed “Water–Hole,” the shared office space facility for the core group of team postdocs. In addition to this collaborative space, lab and desk space will be made available in individual departments where their research is most closely related. After considerable negotiations, space was made available in the Physical Sciences building on campus, which is centrally located amongst all the departments which house our team co–Is. The rooms were not in very good condition, and after further negotiation, the University has committed additional funds ($5K) for their renovation, and worked on an accelerated schedule to have the rooms ready by July, 2004. The construction work has been completed, and we are proceeding with carpet, furniture, and computer equipment procurement so that the facility will be completed by August, 2004 when most of the postdocs will arrive. The University has been very supportive of this program and very responsive to our needs, with the Assistant Vice President for Research and Graduate Education personally overseeing the acquisition and renovation of space.

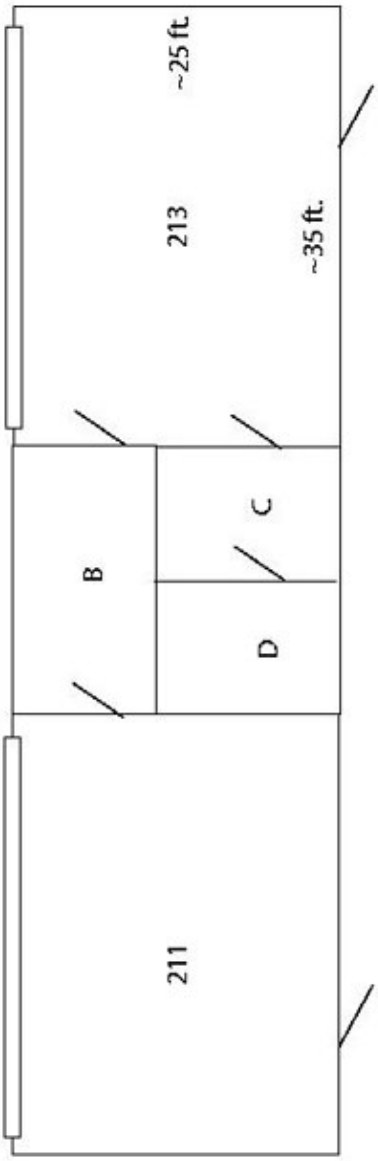


Figure 1. Office Suite layout in the Physical Sciences Building at the University of Hawaii. The postdocs will have office space in Room 213, room B will be a library / lounge, rooms C and D, which are old dark rooms may be converted for some small wet–lab work, and room 211 will be the UH NAI seminar / meeting and classroom for graduate seminars.

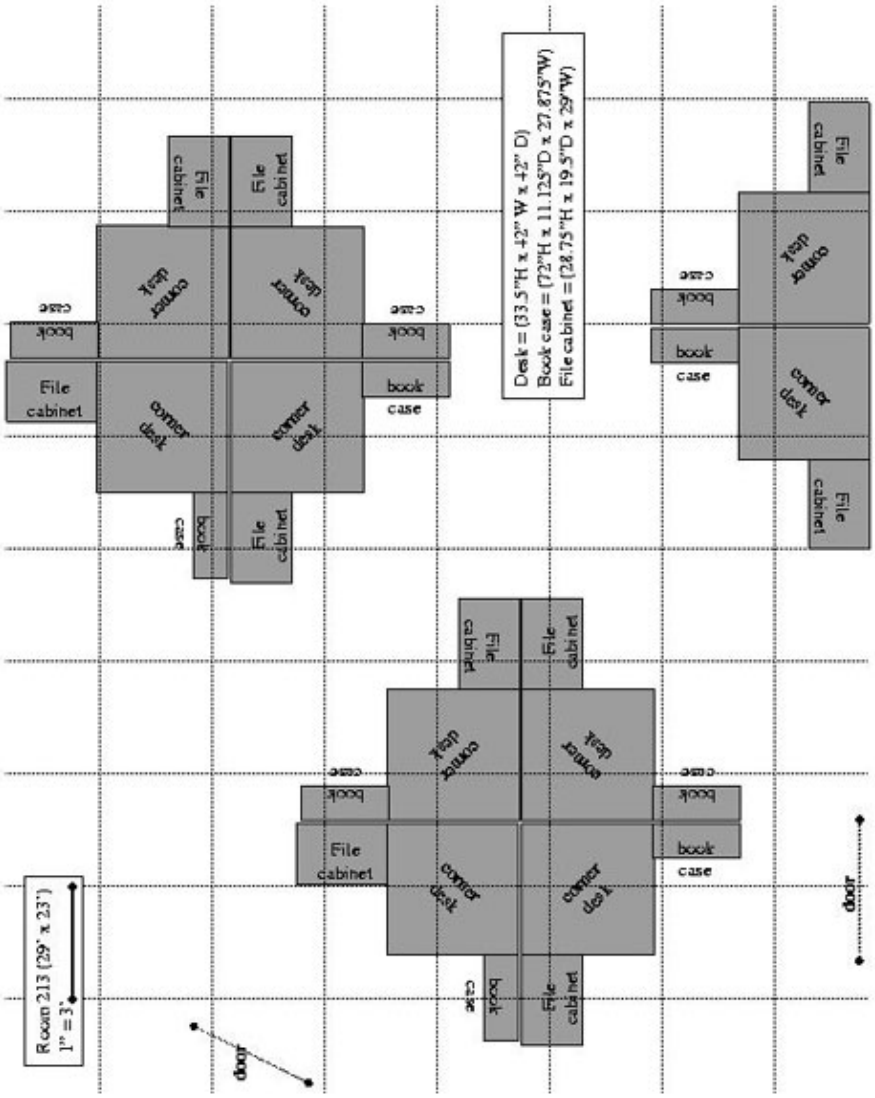


Figure 2. Office space layout for UH NAI postdoc room 213. Set up is for 10 postdocs in total.

Highlights

- Acquisition of approximately 1800 sq. ft. of centrally located campus space for our postdoctoral "Water Hole" (office area and meeting facilities).
- Major renovations on the room are complete, and the procurement has begun for carpeting, furniture, and computer equipment.

Project Report: Ultramafic–hosted Springs in Subduction Zones

Project Investigators:	***James Cowen , Michael Mottl***

Project Progress

We are making progress in characterizing the chemical environment for microbial activity in the extreme environment of the serpentinite mud volcanoes in the Mariana forearc, which we believe to be an ancient, extreme environment for life on Earth, and possibly elsewhere in the Solar System, wherever water, carbon, and ultramafic rock (peridotite) like that of Earth's mantle are in contact. This environment produces some of the most alkaline water found in nature, with in–situ pH at 2°C as high as 13.1. Whereas serpentinization alone produces pH as high as 11.1 at 2°C, the much higher pH appears to result from a combination of two chemical reactions:

1) Oxidation of Fe–end–member olivine (fayalite) during serpentinization:

$$3Fe_2SiO_4 + 2H_2O = 2Fe_3O_4 + 3SiO_2(aq) + 2H_2$$

2) Methanogenesis, reacting carbonate ion with H2 produced in reaction 1:

$$4H_2 + CO_3^{2-} = CH_4 + H_2O + 2OH^-$$

Total alkalinity is conserved in reaction 2, but pH rises greatly as carbonate alkalinity is traded for hydroxyl alkalinity. Reaction 1 can certainly proceed inorganically, wherever water contacts peridotite, but Reaction 2 is probably microbially mediated. Reaction 2 provides methane that fuels Archaea within the shallow subseafloor of serpentinite mud volcanoes in the Mariana forearc. These extremophilic Archaea use sulfate to reduce this methane at pH 13.1, as documented by Mottl *et al.* (2003, *Geochem., Geophys., Geosystems* 4,11: 9009, doi:10.1029/2003GC000588):

3) Anaerobic oxidation of methane utilizing sulfate:

$$CH_4 + SO_4^{2-} + OH^- = CO_3^{2-} + HS^- + 2H_2O$$

Given the abundance of ultramafic rock on the terrestrial planets, including Mars, it is conceivable that these same reactions are possible in extraterrestrial environments, as well as on Earth.

Highlights

- Inorganic generation of hydrogen gas during hydration of mantle rock may fuel microbial life on other planets, as it does on Earth. This process has been demonstrated in serpentinite mud volcanoes in the Mariana forearc, on the floor of the Western Pacific Ocean, where it supports a community of Archaea.
- New team postdoc, Brian Glazer, has arrived and will begin working on this project.

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

EPO: University of Hawaii, Manoa

These are the Education and Public Outreach activities for the University of Hawaii, Manoa.

Astrobiology Laboratory Institute for Instructors

The Ali'i program is a program of workshops for secondary teachers which will (i) improve their science content knowledge using the integrative nature of astrobiology; (ii) allow them to apply this by using appropriate curriculum materials for the classroom; and (iii) provide information on current and future astrobiology research.

The one–week summer workshop in 2004 consisted of lectures, laboratory tours and related curriculum activities. Eight UH NAI team astronomers, oceanographers, geologists, and microbiologists inspired the teachers through presentations about comets, protostars, early Earth's ocean and atmosphere, Mars and Moon rock composition, extremophiles and other topics. Laboratory tours promoted the technical aspects of research, motivating teachers to better understand the workings of the scanning electron microscope, the thermal emission spectrometer, and the polarizing microscope. The final component dealt with the pedagogy of taking these exciting topics into the science classroom. Teachers reviewed the nationally field tested NSF SETI curriculum Voyages Through Time modules, and will be implementing activities from one selected module with their students in the fall of 2004.

The teacher participants could register for 3 UH graduate education credits with a tuition waiver. A few teachers opted to also work on portfolios for credit from the Hawaii Department of Education.

Astrobiology Student Science Fair Projects

Scientists and teachers played a critical role as mentors to ensure successful astronomy and astrobiology research projects conducted by high school students. The NSF/NASA Toward Other Planetary Systems (TOPS) program developed a strong teacher cadre by conducting sequential professional development summer workshops to enhance science content knowledge and provide effective pedagogical strategies. Astrobiology topics and curriculum materials were included. The culmination of 5 summers resulted in teachers mentoring student projects on extrasolar planets, variable stars, galaxies and the Sun in school year 2003–2004. Out of 30 students entering projects in their School Science Fairs, 9 advanced to their State Science Fair, and the

extrasolar planet project won a special award at the 2004 INTEL International Science Fair. Future astrobiology projects will focus on the UH NAI team research using the Faulkes Telescope in Fall, 2004. Our TOPS teachers have agreed to mentor students for projects on comet 9P/Tempel 1 (which is affiliated with our NAI program), as part of the NASA Deep Impact Mission Small Telescope Science Program (STSP). Also, plans are underway for the UH research vessel the R/V Kilo Moana to be used for oceanography research by teachers and students.

"Discoveries in Astrobiology" Web Magazine

This web magazine focuses on promoting astrobiology for the general public, teachers and students by featuring the University of Hawaii NAI lead team's ongoing astrobiology research. The first article entitled "UH Astrobiology Team Studies Water and Life in the Universe", written by team scientists Karen J. Meech and Eric Gaidos, introduces readers to the NAI and the scientific questions by asked by the UH team. Subsequent articles written by team members, postdocs and astrobiology graduate students will focus on water–rock chemistry in the deep oceans, comet ices, minerals in meteorites, molecular cloud chemistry and other topics relating to the origin, history and distribution of water and its relation to life in the universe. This magazine (http://www.ifa.hawaii.edu/UHNAI/NAIweb/) is modeled after the successful Planetary Science Research Discoveries web magazine sponsored by Hawaii Space Grant Consortium and Cosmochemistry Program of NASA Office of Space Science(http://www.psrd.hawaii.edu/).

Hawaii Volcanoes National Park Collaboration

Using the model partnership established between the NAI NASA Ames Research Center team and Yellowstone National Park, the UH NAI team is in the early stages of a collaboration with Hawaii Volcanoes National Park. The Ames team E/PO lead, C. Tsairides, and former NAI director B. Blumberg are serving as advisers to our team and assisting us with the necessary contacts and procedures. We will use their Yellowstone Resources and Issues Guide to serve as a seed for possibly developing one suitable for Hawaii's park. We are in the process of working on an agreement with the park officials as they are planning new signs.

Astrobiology Public Lectures

UH team scientists have been invited to give lectures as follows: Karen J. Meech – "Astrobiology at the University of Hawaii: Water and Life in the Universe," 7/9/04, Public Lecture, Reykjavik, Iceland. "Water and Life in the Universe," 8/4/04, Sakamaki Lecture, University of Hawaii. Eric Gaidos – "Life Under Ice: From Iceland to the Outer Solar System," 7/13/04, 2004 Bioastronomy Conference public lecture. "Reflections on an Ocean Planet," 8/17/04, SOEST Lecture, University of Hawaii.

Hawaii Public Libraries Collaboration

Collaboration began in 2003 when the UH Institute for Astronomy agreed to provide resources to the State Library application for a NASA Traveling Exhibit which was granted. UH NAI scientist Jeff Taylor is giving a public lecture on Aug. 26 to culminate the display of this exhibit. Other events are planned for fall, 2004 such as a NAI lecture and demonstration for children. Astrobiology lectures in spring, 2005, will accompany the Carnegie Institution NAI team Astrobiology Traveling Exhibit at the public libraries on each island. The goal of this collaboration is to take astrobiology to the rural areas of Hawaii, where the people, particularly students, are too often neglected. Some means to promote school field trips to the library will be investigated. The state libraries director has requested that our scientists recommend books for library purchase. NAI team scientists will be consulted so a recommended list of astrobiology books can be generated for distribution to interested parties.

Astrobiology Seminar Series

We have established a graduate seminar series for UH graduate students and advanced undergraduates, to be offered during the Fall 2004. This seminar will highlight the current team research, as well has provide a framework for the whole team to understand the interdisciplinary research of the group. As a basis for grading the students, and as an EPO activity, it will be the student responsibility to produce the Astrobiology Discoveries web articles from the research presentations given by the scientists. These articles will be available on the web, complete with references and glossaries, and may be used within the NAI for other purposes.

Astrobiology 281

This course has been offered at the University of Hawaii for several years, however, this year we will integrate it more fully into our team's activities. The 8 incoming postdocs have volunteered to team teach this undergraduate astrobiology class, adding to the materials developed by K. Meech. Our goal is to make the materials (powerpoint presentations, readings, handouts) available throughout the NAI as a resource.

Astrobiology Winter School

We are collaborating with the University of Arizona NAI team to offer an Astrobiology Winter School for approximately 40 graduate students annually each January. The school will be offered in alternate years in Hawaii and Tucson. A board of directors will be set up for each winter school, with an exchange of 2 scientists from each team to provide continuity and complementary themes. Plans are underway to develop the first winter school in Hawaii for January 2005 with the theme of "Water in Space and on Earth." The program will last 2 weeks, consisting of lectures, discussion, and writing, as well as field trips to see astrobiology facilities. The lecture series will be interdisciplinary and include the following topics: Icy bodies in the solar system and the origin of the Earth's oceans, Glaciers on Earth, Mars and Europa, Water ice in circumstellar disks and the interstellar medium, Geochemical processes near deep–sea vents, and Extremophiles.

The instructors will be scientists from the UH NAI team and collaborators. The goal of the workshop is to provide both content and interdisciplinary training, as well as to begin to form the networks that young astrobiologists will retain throughout their careers.

Deep Impact and the Faulkes Telescope Facility Training

The Institute for Astronomy at the University of Hawaii has entered into a partnership with the Faulkes Telescope Corporation (UK) for the development of a 2–m research grade telescope on the summit of Haleakala, Maui, which is to be used exclusively for outreach. This telescope will be ready for general operations in October 2004. Workshops are being planning for the Spring of 2005 in order to prepare teachers so that they can utilize this resource to contribute to the NASA Deep Impact Mission encounter during July 2005 through the STSP. Through the experiences with Deep Impact, this will be the initiation of a more formal Faulkes training program for teachers and students. We will be seeking outside sources of funding to help with these workshops. During the fall of 2004, we are testing Faulkes operations utilizing the experienced TOPS teachers.

Iceland Astrobiology Teacher Workshop and Collaboration

An educator workshop was organized by UH NAI lead M. Kadooka in collaboration with P. Harman from the SETI team in collaboration with Icelandic geologist (and teacher) A. Thorliefsdottir and held on Wed 7/14/04 from 2–6pm, during the Bioastronomy 2004 Meeting in Reykjavik, Iceland. The goal was to give Icelandic teachers an introduction to the content of astrobiology, and to introduce them to some of the available curriculum materials. The event was very successful, and is leading to discussions of a more formal outreach collaboration between Hawaii and Iceland, including a teacher exchange program.

Astrobiology on TV

NAI University of Hawaii (UH) geologist G. Jeffrey Taylor appeared on the local TV channel KHNO early morning show on Aug. 26. He discussed the Moon and Mars research in a 4 minute time slot. He will be returning in October to present more research highlights. He will be assisting our team with setting up more feature spots on this TV morning show to inform the public in Hawaii about astrobiology at the University of Hawaii.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

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Team Reports: University of Rhode Island

University of Rhode Island
Executive Summary
Principal Investigator: Steven D'Hondt

The University of Rhode Island (URI) team of the NASA Astrobiology Institute (NAI) works to gain a fundamental understanding of Earth's subsurface life. Our principal research objectives are to understand (1) the subsurface microbial ecosystems of marine sediments, (2) their role in Earth's biogeochemical cycles, and (3) their relevance to the search for life on other planets. Our investigators are based at URI, Woods Hole Oceanographic Institution (WHOI), and the University of North Carolina at Chapel Hill (UNC). To effectively accomplish our objectives, URI team researchers collaborate with each other and with scientists at other institutions throughout the world. Our current collaborators include members of other NAI teams at the NASA Ames Research Center, the Marine Biological Laboratory (MBL), and Pennsylvania State University. Other collaborators include scientists at the Massachusetts Institute of Technology, the University of Bremen (Germany), the Max Planck Institute for Marine Microbiology (Germany), the Scripps Institution of Oceanography, the Japan Marine Science and Technology Center, Roger Williams University, the University of Aarhus (Denmark), and other institutions throughout the world. To gain access to subsurface environments, URI team members participated in international expeditions through the Ocean Drilling program (ODP) and its successor, the International Ocean Drilling Program (IODP).

Members of our team at URI principally focus on studies of subsurface metabolic activities and biogeochemical fluxes. To further these studies, team members are developing new techniques to study the activity and physiology of energy−limited microbial communities. For one example, members of our URI group are working to develop a robust tritium−based method for quantifying metabolic activity at rates that are well below the detection limit of current radiotracer techniques (Soffientino et al., 2004). If their effort is successful, this assay will be the first measure of enzymatic activity applicable to environments with extremely low levels of metabolism. For another example, in the last year, we developed a numerical model that uses profiles of chemical and physical properties to quantify metabolic rates at depth (Manor et al., 2004). Although our model is still being refined, it is already flexible enough to quantify complex variation in rates throughout sediment columns of great depth. Other activities by the URI group include exploratory work on a novel cell extraction, analyses of adenosine triphosphate (ATP) concentrations and dissolved organic

compounds in deep subseafloor, and quantification of biogeochemical fluxes and thermodynamic equilibria of biogeochemical reactions.

Our biogeochemical studies demonstrate that metabolic interactions in deep subseafloor ecosystems are complex (e.g., D'Hondt et al., in review). For example, several hypothetically competing processes, including metal reduction, sulfate reduction and methanogenesis, commonly occur in deeply buried sediments. At some sites, aerobic communities live deep beneath anaerobic communities because the underlying basaltic aquifer supplies oxygen and nitrate to the deep sediments. The sedimentary communities may, in turn, fuel life in the underlying basalts by supplying electron donors and nutrients.

Closer study of some hypothetically competing processes suggests that they may actually cooperate under some subsurface conditions. For example, sulfur reduction and iron reduction co−occur with low and relatively constant free energy yields in some deep subseafloor sediments (Figure 1) (Wang et al., 2004). Positive feedback between these reactions [e.g., co−precipitation of their waste products Fe(II) and S^{-2}] may help to sustain them (Wang et al., 2004).

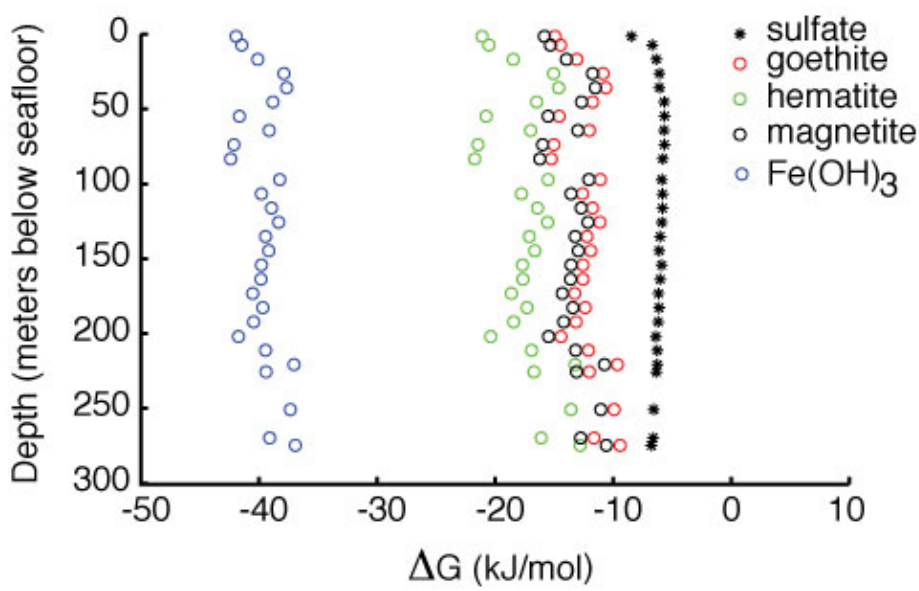

Figure 1. Estimates of free energy yields (delta G) from some iron−reducing reactions and a sulfate−reducing reaction at ODP Site 1226 (Wang et al., unpublished). The iron−utilizing yields assume that the solid phases are present and that dissolved Fe (III) concentrations are at equilibrium. At depths where these assumptions are incorrect, in situ delta G values will be more positive than the estimated yields.

Team members at UNC have focused primarily on exploring the taxonomic composition of subseafloor ecosystems. Studies of the UNC group have focused on (1) the taxonomic composition of low−biomass communities in organic−poor open ocean sediments, (2) the taxonomic composition of methane−oxidizing prokaryotic communities, and (3) with Virginia Edgcomb

(NAI Postdoctoral Fellow at MBL), on the environmental stress tolerance of hyperthermophilic vent archaea. To obtain DNA from the low−biomass sediments, we have continued to develop DNA isolation methods. Consequently, we now have an array of DNA isolation procedures that allow expansion of our archaeal 16S rDNA sequence datasets from these low−activity sites. However, it should be noted that the results of these analyses are near the sensitivity limit for molecular (nucleic acid−based) procedures.

Our studies of 16S rRNA genes indicate that two uncultured archaeal lineages, the Deep−Sea archaeal group (DSAG), and the Marine Benthic Group A (MBGA) are cosmopolitan members of subseafloor sedimentary communities (Lauer et al., 2004). Another uncultured lineage, the marine group I archaea (MGI), is ubiquitous in the marine water column. 16S assays and functional gene analyses indicate that known methanogens are unexpectedly scarce in subseafloor sediments (Inagaki et al., 2003; Mark Lever, unpublished), although methanogenesis appears to occur in all subseafloor sediment columns (D'Hondt et al., in review).

Analyses of the communities in the consistently cold sediments of our lowest−biomass site to date, Peru Basin ODP Site 1231, yielded a highly diverse archaeal community that including members of several deeply branching lineages that were previously known only from hydrothermal vents (DHVE 6; the newly described Peru Basin cluster, the UCIIb cluster) (Sørensen et al. 2004) (Figure 2). This conspicuous occurrence pattern suggests that some phylotypes that were originally found in hydrothermal systems may not be indigenous to hot vent systems, but originate in cooler subsurface habitats from which they are flushed out as seawater is entrained into the hydrothermal circulation system (Sørensen et al., 2004). In other words, cold subsurface sediments may harbor seed populations of vent systems.

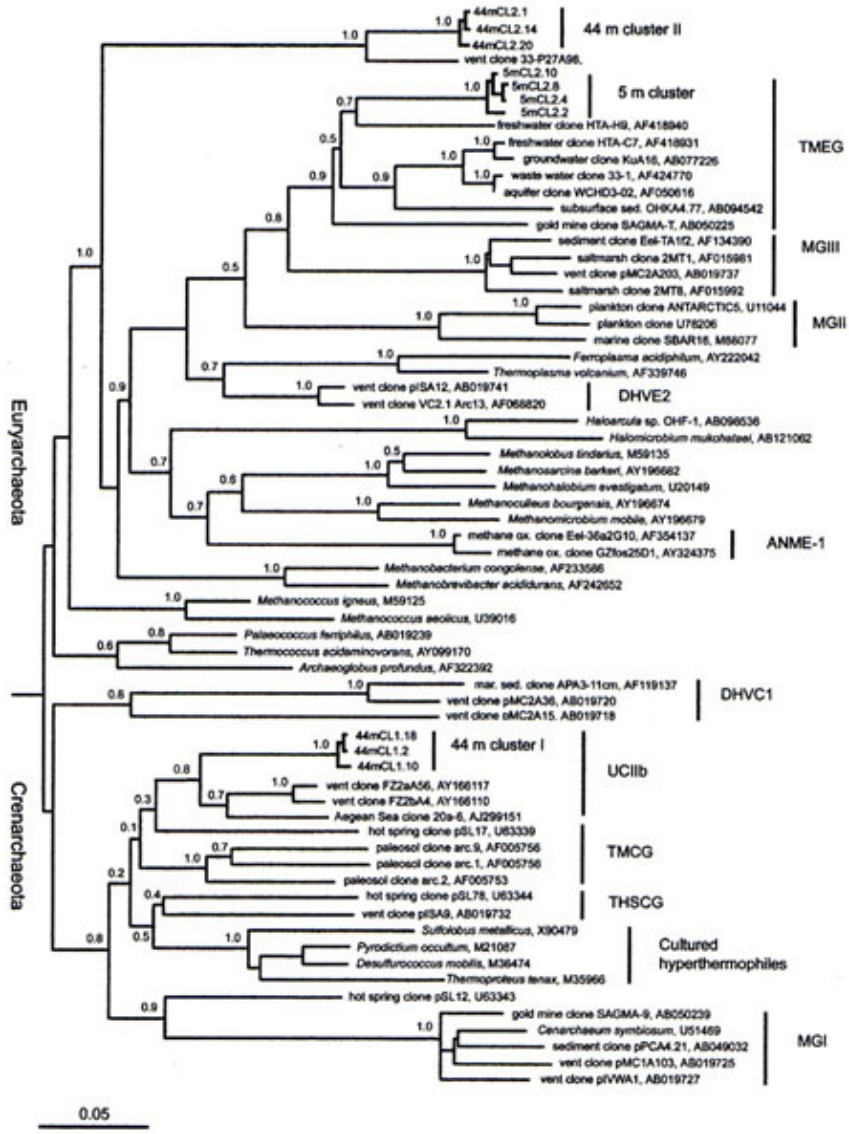

Figure 2. Novel archaeal lineages from subsurface sediments of ODP Site 1231, identified from 16S rRNA gene sequencing. Site 1231 differs from sites with higher biomass by containing unusual archaeal lineages that are in some cases related to 16S rRNA genes collected from hydrothermal vents (44 m cluster; UCIIb cluster). Figure from Sorensen et al. (2004).

The aim of our collaboration with Edgcomb was to define physiological adaptations or incompatibilities of vent archaea for growth or survival under vent and subsurface regimes. High concentrations of heavy metals were tolerated by hydrothermal vent archaea due to metal–sulfide speciation and formation of dissolved or solid metal–sulfide complexes that are biologically unavailable. Dissolved metal cations without adequate sulfide complexation remain highly toxic, even to vent archaea that specialize in this metal–rich habitat (Edgcomb et al., 2004). These experiments provide intriguing support for our hypothesis that metal and sulfur reducers may indirectly cooperate with each other.

We are continuing our survey of methane−sulfate interfaces and anaerobic methane−oxidizing communities in diverse environmental settings, such as the surficial sediments of the Guaymas Basin (Dhillon et al., 2004; Lever, unpublished), methane seep sediments in the Gulf of Mexico (Karen Lloyd, unpublished, in collaboration with Chris Martens and Laura Lapham of UNC Chapel Hill), and deep subseafloor sediments (Lever, unpublished; Inagaki et al., 2003).

In all settings, 16S rRNA and functional key genes for sulfate reduction and methanogenesis are combined (if detectable) for a comprehensive picture of the microbial community. As much as possible, biogeochemical data are used to define ecological niches for each microbial community.

Team members at WHOI continue to principally focus on organic biogeochemical and isotopic signatures of life in subsurface environments. In collaboration with Roger Summons (MIT), team members at WHOI have shown that analyses of intact polar lipids (IPLs) can provide taxonomic specificity allowing distinction of prokaryotes at levels of species to orders. For example, their analyses provided the first evidence for live archaea in deeply buried sulphate−methane sedimentary transition zones (Sturt et al., 2004). In studies of natural ecosystems, the low selectivity of IPL analyses rapidly provides an unbiased view of the dominant microbial players.

Our studies provide strong evidence for biological production of ethane and propane in marine sediments (e.g., D'Hondt et al., 2003). Studies by team member Kai−Uwe Hinrichs and collaborators of isotopic compositions, abundances of potential reactants and products, and bioenergetic modelling point to a mechanism involving hydrogenation of acetate (and bicarbonate) to yield ethane and propane (Hinrichs et al., submitted). These reactions proceed close to the biological energy quantum and provide a previously unexplored sink for major products of fermentation.

Team members John Hayes, Sean Sylva and Helen Sturt, with collaborators Bradley (MIT) and Summons, have shown that lipid extracts from samples of the Lost City Hydrothermal Field are dominated by glycerol ethers from archaea and bacteria. They have also discovered that these ether−linked lipids have remarkably high δ values (Kelley et al., submitted). This discovery raises the possibility that seawater DIC is the carbon source used by both the archaea and sulfate reducers. This could be a consequence of the high concentrations of H_2 supporting simultaneous, independent growth of both groups.

With collaborators Rothman and Summons, Hayes used biogeochemical analyses and modeling to assess the isotopic dynamics of the Neoproterozoic carbon cycle. They conclude that high concentrations of dissolved organic carbon might have played a major role in shaping the isotopic record (Rothman et al., 2003).

Some of our activities are closely integrated with the work of several collaborators at the University of Bremen. This integration is given special impetus by Hinrichs, who is a Marine Scientist at WHOI and a Professor at the

University of Bremen. For example, team member Lever and collaborators Verena Heuer (University of Bremen) and Fumio Inagaki, Japan Agency for Marine−Earth Science and Technology (JAMSTEC), are currently participating in the first IODP expedition (at the Juan de Fuca Ridge). Team member Steven D'Hondt was a co−proponent of this expedition. Samples from these geothermally heated sediments with high organic contents will complement our ongoing activities at cold sites. The work of Julius Lipp (University of Bremen) complements our team's work at WHOI on IPLs in the deep biosphere. Lipp primarily focuses on tracing microbial metabolism by isotopic investigations of bulk IPL fractions that are representative of the living prokaryotic community. Our previous development of analytical procedures for rapid determination of isotopic compositions in chemical intermediates of microbial metabolism (Hayes, Hinrichs, Hmelo) is now complemented by work at University of Bremen, where Marcus Elvert, Hmelo and Hinrichs are testing a new procedure that involves direct coupling of HPLC to an isotope−ratio MS.

To build greater understanding and interest in astrobiology and study of subsurface life by professional scientists, URI team members served prominent roles at several international conferences. For example, team member David C. Smith chaired the session on *Life in Extreme Environments* at the UK−US Frontiers of Science Conference in, Cambridge, UK (June 20−22, 2004). This meeting was jointly sponsored by the Royal Society and by the U.S. National Academy of Science. D'Hondt delivered Distinguished Professor Lectures in the *Short Course on Geomicrobiology*, Shanghai (June 13−19, 2004). These lectures were hosted by Tongji University, sponsored by IODP−China, and attended by Earth and life scientists from throughout China. D'Hondt also served as a Keynote Speaker at the *International Workshop on Geomicrobiology – a research area in progress* (hosted and sponsored by the University of Aarhus, Denmark) in January, 2004, and as an Invited Speaker at the 8th Annual DOSECC Workshop on Continental Scientific Drilling, at Rutgers University (USA) in May, 2004 [hosted by the DOSECC (Drilling, Observation and Sampling of the Earth's Continental Crust) organization and sponsored by the U.S. National Science Foundation].

Graduate, undergraduate and post−doctoral education and research are integral parts of the URI team's mission. During the Year−6 report interval, our active research team included four post−doctoral scholars (Antje Lauer, Ketil Sørensen, Bruno Soffientino, and Sturt,), four graduate students (Lever, Lloyd, Colleen Mouw, and Guizhi Wang) and six undergraduate students. All of these individuals played vital roles in our ongoing program.

To introduce astrobiology to young scientists with particularly strong potential, each year the URI team initiated nationally competed summer research fellowships for upper−class (junior or senior) students to work with URI investigators on projects of astrobiological significance. Two summer fellows (Uri Manor and Beverly Chen) were selected in 2003 and two additional summer fellows were selected in 2004 (Kristopher Carlson and Kelly Hanks). Chen worked with D.C. Smith on developing and applying ATP assays to subseafloor sediments. Manor worked with Scott Rutherford, Wang, and D'Hondt to develop a modeling program for quantifying net rates of microbial activity in deep subsurface sediments. Carlson is working with Soffientino and

D.C. Smith to develop and test protocols for separating live prokaryotic cells from subseafloor sediments. Hanks is working with D'Hondt and Arthur Spivack to quantify possible rates of radiolytic hydrogen and oxygen production in subseafloor sediments and rocks.

To build a deeper institutional base of astrobiology awareness among undergraduate and graduate scientists and engineers, URI astrobiologists expanded the academic programs of their home institutions by integrating astrobiological themes into existing courses, and by offering a new URI graduate course titled "Astrobiology" (Autumn, 2003). To introduce our work and the field of astrobiology to the broader public, URI team investigators gave public presentations and lectures at a variety of universities and other venues. To disseminate our work and its relevance more broadly, in the Year−6 interval the team continues to maintain a website on URI astrobiology efforts in research and education (http://www.gso.uri.edu/astrobiology).

In short, research, education and outreach by the NAI URI Team and its collaborators continue to steadily advance knowledge and awareness of life deep beneath Earth's surface, its role in Earth's surface processes, and its relevance to the search for life on other planets.

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Project Report: Subsurface Biospheres

Project Investigators:	***Arthur Spivack , Steven D'Hondt , John Hayes , Kai−Uwe Hinrichs , David Smith , Andreas Teske***

Project Progress

Members of our team at University of Rhode Island (URI) focus on studies of subsurface metabolic activities and biogeochemical fluxes. To further these studies, team members are developing new techniques to study the activity and physiology of energy−limited microbial communities. For example, Bruno Soffientino and Arthur Spivack are working to develop a robust tritium−based method for quantifying metabolic activity at rates that are well below the detection limit of current radiotracer techniques. Other activities include exploratory work on a novel cell extraction method (Kristofer Carlson, Soffientino, David Smith), development of a numerical model to quantify biogeochemical reaction rates at depth (Scott Rutherford, Uri Manor, Guizhi Wang, Steven D'Hondt, and Spivack), analyses of ATP concentrations and dissolved organic compounds in deep subseafloor sediments (Smith, Beverly Chen, Colleen Mouw), and quantification of biogeochemical fluxes and thermodynamic equilibria of biogeochemical reactions (Spivack, Wang, D'Hondt).

Members of our team at University of North Carolina (UNC) Chapel Hill (Andreas Teske, Antje Lauer, Ketil Sørensen, Mark Lever, Karen Lloyd) focus on genetic analyses of subseafloor communities, with a particular emphasis on organic−poor open ocean sediments. These analyses have required development of DNA isolation procedures for geologically complex low−biomass samples. They are positioned near the sensitivity limit for nucleic acid procedures. Lauer, Teske and Sørensen analyzed archaeal communities from subseafloor sediments with the lowest biomass that have been studied to date. Lever and Teske are undertaking functional gene analyses to determine the principal community members associated with specific subseafloor biogeochemical processes. With collaborator Virginia Edgcomb, Teske also explored the environmental stress tolerance of hyperthermophilic vent archaea.

Members of our team at Woods Hole Oceanographic Institution (WHOI) principally focus on organic biogeochemical and isotopic signatures of life in subsurface environments. Kai Hinrichs, Helen Sturt, Kristin Smith, and

collaborator Roger Summons, are using analyses of intact polar lipids to identify active prokaryotes at levels of species to orders. Studies by Hinrichs and collaborators are developing an understanding of a ubiquitous, but previously unknown, process, the biological production of ethane and propane in marine sediments. Hayes, Sean Sylva, Sturt, Summons, and Bradley are using organic and isotopic biogeochemistry to document community composition and metabolic structure of the ecosystem in the Lost City Hydrothermal Field. With collaborator Rothman, Hayes and Summons are using isotopic signatures and biogeochemical modeling to improve understanding of the Neoproterozoic carbon cycle.

Highlights

- The hydrogenase assay under development will be the first measure of enzymatic activity applicable to environments with extremely low levels of metabolism. It may provide a robust method for quantifying metabolic activity at rates that are well below the detection limit of current radiotracer techniques (Soffientino et al., 2004).
- We have developed a numerical model that uses profiles of chemical and physical properties to quantify metabolic rates at depth (Manor et al., 2004). Our model is flexible enough to quantify complex variation in rates throughout sediment columns of great depth.
- Our biogeochemical studies demonstrate that metabolic interactions in deep subseafloor ecosystems are complex (D'Hondt et al., in review). Several hypothetically competing processes, including metal reduction, sulfate reduction and methanogenesis, commonly occur in deeply buried sediments. At some sites, aerobic communities live deep beneath anaerobic communities, because the underlying basaltic aquifer supplies oxygen and nitrate to the deep sediments. The sedimentary communities may, in turn, fuel life in the underlying basalts by supplying electron donors and nutrients.
- Sulfur reduction and iron reduction co−occur, with low and relatively constant free−energy yields, in some deep subseafloor sediments (Wang et al., 2004). The organisms that rely on these reactions are traditionally assumed to compete with each other. However, our results suggest that positive feedback between these reactions may help to sustain them.
- The archaeal community in the cold metal−reducing ecosystem of our lowest biomass site includes members of several deeply branching phylogenetic lineages that were previously known only from hydrothermal vents (Sørensen et al., 2004). This conspicuous occurrence pattern suggests that cold subsurface sediments may harbor seed populations of vent systems.
- Three archaeal lineages are common in subseafloor sediments throughout much of the world ocean (Lauer et al., 2004). Two of these lineages (Deep−Sea Archaeal Group and Marine Benthic Group A) occur selectively in marine sedimentary habitats. Unexpectedly, known methanogens are scarce in subseafloor sediments, although methane production clearly occurs in subseafloor sediments throughout the world ocean.

- In deeply buried methane/sulfate transition zones of the Peru Margin, we have found intact polar lipid types previously only found in *Sulfolobus spp*. (Sturt et al., 2004). These observations raise the possibility that Crenarchaea are involved in subseafloor anaerobic oxidation of methane.
- Our isotopic and bioenergetic studies suggest that ethane and propane are commonly produced in marine sediments by biogeochemical reactions in which acetate serves as electron acceptor (Hinrichs et al., submitted). These reactions proceed close to the biological energy quantum and provide a novel sink for major products of fermentation.
- Many biomarker lipids from the H_2–rich, Lost City Hydrothermal Field are marked by extraordinary enrichment of ^{13}C (Kelley al., submitted). The pattern is that expected in systems in which autotrophs flourish so strongly that seawater DIC becomes the limiting nutrient.
- Biogeochemical principles and isotopic records both suggest that concentrations of dissolved organic carbon in the Neoproterozoic ocean were probably high and that surging flows of carbon into and out of that reservoir were a key feature of the Neoproterozoic CO_2 and redox balances (Rothman et al., 2003).

Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	MSL	Background Research
3	Future missions to Mars, Europa, and other planetary bodies.	Research or Analysis Techniques

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF,

Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Results from our subseafloor studies, such as the thermodynamically balanced co–occurrence of hypothetically competing iron and sulfate reduction, provide models for possible life on Mars. Consequently, they can help to inform scientific planning for the MSL mission and future missions to other planetary bodies.

Techniques that we are developing (such as the tritium assay of hydrogenase activity) and applying (such as the thermodynamic assessment of metabolic reactions) will ultimately be useful for testing and quantifying the occurrence of metabolic activity and for testing the occurrence of specific metabolic pathways on other planetary bodies.

Field Expeditions

Field Trip Name: IODP Leg 301

Start Date: June	***End Date:*** July
Continent: eastern Pacific Ocean	***Country:*** U.S.A.
State/Province:	***Nearest City/Town:*** Astoria, Oregon
Latitude: 48 degrees N	***Longitude:*** 128 degrees W
Name of site(cave, mine, e.g.): Juan de Fuca Ridge	***Keywords:*** Subsurface, mid–ocean ridge, prokaryote

Description of Work: Team member Mark Lever (UNC) sailed as a microbiologist on the first Integrated Ocean Drilling Program expedition (Leg 301, Juan de Fuca Ridge) to study life in relatively hot sediments that overlie young basalt, and to study life in the hot (70–80 degree C) basaltic aquifer. Collaborators Verena Heuer (organic biogeochemist) and Fumio Inagaki (microbiologist) also sailed on the expedition.

Members Involved:

Cross Team Collaborations

With Virginia Edgcomb (NAI Postdoctoral Fellow at the Marine Biological Laboratory), URI Team member Andreas Teske is working to define physiological adaptations or incompatibilities of vent archaea for growth or survival under vent and subsurface regimes. Recent results are described by

Edgcomb et al. (2004) and briefly outlined in the Executive Summary of this annual report.

With Victoria Orphan (NASA Ames Research Center NAI Team) and Christopher House (Pennsylvania State University NAI Team), URI Team member Kai Hinrichs is studying the microbiology and biogeochemistry of anaerobic methane−oxidizing communities at seafloor methane seeps. Results to date include several publications, most recently Orphan et al. (2004).

With Christopher House (Pennsylvania State University NAI Team), URI Team members are studying the microbiology and biogeochemistry of anaerobic methane−oxidizing communities in subseafloor environments of the eastern Pacific Ocean.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

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University of Washington
Executive Summary
Principal Investigator: Peter Ward

Our group has had a diverse year, with members participating in NASA missions, geological and oceanographic expeditions, and diverse laboratory and theoretical studies. Through all, our NAI–sponsored research at the University of Washington has concentrated on the following important astrobiological questions:

1. What are the characteristics of planets that can evolve complex organisms?
2. Where might such planets occur?
3. How does biological complexity evolve on a planet, and how might it end?
4. What are the limits and permissible chemistries of life and how might they arise?

We are beginning the fourth year of research into these questions. Below, our results and progress are summarized based on specific research problems defined in our original proposal.

How often, where, and under which conditions do habitable planets form and persist?

The rapid discovery of ever more extra–solar planets has now made clear that the Universe is filled not only with stars, but also with planets orbiting those stars. Even a decade ago we could not, with confidence, predict how many planets there might be beyond our own solar system. While there was no indication that there was anything special about our own solar system and star that would make us unique in having planets, there was no real data to the contrary. Now there is definite evidence that planet formation is not only common, but might be ubiquitous to every region in our Milky Way Galaxy, and perhaps in most or all of the far flung galaxies making up the known Universe. We have gone from asking, “how many stars have planets,” to “how many planets have life?”

We define a habitable planet as a solid body capable of supporting life as we know it. The study of extra–solar habitable planets involves a broad interdisciplinary approach that extends from understanding how planets are formed, to understanding the conditions that allow such life to originate, survive, and evolve.

During the past year (2003–2004), Lucio Mayer and Tom Quinn have continued performing simulations of giant planet formation by fragmentation of a gaseous disk, and this work is progressing on several fronts, with special attention to the formation of binary star systems. Lufkin and Quinn have published their work on giant planet migration, showing that migration is not smooth, but probably chaotic. This work continues with a more complete look at migration dynamics. Barnes and Quinn, in collaboration with Lissauer (Ames), continue their simulations of planetesimal accretion in the terrestrial region, and now are concentrating on the timescales for runaway growth.

Finally, Barnes, Quinn, and Raymond continued to investigate the stability of newly discovered extraplanetary systems.

What caused the delivery and retention of organics and volatiles through Earth history?

The volatile and organic composition of impacting bodies is a key factor in the evolution of habitable planets. What are the relative roles of large comet and asteroid fragments and interplanetary dust particles (IDPs) in bringing these materials to a planet? Principle Investigator (PI) Brownlee has made major discoveries about the nature of cometary composition and construction through the successful flyby of the Stardust mission. Also, Kress and Brownlee, in collaboration with George Cody, have investigated the thermal alteration of organic material entering the atmosphere in small extraterrestrial particles. Matrajt and Brownlee worked on a variety of problems related to the nature and abundance of organic materials in small extraterrestrial materials that enter the Earth's atmosphere. They have developed methods for mounting and handing micrometeorites for organic studies by electron energy loss spectroscopy (EELS) in the transmission electron microscope. This work has been very successful but a challenge due to multiple sources of contamination and substrate interference. This work is yielding direct information on the fine–scale distribution and composition of organic materials in small cometary and asteroidal particles. Working with S. Pizzarello and S. Taylor , they determined the a –aminoisobutyric acid (AIB) amino acid content of micrometeorites recovered from pre–industrial ice at the South Pole.

How do mass extinctions and impacts affect the evolution and survival of complex organisms, i.e., the long–term habitability of planets?

Mass extinctions are short–term events that kill off a significant proportion of a planet's biota, and on Earth have been of greatest consequence to more complex organisms such as metazoans. Surface life is vulnerable to major planetary catastrophes, for example, impact of a large comet or asteroid, radiation and particles from a nearby supernova, or catastrophic climate changes such as intense intervals of greenhouse heating or Snowball–Earth type episodes. It is now known that at least one of the major mass extinctions was caused by large body impact, and we would very much like to know if others as well are related to this. The major line of study involves the study of impact craters and their history.

Impact cratering involves evaluation of projectiles, which, to first order, is a measure of the asteroids and comets passing in near−Earth space. More broadly, it involves the origin of those objects, the orbital evolution of the time of their existence, and at least in the case of asteroids, a series of collision and fragmentation processes that occurred in the asteroid belt. Once the material is in near−Earth space, it involves the evaluation of the material passing through atmospheres of various densities (and in some cases not passing through the atmosphere), and then the mechanism of the hypervelocity impact event itself. The physics of the impact include the explosive release of the kinetic energy, which produces the vaporization and melting of rocks, and excavation of material, not only as an eject blanket in the immediate vicinity of the crater, but in the case of large impact events (which can be biologically significant), the ejection of debris through the atmosphere into space, where it can then envelope the entire planet. The biological consequence for the sudden release of this energy can occur on many scales, from affecting individuals, to the death of species and even removal of entire ecosystems or biota. The mechanics, biological, and geological consequences of impact cratered is an enormous field in the very sweep of its questions.

During the past year, two major mass extinction boundaries were studied: the Permian−Triassic (P/T) boundary in Africa and Canada , and the Triassic−Jurassic (T/J) boundary in the Queen Charlotte Islands , Nevada , Italy , and the Newark Basin . Isotopic and paleontological results from these sites are now either in progress or are finished. Our new work suggests that neither the P/T nor T/J mass extinctions were caused by large body impact.

What can we learn from the geological and fossil record about the evolution of eukaryotes and metazoans?

Research by co−I Buick and his group continued in the following six areas: late Archean – early Paleoproterozoic hydrocarbon biomarker molecules, early Archean sulfur isotopes, metamorphism of early Archean biosignatures, nutrient availability (N, P) in Archean oceans, geochronology of a late Archean flood basalt province, and diamond drilling of astrobiologically significant Archean and early Proterozoic sedimentary horizons in the Pilbara Craton of Australia. Field work was conducted on early Archean supracrustal rocks of the Warrawoona and Coonterunah Groups in the Pilbara Craton, Australia . Principal outcomes showed that cyanobacterial and eukaryotic geolipids are present in rocks half a billion years before other fossils of these groups appear in the geologic record and that molecular fossils can survive for much longer under high−temperature regimes than previously expected. Also, a thorough review of the Archean sulfur cycle and constraints upon sulfur isotopic fractionation confirmed the existence of microbial dissimilatory sulfate reduction in ~3.5−billion−year−old oceans, establishing that complex metabolic pathways and peripherally branching bacterial phyla had already evolved.

Further research was performed in 2003−2004 on Archean hydrocarbon biomarker geochemistry, sulfur isotopic fractionation, and Paleoproterozoic hydrocarbon preservation in fluid inclusions. Planning is well underway for planned deep diamond drill coring of three well−preserved sedimentary intervals (Hamersley−Fortescue, Warrawoona−Coonterunah, and Tumbiana) in

the Archean Pilbara Craton, to test syngenicity of hydrocarbon biomarkers and provide unweathered geochemical samples for redox−sensitive environmental indicators.

Co−I Warren has been investigating the ancient Snowball−Earth episodes. During a Neoproterozoic Snowball−Earth event, the ocean surface conditions would determine both the surface climate and the locations for survival of surface life. A process that may be important in the tropical zones (where evaporation exceeds precipitation), as sea ice sublimates, is accumulation of a crust of sea−salt on the ice surface. This can only happen on ice below the eutectic temperature of NaCl brine, −22.9 deg C, but such temperatures are expected on Snowball Earth, even at the equator. No modern surrogate is known to exist in nature now, but we can investigate these processes in our cold−room laboratories. The salt that would accumulate is not NaCl but rather $NaCl{\cdot}2H_2O$, "hydrohalite," which has not received much investigation. Dr. Bonnie Light is collaborating with Warren on this project. She has begun preparations for laboratory studies on (a) migration rates of brine inclusions and salt crystals in ice at low temperatures, (b) the accumulation of salt on sublimating artificial sea ice, (c) suppression of sublimation by a salt crust, (d) cohesive properties of hydrohalite crystals (to determine whether wind will dislodge them), and (e) the absorption spectrum of hydrohalite.

What can we learn from the physiology and molecular characteristics of extant life about the evolutionary pathways by which microbes and their communities evolve, and by which complex organisms originate?

During the past year co−I Staley and his group focused on determining whether the bacterium, *Prosthecobacter dejongeii* , which has alpha− and beta−tubulin analogues previously found only in eukaryotic organisms, contain other eukaryotic proteins. To carry out this work, they compared the genome of *P. dejongeii* with 347 Eukaryotic signature proteins (ESP) from a published list. In addition to *P. dejongeii,* two additional bacteria were included as control organisms, *Gemmata* Wa−1 of the Planctomycetes phylum, and *Caulobacter crescentus* of the Proteobacteria. The protist, *Trypansoma brucei* , was used as a eukaryotic control. *Prosthecobacter dejongeii* had unique ERGO blast matches to alpha−, beta−, and gamma−tubulin, Set2, a transcriptional factor associated with eukaryotic DNA, and LAMMER protein kinase for a total of 12 high ESP matches altogether. *Gemmata* Wa−1 shared six of its 19 high ESP matches with *P. dejongeii* , and that information, coupled with other genomic data, provides strong support that these two phyla are related to one another. If the ESP list is an accurate listing of unique eukaryotic proteins, the low number of high matches between the proteins of these two bacteria with the list raise strong doubts about these organisms being direct ancestors of the Eucarya.

Co−I Leigh used a different approach by continuing his examination of lineages of methanogens. The genome sequence of *Methanococcus maripaludis* is key to studying the evolution of the methanococcal lineage. The genome sequence has been completed and made publically available. A paper on the functional annotation has been submited. Another goal of the project is to use the genetic tools available for *M. maripaludis*, in concert with the genome sequence, to identify the minimal set of genes that is essential for viability. For this purpose

and others, Leigh and his group have devised an efficient method for producing gene deletions in *M. maripaludis* **.** They have also carried out an analysis of lateral transfer of genes involved in utilization of alanine as a nitrogen source.

The nature of early Earth communities

A second way to examine the ancient Earth is through study of microbial communities that likely resemble those of the Precambrian. These communities include those found in (a) anaerobic and photosynthetic microbial mats and biofilms, (b) the sub−seafloor associated with deep−sea hydrothermal vents, and (c) water ice. Co−I Stahl continued to characterize microbial populations in two extreme systems: microbial mats inhabiting hypersaline evaporation ponds (Guerrero Negro, Baja California , Mexico) and associated with hot springs (Yellowstone National Park). Mat population structure was characterized at two spatial scales using polymerase chain reaction (PCR)−amplified rRNA genes: horizontally, over distances up to a kilometer, and vertically at submillimetric scales. Although distribution of dominant populations was stable across large distances (~500m), some variation was observed at fine vertical scales (mm). Diel migration was revealed by significant variation between night/day population profiles, suggesting that some sulfide−oxidizing bacteria may enter the overlying water column at night when oxygen becomes limiting. Parallel analyses of greenhouse mats (with and without sulfate) maintained by members of the Early Microbial Ecosystem Research Group (EMERG) group at NASA Ames revealed few changes in population structure associated with sulfate limitation. However, significant differences were detected between rooftop and field mats. In particular, dominant phototrophs shifted from cyanobacteria to sulfur bacteria, regardless of sulfate treatment.

In Yellowstone, work focused on the enrichment and isolation of thermophilic sulfate reducing prokaryotes (SRP) from three hot springs using a variety of electron donors (organic or hydrogen) at 60°C or 80°C, identifying novel populations by sequencing of 16S rRNA and DSR genes. Sulfide production was observed at 60°C on all substrates. In contrast, sulfide was produced only at 80°C on hydrogen, either autotrophically or with acetate as an alternative carbon source. Sulfide was also produced in enrichments on hydrogen using sulfur, sulfite, or thiosulfate as the electron acceptors, at both 60°C and 80°C. In agreement with the observed lower metabolic diversity at higher temperatures, microscopic analysis of these enrichments revealed a lower number of morphotypes at 80°C than at 60°C. The observation that only hydrogen, among the various electron donors tested, supported the growth of SRP at 80°C argues for the importance of lithotrophic metabolism in these hydrothermal systems.

Metabolism in extreme environments.

Another approach to understanding the habitability of planets is to consider the range of extreme environmental conditions on Earth that support life. For example, the detection of water ice and/or submarine hydrothermal vent systems on another planetary body would satisfy some of the key criteria for habitability, and this area has been investigated by co−I Deming and her group. Laboratory observations of bacterial motility and field observations of bacterial

attachment led to the testable hypothesis that a temperature threshold exists in ice formations (–10°C in sea ice), below which bacteria cease moving as a means to locate optimal resources and conditions and instead become attached to a surface (first–stage biofilm formation), which allows for continued activity down to –20°C (lowest temperature tested yet). The University of Washington (UW) team continued to pursue questions on microbial activity and evolution in subzero salty habitats, taking a multi–faceted approach that includes studies of Bacteria, Archaea, viruses, exopolymers and extracellular enzymes. Much of this work was done while locked in polar ice on an icebreaker. The phenomenon of attachment or sorption to surfaces (first–stage biofilm formation) under extreme conditions of temperature and salt concentration provides an important focal point. Although much of our work is influenced by NAI objectives, specific accomplishments this year stem from three efforts. Postdoctoral work by Karen Junge has yielded evidence that high molecular weight polymeric substances (EPS), derived from the spent medium of cold–adapted bacterium *Colwellia psychrerythraea* strain 34H, facilitate bacterial activity (incorporation of tritiated leucine into macromolecules) at temperatures below –20°C (Junge et al., in preparation). This work reinforces the importance of EPS to microbial survival (and continuing evolution) in deeply frozen environments, as well as the potential of EPS as biosignatures on icy planets and moons.

The variety of life

The University of Washington team has added Stephen Benner to its group. Benner and his colleagues have been investigating alternatives to “life as we know it,” as well as studying chemical pathways to the formation of RNA and other biological molecules and materials. Benner has looked in particular at the “RNA–first” hypothesis by looking at avenues of prebiotic chemistry that includes borate minerals. Work still continues on the outstanding problem of RNA instability.

The role of plate tectonics

Co–I Solomatov has been studying the role of plate tectonics in Astrobiology. Plate tectonics plays an important role in the evolution of global planetary climate and life. Yet, there is very little consensus on when and how plate tectonics began on Earth. Various scenarios have been proposed ranging from initiation of plate tectonics as early as after crystallization of magma ocean, to a relatively late start of plate tectonics, in the Late Archean. The most difficult aspect of plate tectonics is initiation of subduction. Although initiation of subduction has been extensively studied, the focus has been on the present–day Earth where plate tectonics is already occurring. The major difference between initiation of subduction on the present–day Earth and the early Earth is that in the absence of plate tectonic forces associated with plate tectonics are absent, and cannot participate in subduction initiation. Solomatov has developed constraints for this mechanism with the help of systematic finite element simulations in two dimensions (paper published) and began a systematic study in three dimensions (paper submitted). Two–dimensional studies showed that small–scale convection generates stresses comparable with the stresses required for initiation of subduction on the present–day Earth

and can indeed be a trigger mechanism for plate tectonics. This conclusion seems to be even stronger in spherical geometry. The derived scaling relationships provide a theoretical basis for predicting plate tectonics on a silicate planet with arbitrary parameters.

Project Report: Bacterial tubulin and its implications on the evolution of Eukaryotes

Project Investigator:	***James Staley***

Project Progress

During the past year we have focused on determining whether the bacterium, *Prosthecobacter dejongeii* , which has alpha– and beta–tubulin analogues previously found only in eukaryotic organisms, contain other eukaryotic proteins. To carry out this work, we compared the genome of *P. dejongeii* with 347 Eukaryotic signature proteins (ESP) from a published list. In addition to *P. dejongeii,* two additional bacteria were included as control organisms, *Gemmata* Wa–1 of the Planctomycetes phylum and *Caulobacter crescentus* of the Proteobacteria. The protist, *Trypansoma brucei* , was used as a eukaryotic control. *Prosthecobacter dejongeii* had unique ERGO blast matches to alpha–, beta–, and gamma–tubulin, Set2, a transciptional factor associated with eukaryotic DNA, and LAMMER protein kinase for a total of 12 high ESP matches altogether. *Gemmata* Wa–1 shared six of its 19 high ESP matches with *P. dejongeii* , and that information coupled with other genomic data provide strong support that these two phyla are related to one another. If the ESP list is an accurate listing of unique eukaryotic proteins, the low number of high matches between the proteins of these two bacteria with the list raise strong doubts about these organisms being direct ancestors of the Eucarya. However, this does not rule out the possibility that ancestral members of either the Verrucomicrobia or Planctomycetes may have played a role in the evolution of a Proto–eukaryotic organism.

We are also continuing our study of Bacteria and Archaea from desert varnish by use of sequence analyses of 16S rDNA obtained from DNA extracts of desert varnish. The dark varnish is an analogue for possible rock coatings found on Mars and other extra–terrestrial environments. The main question we are addressing is: Do biological signatures indicative of varnish coatings occur on Earth? Samples analyzed to date provide evidence that members of both the Bacteria and Archaea occur in the rock coatings.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules

Cross Team Collaborations

We are also continuing our study of Bacteria and Archaea from desert varnish by use of sequence analyses of 16S rDNA obtained from DNA extracts of desert varnish. The dark varnish is an analogue for possible rock coatings found on Mars and other extra–terrestrial environments. The main question we are addressing is: Do biological signatures indicative of varnish coatings occur on Earth? Samples analyzed to date provide evidence that members of both the Bacteria and Archaea occur in the rock coatings. We are collaborating with Mitch Sogin on this work. He is looking at signatures for eukaryotic microorganisms.'ÇÇ

Project Report: First–Stage Biofilm Formation Under Extreme Conditions in Ice

Project Investigator:	***Jody Deming***

Project Progress

We continue to pursue questions on microbial activity and evolution in subzero salty habitats, taking a multi–faceted approach that includes studies of Bacteria, Archaea, viruses, exopolymers and extracellular enzymes. The phenomenon of attachment or sorption to surfaces (first–stage biofilm formation) under extreme conditions of temperature and salt concentration provides an important focal point. Although much of our work is influenced by NAI objectives, specific accomplishments this year stem from three efforts. Postdoctoral work by Karen Junge has yielded evidence that high molecular weight polymeric substances (EPS), derived from the spent medium of cold–adapted bacterium *Colwellia psychrerythraea* strain 34H, facilitate bacterial activity (incorporation of tritiated leucine into macromolecules) at temperatures below –20°C (Junge et al., in preparation). This work reinforces the importance of EPS to microbial survival (and continuing evolution) in deeply frozen environments, as well as the potential of EPS as biosignatures on icy planets and moons. Work by the PI (on sabbatical leave this year) during an over–wintering expedition in the Arctic included development of new approaches to studying enzyme activity in natural and unmelted ice formations. Sea–ice samples laden with particles or EPS gave the most promising results (in keeping with earlier work by Junge et al., 2004). Theoretical considerations to improve the design of experiments in deeply frozen systems were then developed jointly with co–I Eicken during sabbatical time in Fairbanks . Work by doctoral candidate Llyd Wells has resulted in numerous accomplishments this year, including a detailed phenotypic characterization of a cold–adapted phage–host system, using novel techniques developed for work at low temperature, and presumptive evidence for horizontal gene transfer in the cold using a genomic approach. Viral activity was also measured in field samples (again paying attention to particle–rich samples, as well as those that may contain Archaea) under various extreme conditions, including low temperature, limited host–food availability, and the subzero salty conditions of winter–time sea–ice brines. Although these efforts have not yet been brought to publication, other work reported last year has reached the press (see reference list).

Highlights

- Evidence that exopolymers facilitate bacterial activity in deeply frozen systems was obtained (Junge et al., in preparation).
- Novel techniques for working with bacterial viruses in the cold were developed, enabling detailed characterization of a cold–adapted phage–host system (Wells and Deming, unpublished).

Roadmap Objectives

- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	JIMO (Jupiter Icy Moons Orbiter)	Planning Support

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

We contribute to development of flight mission goals and life–detection concepts by providing background research on the integrated physics, chemistry and microbiology of deeply frozen systems on Earth and as members of the Europa Focus Group.

Field Expeditions

Field Trip Name: Chinare 2003 (Arctic expedition aboard the Chinese icebreaker XueLong)

Start Date: August 3, 2003	***End Date:*** August 16, 2003
Continent: north of North America –– Canada Basin, Arctic Ocean	***Country:*** international waters
State/Province: north of Alaska, USA	***Nearest City/Town:*** Barrow, AK
Latitude: 74–75°N	***Longitude:*** 150–160°W
Name of site(cave, mine, e.g.): Canada Basin, Arctic Ocean	***Keywords:*** Arctic seawater, sea ice, extremophiles

Description of Work: The funded work (by NOAA Office of Arctic Research), targeting multi–year sea ice and deep Arctic waters, involved attempting to bring into culture potentially novel microorganisms able to function at subzero temperatures, high salt concentrations, and/or high hydrostatic pressures. Some of the resulting organisms may provide useful models for NAI research.

Members Involved:

Field Trip Name: CASES 2003–2004 (over–wintering expedition of the Canadian Arctic Shelf Exchange Study aboard the Canadian Coast Guard icebreaker Amundsen)

Start Date: November 26, 2003	***End Date:*** April 2, 2004
Continent: north of North America, Arctic waters	***Country:*** Canada
State/Province: Northwest Territories	***Nearest City/Town:*** Tuktoyaktuk
Latitude: 70°N	***Longitude:*** 126°W
Name of site(cave, mine, e.g.): Franklin Bay, Canadian Archipelago	***Keywords:*** Arctic seawater, sea ice, extremophiles

Description of Work: The funded work (by NSF Office of Polar Programs and NOAA Office of Ocean Exploration) included regular sampling over three months to evaluate microbial succession and extracellular enzyme activity under conditions of very low temperatures and high salt concentrations, as well as attempts to bring into culture potentially novel extremophiles. We took advantage of this extended overwintering expedition to conduct experiments related to our NAI interests in exopolymer facilitation of microbial attachment and enzyme behavior and possible viral activity under severe winter conditions.

Members Involved:

Cross Team Collaborations

Eicken and Deming continued to interact with Giles Marion (co–I at Arizona State) on the subject of geochemical and microbial reactions at low

temperatures, high salt concentrations and high pressures. The outcomes this year were development of research plans to experiment with more extreme conditions than we have used previously, some co−advising of UW Astrobiology graduate student, Steve Vance (in the Earth and Space Sciences Department), and a publication on the search for life on Europa (Marion et al., 2003). Deming (and doctoral candidate Wells) also joined the new NAI Virus Focus Group, while Eicken continued as a member of the Jupiter Icy Moons Orbiter (JIMO) Science Definition Team, participated in a number of JIMO SDT meetings in the last year, and contributed to the "Report of the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO)," February 2004. Deming and Eicken remain members of the NAI Europa Focus Group.

Project Report: Evolution of biocomplexity from an ancient autotrophic lineage

Project Investigator:	***John Leigh***

Project Progress

The genome sequence of *Methanococcus maripaludis* is key to studying the evolution of the methanococcal lineage. The genome sequence has been completed and made publically available. A paper on the functional annotation has been submited. Another goal of the project is to use the genetic tools available for *M. maripaludis*, in concert with the genome sequence, to identify the minimal set of genes that is essential for viability. For this purpose and others, we have devised an efficient method for producing gene deletions in *M. maripaludis*. We have also carried out an analysis of lateral transfer of genes involved in utilization of alanine as a nitrogen source. A paper has been submitted that combines the latter two advances, focusing on the alanine utilization genes for mutagenesis and phylogeneitc analysis.

Highlights

- The genome sequence of *Methanococcus maripaludis*, a mesophilic hydrogenotrophic methanogen, has been completed and is publically available.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.3:*** Origins of energy transduction
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: University of Washington

Project Report: Dynamics of comets, asteroids, and planets

Project Investigator:	***Thomas Quinn***

Project Progress

Mayer and Quinn have continued performing simulations of giant planet formation by fragmentation of a gaseous disk. This work is being extended on several fronts. We are studying the fragmentation scenario in binary star systems. This is clearly important since a majority of stars are in binaries. We conclude that if a binary companion is sufficiently close, planet formation in either the fragmentation model or the planetesimal model is completely suppressed. We are also investigating the quality of our simulations on several fronts. First, with Mejia, we are comparing the results of Lagrangian simulations with Eulerian simulations of the same system. Second, with Lufkin , we are incorporating radiative transfer into the simulations in the flux−limited diffusion approximation. With Mejia, we are also incorporating solids into our gas dynamical simulations.

Lufkin and Quinn have published their work on planet migration in gaseous disks, where they demonstrate that the standard picture of a smooth migration inward is probably incorrect, and that the process is rather chaotic involving close encounters and collisions of giant planets. A more complete survey of migration parameters is now underway as part of Lufkin 's Ph.D. thesis.

Barnes and Quinn, in collaboration with Lissauer (Ames), continue their simulations of planetesimal accretion in the terrestrial region. The simulations are reaching the point where the timescales for run−away growth can be seen. The aim is to determine the mass spectrum of planetesimals coming out of the middle stage of planet formation as a function of distance from the Sun.

Barnes, Quinn and Raymond continue to investigate the stability of extra−solar planetary systems as they are being discovered. They continue to find that most planetary systems, including our own, are on the edge of being unstable. If this is a general principle of planet formation, then predictions can be made about unseen planets in existing extrasolar planetary systems. We are investigating this possibility and have submitted several papers with our predictions.

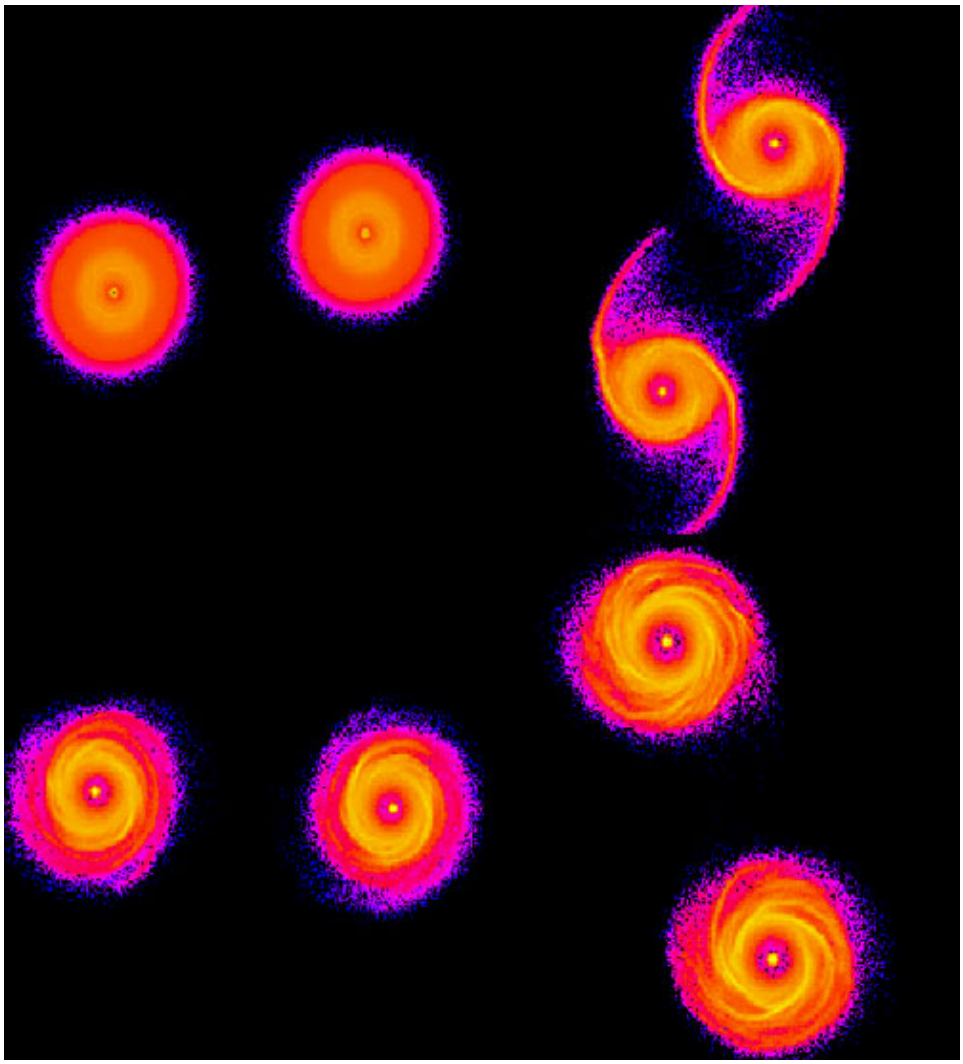

Figure 1. Color coded plots of the gas density in a pair of protoplanetary disks in a binary system. The images are about 100 AU on a side. From top−left to bottom−right, snapshots at 16 years, 200 years (shortly after first pericenter passage), 400 years and 550 years (close to second pericenter passage) are shown.

Highlights

- Planet formation is highly suppressed in binary star systems with separations less than approximately 100 AU.
- It may be possible to form terrestrial planets in the 55 Cnc system but not in the other extra solar multiple planet systems.
- Several of the extra solar multiple planet systems may host Saturn−size planets in the habitable zone of the star.
- Migration of gas giants via interaction with a stable gas disk happens on a shorter timescale than previously suggested.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Background Research
1	Kepler	Background Research
2	SIM	Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Fundamental theoretical research on planet formation is need both for mission planning, particularly in the case of TPF, and in interpreting mission results.

Cross Team Collaborations

The research on terrestrial planet formation involves collaboration with Jack Lissauer, a member of the Ames Lead Team. The expertise of the Ames planetary scientists is helping to formulate the best computational experiments to perform.

Project Report: Delivery of organic materials to planets

Project Investigator:	***Thomas Quinn***

Project Progress

Kress and Brownlee, in collaboration with George Cody, have investigated the thermal alteration of organic material entering the atmosphere in small extraterrestrial particles. An interesting aspect of this process is that even the most severely heated particles eject sublimed compounds that survive. This work has involved the analysis of organics released from pulse heated carbonaceous chondrites under conditions that simulate the atmospheric entry of 200−µm particles. Most of the Earth's 30,000 tons of annually accreted material arrives in comet and asteroid particles of this size. This work is underway but will provide a good estimate of the nature and amounts of simple organic compounds accreted by habitable zone planets.

Matrajt and Brownlee worked on a variety of problems related to the nature and abundance of organic materials in small extraterrestrial materials that enter the Earth's atmosphere. They have developed methods for mounting and handing micrometeorites for organic studies by electron energy loss spectroscopy (EELS) in the transmission electron microscope. This work has been very successful but a challenge due to multiple sources of contamination and substrate interference. This work is yielding direct information on the fine scale distribution and composition of organic materials in small cometary and asteroidal particles. Working with S. Pizzarello and S. Taylor , they determined the α −aminoisobutyric acid (AIB) amino acid content of micrometeorites recovered from pre−industrial ice at the South Pole. Working with L. Leshin (Arizona State University (ASU)) and M. Genge (Open University) they are studying the organic, mineralogical, and oxygen isotopic composition of a large suite of unmelted micrometeorites >100 µm collected from South Pole ice. They are also comparing these materials with those that form meteorites, and have found that carbon−rich bodies are the dominant source of particles <1 mm diameter.

Brownlee and his Stardust collaborators made a close flyby of comet Wild 2 on January 2, 2004 , providing an unprecedented wealth of information on a Kuiper belt comet, a class of body that delivers organic materials and water to habitable zone planets. This work showed that comets are considerably different than asteroids and other solar system bodies. See figure 2.

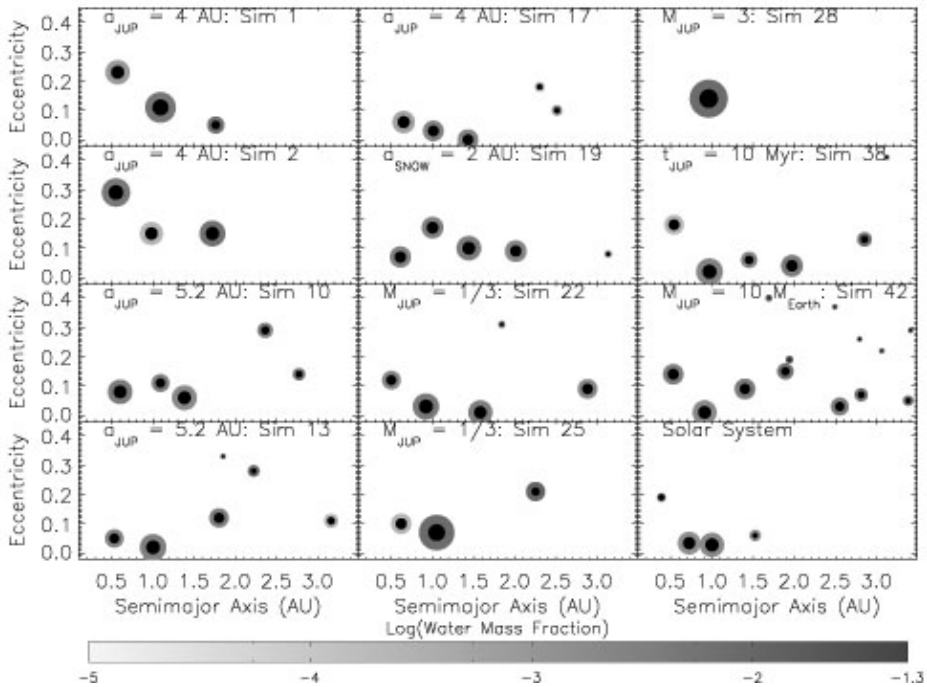

Figure 1. Final states of late stage accretion simulations containing an earth−size planet in the habitable zone. The size of each planet is proportional to its mass, and the color indicates the water content. The central black circle indicates the amount of iron that the planet contains. The Solar System is shown in the lower right corner for comparison.

Figure 2.

Highlights

- First close−up imaging of a comet formed beyond Neptune−in the Kuiper belt.
- Detection of amino acids in micrometeorites collected from South Pole ice.
- Analysis of the form, abundance, and atmospheric alteration of organic materials in interplanetary dust.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Science Team Member
1	Kepler	Background Research
1	SIM	Background Research
1	Stardust	Project Investigator
2	Hera	Co−Investigator
1	Kepler	Science Team Member

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

n the case of TPF, estimates of the amount and kind of volatiles that terrestial planets can have will make a significant difference in the mission design in order insure the success of the mission.

For the other missions, Fundamental theoretical research on planet formation is need both for mission planning, particularly in the case of TPF, and in interpreting mission results.

Cross Team Collaborations

George Cody

Project Report: Causes of mass extinctions: testing impact models_Ward

Project Investigator:	***Peter Ward***

Project Progress

This project was instituted to examine the relationship between impact and mass extinction. We know that one of the largest mass extinctions of the past 500 million years was caused by impact (the Cretaceous/Tertiary (K/T) event 65 million years ago (Alvarez et al, 1980)). What of the many other mass extinctions? A major thrust of the University of Washington NASA Astrobiology Institute's research has been to test for hypotheses of impact being related to other mass extinctions. In the third year of our grant we have made significant progress toward understanding the cause of the largest mass extinction of all time, the Permian extinction of 251 million years ago, and the second or third most catastrophic extinction, the Triassic/Jurassic (T/J) event of 200 million years ago. In this summary we will outline this progress.

1. Stable isotope and rates of extinction, Permian extinction, and Triassic/Jurassic extinction events (PI Ward, Co–I Buick, Kring, and NAI NRC post–Doc (with Ward) Garrison

- Permian strata from South Africa. We have concluded research on samples obtained during 2001 in South Africa using the new stable isotope facility at the University of Washington . We have succeeded in obtaining a new curve for both carbonate and organic carbon isotopes from the highest Permian and lower Triassic of this. Our results, coupled with new data about the disappearance of vertebrate fossils in this region suggest that the extinction had a more protracted nature than the signal in both isotopes and extinction metrics at the impact caused K/T event. We believe that our new evidence does not support hypotheses of impact–induced extinction at the end of the Permian (i.e., Becker et al., 2004). These results have been written up as a manuscript now undergoing internal review. It will be submitted to Science Magazine in mid–summer.
- Permian strata from Alberta. We have concluded analysis of material sampled by Garrison at a marine Permian/Triassic boundary section in Alberta . These data, coupled with paleontological data, show an extended period of light stable isotopes after the Permian/Triassic boundary in the region. Again, this pattern does not appear similar to

the pattern observed at the end of the Cretaceous from similar marine facies. Our new data are better explained by a protracted oceanographic event brought about by changes in the atmosphere than an impact event. This work is now being written up for submission.

- Triassic/Jurassic boundary in the Queen Charlotte Islands. During 2003–2004, we finished analyzing carbon isotope data from the T/J section of the Queen Charlotte Islands that was the site of the study by Ward et al. (2001). Our new results, now in press (Ward et al., in press, *Earth and Planetary Science Letters*), demonstrated an extended period of isotopic perturbations occurring after the level of mass extinction. These data do not support an impact event explanation for the T/J mass extinction event.
- T/J boundary, Nevada. In April, 2003, we sampled from the classic T/J section at Muller Canyon . Our results show a series of isotopic perturbations around the boundary that are not consistent with the patterns found at the one known impact extinction boundary, the K/T event. These results have been written and are in review in *Geology* .

2. Helium as an Indicator of Extraterrestrial Impacts

Over the last few years helium concentrations and isotopic compositions of sedimentary rocks have been used to detect important solar system events including catastrophic bolide impacts with Earth at several different extinction horizons. The basic idea is that extraterrestrial matter is highly enriched in the rare isotope of helium (^{3}He) compared with terrestrial material that constitutes most sedimentary rocks. The presence of high concentrations of extraterrestrial ^{3}He coincident with an extinction horizon would provide strong indirect evidence of an extraterrestrial cause for the extinction. Extraterrestrial ^{3}He may be present in fullerenes released directly from an impactor (Becker et al., 2001a) or in interplanetary dust particles (IDPs) (Poreda and Becker, 2003) , . While IDPs accumulate from multiple sources and need not be indicative of a significant extraterrestrial event, an enhanced IDP flux may be associated with showers of long–period comets (Farley et al., 1998) and with major collisions in the asteroid belt (Kortenkamp and Dermott, 1998) . Both of these events raise the likelihood of impact, in some cases enormously so (Hut et al., 1987) . One advantage of using ^{3}He as an impact tracer is that elevated levels associated with major solar system events can last for a few million years (Farley et al., 1998; Kortenkamp and Dermott, 1998) , making detection far easier than the location of a single ejecta layer in a long stratigraphic sequence.

In 2003–2004 we completed detailed helium isotopic investigations of two possibly impact–induced extinction boundaries: the Permian/Triassic and the Triassic/Jurassic.

A. Permian/Triassic Boundary

Multiple lines of evidence have been presented in favor of an extraterrestrial impact associated with the Permian/Triassic (P/T) boundary. Recent observations favoring impact include extraterrestrial noble gases in fullerenes and in IDPs in purported boundary sediments (Becker et al., 2001b; Poreda and Becker, 2003) , meteorite fragments in P/T age sediments from Antarctica

(Basu et al., 2003) , and a proposed impact crater in the Indian Ocean alleged to be of the appropriate age (Becker et al., 2004) . These observations have been very controversial. Some of the original observations could not be reproduced by another laboratory (Farley and Mukhopadhyay, 2001) , the identification of the P/T boundary in relation to the fullerene spike is doubtful in at least one case (Isozaki, 2001) , and the existence of an impact crater and its likely age have been rejected (Renne et al., submitted 2004). Although a great deal of very suggestive data has been published on the topic, no incontrovertible evidence for a P/T−age impact event yet exists.

Helium concentration and isotopic composition were measured in a suite of 33 cherts, siltstones, and shales across the P/T boundary at Opal Creek , Canada (Henderson, 1997) . No extraterrestrial ^{3}He was detected, implying that neither fullerene hosted nor IDP−hosted He is present at or near the boundary. This observation is consistent with similar studies of other P/T sections, but contrasts sharply with reports from a single group of both fullerene and IDP−hosted extraterrestrial ^{3}He at some other P/T sections. If extraterrestrial ^{3}He is present at the P/T boundary, it must be very heterogeneously distributed. As such, we conclude that the ^{3}He−based evidence for impact at P/T time is uncompelling.

While no extraterrestrial ^{3}He was detected, there is a sharp increase in nucleogenic ^{3}He, very close to or at the P/T boundary. This presumably arises from the major lithologic change at this time, from cherts in the Permian to shales and siltstones in the Triassic. Increased nucleogenic ^{3}He is associated with increases in both lithium and organic carbon content into the Triassic. Either the production rate or the retention of this ^{3}He is higher in the shales and silstones than in the cherts. One important conclusion of this new work is that care must be taken to eliminate such artifacts before interpreting changes in ^{3}He concentration in terms of fluctuations in the delivery of ^{3}He from space.

A manuscript has been completed on this work and should be submitted shortly.

B. Triassic/Jurassic Boundary

On the basis of a small Iridium anomaly, Olsen et al., (2002) proposed an extraterrestrial impact in association with the T/J extinction event. Ward et al., (in press), concluded that the stable isotopic evidence argues against such an interpretation. To assess whether ^{3}He provides any insight to this question we analyzed thirty silty limestones spanning 40 meters centered on the T/J boundary, from Muller Canyon , Nevada (Hallam and Wignall, 2000) .

The preliminary results provide no support for extraterrestrial ^{3}He at or near the boundary – no evidence for either fullerene−hosted ^{3}He or enhanced interplanetary dust flux. This conclusion is consistent with work undertaken at several other T/J sections in eastern North America (Farley and Olson, unpublished). Further work is required to conclusively establish the origin of the ^{3}He in this section, but it is probably nucleogenic.

Highlights

- We have recovered detailed carbon isotope curves from a marine and non–marine section of late Permian age, and two marine sections of late–Triassic, early–Jurassic age. These results are not consistent with environmental effects of large body impact on the Earth.
- We have analyzed fossil records across these same horizons. The extinctions do not appear to be sudden/catastrophic.
- We have analyzed for extraterrestrial material from these boundary sections. We do not recognize an unambiguous extraterrestrial signal.

Roadmap Objectives

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Field Expeditions

Field Trip Name: Triassic of SE Alaska	
Start Date: 7/3/03	***End Date:*** 7/12/03
Continent: North America	***Country:*** USA
State/Province: Alaska	***Nearest City/Town:*** Kake
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Collection of fossil material for isotopic analysis	
Members Involved:	

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Project Report: Causes of mass extinctions: testing impact models_Kring

Project Investigators:	***David Kring , Peter Ward***

Project Progress

In the past year the University of Arizona module of the University of Washington–led Astrobiology node (1a) completed a petrological and provenance study of Triassic/Jurassic (T/J) boundary sediments from British Columbia, testing the impact–mass extinction hypothesis, (1b) provided splits for C–isotope analyses to determine the extent of productivity collapse and the possible role of other, non–impact processes; (2a) sampled a second suite of T/J boundary sediments from Nevada, (2b) began a petrological and provenance study of them, and (2c) provided splits for C–isotope analyses; (3) completed a study of the ignition threshold of impact–generated wildfires and demonstrated the T/J–era Manicouagan impact event could have produced continental–scale wildfires (this study augments the previous year's study of the effect of a continental–scale impact air–blast produced by the Manicouagan impact event); and (4) completed a study of impact–generated acid rain trauma following the Chicxulub impact event and its possible role in the Cretaceous/Tertiary (K/T) boundary mass extinction event.

Highlights

- The T/J boundary has been pin–pointed! Negative C–isotope excursions suggest the boundary is associated with a productivity collapse.
- C–isotope data at T/J boundary sections, however, also indicate the T/J transition was complex and may not have been the result of a single, traumatic blow to the biosphere.
- Chicxulub is the only known impact event in the Phanerozoic to have been large enough to create globally–distributed wildfires.
- Manicouagan and Popigai impact events were large enough to have created continental–scale wildfires.
- The Chicxulub–generated acid rain trauma was sufficient to acidify continental lakes and waterways if they were not buffered by carbonate catchements.

Roadmap Objectives

- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

Project Report: Building a habitable planet: the geological record

Project Investigator:	***Roger Buick***

Project Progress

Research continued in the following six areas: late Archean – early Paleoproterozoic hydrocarbon biomarker molecules, early Archean sulfur isotopes, metamorphism of early Archean biosignatures, nutrient availability (N, P) in Archean oceans, geochronology of a late Archean flood basalt province, and diamond drilling of astrobiologically significant Archean and early Proterozoic sedimentary horizons in the Pilbara Craton of Australia . Field–work was conducted on early Archean supracrustal rocks of the Warrawoona and Coonterunah Groups in the Pilbara Craton, Australia . Principal outcomes were:

- Publication of complete results on hydrocarbon biomarker molecules in late Archean and early Paleoproterozoic sediments, showing that cyanobacterial and eukaryotic geolipids were present in rocks half a billion years before other fossils of these groups appear in the geologic record, and that molecular fossils can survive for much longer under high–temperature regimes than previously expected.
- A thorough review of the Archean sulfur cycle and constraints upon sulfur isotopic fractionation confirmed the existence of microbial dissimilatory sulfate reduction in ~3.5–billion–year–old oceans, establishing that complex metabolic pathways and peripherally branching bacterial phyla had already evolved.
- Analysis of carbon isotopes in 3.52–billion–year–old sedimentary rocks show that, despite low–grade metamorphism (greenschist facies), isotopic fractionations resembling those imparted by Calvin–Benson cycle Rubisco autotrophy and by methanogenesis, survive in carbonates and cherts.
- U–Pb dating of zircons in felsic tuffs and volcanics interbedded with late Archean flood basalts constrained the age of the oldest–known reversal of the Earth's magnetic field and allowed calculation of continental drift rates, implying very rapid horizontal tectonic processes on the early Earth.
- Planned deep diamond drill coring of three well–preserved sedimentary intervals (Hamersley–Fortescue, Warrawoona–Coonterunah, and Tumbiana) in the Archean Pilbara Craton will test syngenicity of

hydrocarbon biomarkers and provide unweathered geochemical samples for redox−sensitive environmental indicators.

Fig. 1 Graham Logan, Roger Summons, Jochen Brocks and Roger Buick using gas chromatography−mass spectrometry to investigate hydrocarbon biomarkers of cyanobacteria and eukaryotes in 2.7 Ga kerogenous shales

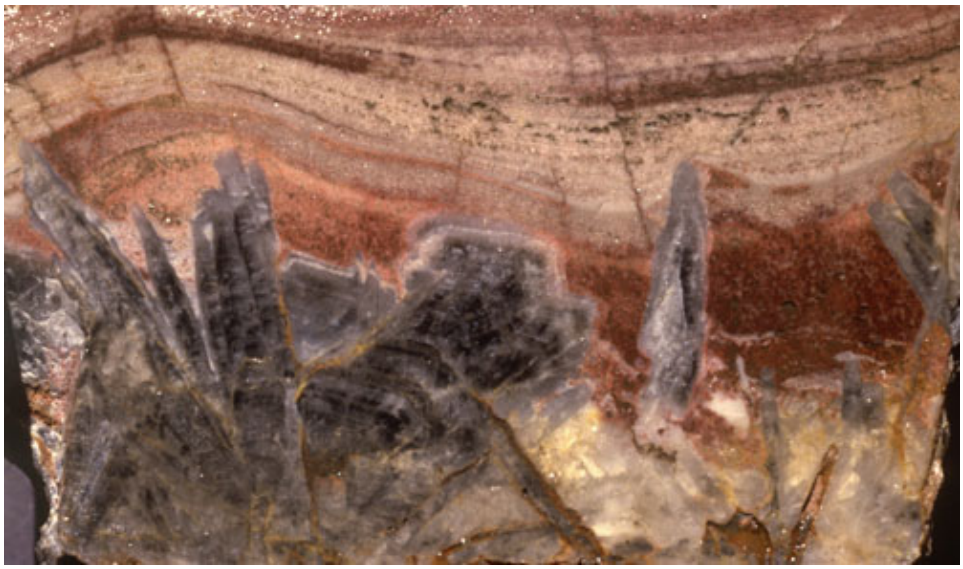

Fig. 2 Bedded barite from North Pole, Australia containing microcrystalline pyrite with fractionated sulfur isotopes indicating bacterial sulfate reduction at 3.45 Ga

Highlights

- A full documentation of the molecular biomarker record from late Archean – early Paleoproterozoic rocks from the Hamersley Basin, Australia (Brocks et al., 2003a, 2003b, 2003c) shows that cyanobacteria

and eukaryotes evolved early in Earth history, allowing reconstruction of ancient ecosystems (Fig. 1).
- A thorough review of the early Archean sulfur isotope record (Shen and Buick, 2004), shows that dissimilatory sulfate reduction arose early in Earth history, allowing time calibration of the Tree of Life, and providing a potential biosignature for primordial life on other sulfate–bearing planets, i.e., Mars (Fig. 2).

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Field Expeditions

Field Trip Name: Pilbara	
Start Date: 27 July 2003	***End Date:*** 17 August 2003
Continent: Australasia	***Country:*** Australia
State/Province: Western Australia	***Nearest City/Town:*** Marble Bar
Latitude: 21S	***Longitude:*** 119E
Name of site(cave, mine, e.g.): Coonterunah Group	***Keywords:***
Description of Work: mapping metamorphic gradients in early Archean biosignature–bearing sediments	
Members Involved:	

Cross Team Collaborations

Roger Summons (Ames, URI): papers on Archean biomarkers, abstract on Archean drilling Ariel Anbar (PSU, Colorado): 3 abstracts on Archean drilling Jay Kaufman (PSU): abstract on Archean drilling Tim Lyons (PSU): abstract on Archean drilling Mark Barley (PSU): manuscript on Archean geochronology Steve Mojzsis (UCLA, Colorado): abstract on Archean drilling

Project Report: Plate tectonics on the terrestrial planets

Project Investigator:	***Viatcheslav Solomatov***

Project Progress

Plate tectonics plays an important role in the evolution of global planetary climate and life,however there is very little consensus on when and how plate tectonics began on Earth. Various scenarios have been proposed ranging from initiation of plate tectonics as early as after crystallization of magma ocean to a relatively late start of plate tectonics, in the Late Archean. The most difficult aspect of plate tectonics is initiation of subduction. Although initiation of subduction has been extensively studied, the focus has been on the present−day Earth where plate tectonics is already occurring. The major difference between initiation of subduction on the present−day Earth and the early Earth is that, in the absence of plate tectonics, forces associated with plate tectonics are absent and cannot participate in subduction initiation. We have been working on the hypothesis that sublithospheric small−scale convection might be the mechanism of initiating plate tectonics. Sublithospheric small−scale convection was proposed as an explanation for the bathimetry, the heat flow, and the geoid in the old oceanic region and for the heat flow and seismic velocity anomalies in the continental regions. Sublithospheric small−scale convection was proposed to be the major convective mode on other terrestrial planets. We developed constraints for this mechanism with the help of systematic finite element simulations in two dimensions (paper published) and began a systematic study in three dimensions (paper submitted). Two−dimensional studies showed that small−scale convection generates stresses comparable with the stresses required for initiation of subduction on the present−day Earth and can indeed be a trigger mechanism for plate tectonics. This conclusion seems to be even stronger in spherical geometry. The derived scaling relationships provide a theoretical basis for predicting plate tectonics on a silicate planet with arbitrary parameters. This will be the focus of our next paper.

Highlights

- Sublithospheric small−scale convection can play an important role in initiating and sustaining plate tectonics on Earth−like planets.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: University of Washington

Project Report: Ocean Surfaces on Snowball Earth

Project Investigator:	***Stephen Warren***

Project Progress

1. Low–temperature life.
Warren and his student, Stephen Hudson, wrote a comment that casts doubt on a published claim of bacterial activity in South Polar snow, because of the lack of liquid water: Warren, S.G., and S.R. Hudson, 2003: Bacterial activity in South Pole snow is questionable. Applied and Environmental Microbiology, 69, 6430–6431.

2. Snowball Earth review.
Warren is drafting a paper "Ocean surfaces on Snowball Earth: implications for survival of surface life.". This paper identifies 13 different surface types that would occur at different times and latitudes during a snowball event, and recommends their albedos for use in climate modeling. Warren presented a poster on this topic at the conference on "Challenges in the Climate Sciences," Blois , France , 23 May 2004 .

3. Laboratory experiments relevant to Snowball Earth.
During a Neoproterozoic "Snowball Earth" event, the ocean surface conditions would determine both the surface climate and the locations for survival of surface life. A process that may be important in the tropical zones (where evaporation exceeds precipitation), as sea ice sublimates, is accumulation of a crust of sea–salt on the ice surface. This can only happen on ice below the eutectic temperature of NaCl brine, –22.9° C, but such temperatures are expected on Snowball Earth, even at the equator. No modern surrogate is known to exist in nature now, but we can investigate these processes in our cold–room laboratories. The salt that would accumulate is not NaCl but rather $NaCl{\cdot}2H_2O$, "hydrohalite," which has not received much investigation. Bonnie Light is collaborating with Warren on this project. She has begun preparations for laboratory studieson (a) migration rates of brine inclusions and salt crystals in ice at low temperatures, (b) the accumulation of salt on sublimating artificial sea ice, (c) suppression of sublimation by a salt crust, (d) cohesive properties of hydrohalite crystals (to determine whether wind will dislodge them), and (e) the absorption spectrum of hydrohalite.

Roadmap Objectives

- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments

Project Report: Microbial Mat Communities

Project Investigator:	***David Stahl***

Project Progress

We continued to characterize microbial populations in two extreme systems: microbial mats inhabiting hypersaline evaporation ponds (Guerrero Negro, Baja California , Mexico) and associated with hot springs (Yellowstone National Park (YNP)). Mat population structure was characterized at two spatial scales using PCR–amplified ribosomal rRNA genes: horizontally, over distances up to a kilometer, and vertically at submillimetric scales. Although distribution of dominant populations was stable across large distances (~500m), some variation was observed at fine vertical scales (mm). Diel migration was revealed by significant variation between night/day population profiles, suggesting that some sulfide–oxidizing bacteria may enter the overlying water column at night when oxygen becomes limiting. Parallel analyses of greenhouse mats (with and without sulfate) maintained by members of the EMERG group at NASA Ames revealed few changes in population structure associated with sulfate limitation. However, significant differences were detected between rooftop and field mats. In particular, dominant phototrophs shifted from cyanobacteria to sulfur bacteria, regardless of sulfate treatment.

In Yellowstone, we focused on the enrichment and isolation of thermophilic sulfate reducing prokaryotes (SRP) from three hot springs using a variety of electron donors (organic or hydrogen) at 60°C or 80°C, identifying novel populations by sequencing of ^{16}S rRNA and dissimilatory sulfate reductase (DSR) genes. Sulfide production was observed at 60°C on all substrates. In contrast, sulfide was produced only at 80°C on hydrogen, either autotrophically or with acetate as an alternative carbon source. Sulfide was also produced in enrichments on hydrogen using sulfur, sulfite, or thiosulfate as the electron acceptors, at both 60°C and 80°C. In agreement with the observed lower metabolic diversity at higher temperatures, microscopic analysis of these enrichments revealed a lower number of morphotypes at 80°C than at 60°C. The observation that only hydrogen, among the various electron donors tested, supported the growth of SRP at 80°C argues for the importance of lithotrophic metabolism in these hydrothermal systems.

Highlights

- Sulfur cycle microbes track daily changes in redox boundary in a photosynthetic microbial mat.
- Reduced sulfate levels corresponding to phenotypic decreases in rates of sulfur metabolism do not result in significant genotypic changes in a hypersaline microbial mat community.
- Hydrogenotrophic autotrophs dominate in YNP high temperature hot springs.

Roadmap Objectives

- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 3.3:*** Origins of energy transduction
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems

Field Expeditions

Field Trip Name: Yellowstone National Park

Start Date: 9/2/2003	***End Date:*** 9/14/2003
Continent: North America	***Country:*** USA
State/Province: Wyoming	***Nearest City/Town:*** West Yellowstone, MT
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:*** sulfate reduction
Description of Work: Measurement of endogenous sulfate reduction rates in Yellowstone hot springs. Laboratory cultivation of novel thermophilic sulfate–reducing microorganisms.	
Members Involved:	

Cross Team Collaborations

Received microbial mat samples from the EMERG research group at NASA Ames (Brad Bebout). Analyzed microbial community structure in mcrobial mats maintained under different sulfate concentrations.

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Annual Reports :: Year 6 :: University of Washington

Project Report: Galactic Chemical Evolution and Extrasolar Planets

Project Investigator:	***Guillermo Gonzalez***

Project Progress

During this past year Laws and Gonzalez completed the reduction and initial analysis of all our remaining spectra of planet–hosting stars and proper motion pairs. Laws and Claire developed extensive new software tools to enable processing of large volumes of echelle data and resultant stellar spectra in significantly less time than previously possible. With these tools in hand, we began an ambitious survey program at the Apache Point Observatory to observe several dozen additional stars that are not currently known to harbor planets, but which are under observation by various Doppler–search groups and are furthermore implicated by photometry to be metal–rich.

We reported our initial findings on the non–Fe elemental abundances of stars (and proper motion pairs) hosting giant planets at the Winter Meeting of the American Astronomical Society. We discovered a small but significant trend of increasing elemental abundance with higher condensation temperature that further correlated with decreasing convective envelope mass. We suggested that this is evidence that planet–hosting stars have indeed accreted volatile depleted materials, although not in sufficient quantities to be responsible for the general excess of metals in these stars, which we previously discovered and confirmed. We are currently preparing a full journal article that expands on these findings, as well as a second paper describing our results on the proper motion pairs (with and without planetary companions).

Our paper on the unusual star J37, an A star in the young cluster NGC6633, was published in October, 2003. We determined that no known single process can account for the observed pattern of elemental abundances in J37, and found evidence suggesting that this star has accreted material similar in composition to that of the Earth.

Highlights

- We have found evidence that most, if not all, planet–harboring stars have accreted volatile–depleted material into their outer atmosphere. However, the amount of material accreted is insufficient to produce the observed enhancement in Fe abundance previously discovered.

- We have found an elemental abundance pattern in the A−type star J37 in NGC 6633 that strongly suggests the accretion of circumstellar material of Earth−like composition.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets

EPO: University of Washington

These are the Education and Public Outreach activities for the University of Washington.

Astrobiology Public Lecture Series at UW

The goal of the lecture series is to present current astrobiological research results to the broader community. The lectures are presented by participating faculty and distinguished visitors, carefully chosen for their ability to communicate well with the public. The lectures cover the many aspects of Astrobiology and occur each autumn and spring academic quarter. In October 2003, astrobiologist Steve Benner addressed both the general public and a student audience (each in excess of 200), discussing the chemical precursors of life. A standing–room only (in excess of 400) audience of adults and students in June 2004 enthusiastically received SETI expert Frank Drake. As the lecture series is also intended to interest middle and high school students, we announce the series to Puget Sound science teachers and our Project AstroBio teacher partners.

Center for Astrobiology & Early Evolution Newsletter

The Center for Astrobiology and Early Evolution newsletter, titled Planets and Life is published each autumn and spring academic quarter, and disseminated to an interested public via mailing lists, lectures, workshops, and among our astrobiology community on campus. Each issue (seven to date) includes astrobiology research news and news of the UW astrobiology community. Newsletters will soon be available online via our web site. A listing of the articles submitted by the UW Astrobiology team to date include:

Issue # 1, June 2001 Life on the Rocks: Geo–microbiology at deep–sea hydrothermal vents, Matthew Schrenk (graduate student, Oceanography) Mars Evolution: Understanding planetary climate change, John Armstrong (graduate student, Astronomy)

Issue # 2, November 2001 Life in the Cold: Sea–ice Microbiology, Karen Junge (graduate student, Oceanography) Collapse of Simple Life Forms Linked to Mass Extinction 200 Million Years Ago, Peter Ward (professor, Earth and Space Sciences)

Issue # 3, May 2002 How the Ingredients for Life Came to Earth: Clues from Antarctic Micrometeorites, Monika Kress (post doc, Astronomy) The Earliest

Earth: An Analog for a Lively Mars? Roger Buick (professor, Earth and Space Sciences)

Issue # 4, October 2002 Complex Organisms and the Breath of Life, David Catling (professor, Atmospheric Sciences) Microbial Mats: Analogs of Earth's Earliest Communities? Jesse Dillon (post doc, Microbiology/Civil Engineering)

Issue # 5, April 2003 A New Kind of Hot Spring in the Abyss: The Lost City Hydrothermal Field, Deborah Kelley (researcher, Oceanography) Signs of Liquid Water: Life on Jupiter's Moon Europa? Steve Vance (graduate student, Earth and Space Sciences)

Issue # 6, October 2003 Invertebrate Ancestors: A Tale of Sea Squirts, Sea Stars, and Worms, Billie Swalla (professor, Biology) How habitable planets form: what computer simulations tell us, Sean Raymond (graduate student, Astronomy)

Issue # 7, June 2004 A search for meteorites on the coldest, windiest, driest continent on Earth, Monika Kress (post doc, Astronomy) Space dust may have contributed to the origin of life by delivering extraterrestrial amino acids to a primitive Earth: results from a study of Antarctic micrometeorites, Graciela Matrajt (post doc, Astronomy)

Developing an Astrobiology Curriculum

In addition to working directly with students and teachers, UW astrobiologists are also developing curricula and curriculum materials, and UW astrobiology graduate students are assisting these courses as Teaching Assistants (TA's). Linda Sauter TA'd the undergraduate Astrobiology 101 course in spring, 2004, under the supervision of Woody Sullivan. Sullivan also reviewed astrobiology manuscripts for education.

During autumn quarter 2003, Atmospheric Scientist David Catling coordinated and supervised the ASTBIO 502 course, arranging for the annual workshop and the weekly seminars. Astronomer Woody Sullivan performed the same service in winter quarter, 2004.

Astronomer Woody Sullivan and oceanographer John Baross are continuing work on their graduate–level textbook on Astrobiology titled, "Planets and Life " (Cambridge University Press) with chapters contributed by both UW and non–UW NAI researchers. The text is loosely based on the Crystal Mountain conference on Astrobiology hosted by the UW in August 2001. Chapters are now submitted and editing is nearly completed, with an anticipated release date of Winter 2005.

Project AstroBio: Year–Long Program of Science/Teacher Partnerships in Puget Sound

Project AstroBio has expanded on the success of Project ASTRO/Seattle, a science education and public outreach program administered by the UW Department of Astronomy since 1997. Project ASTRO/AstroBio created over

150 partnerships (and has sustained 42 of those) between teachers of grades 3 – 12 and professional and amateur astronomer and Earth and space scientists in the Puget Sound region of Washington. This year is our third as Project AstroBio and we continue to train new partnerships. The partnerships work together in the classroom, providing resource expertise and hands–on science activities as an adjunct to the regular teaching schedule. In each Project AstroBio partnership, students are guided through inquiry–based, hands–on activities in topics relevant to Astrobiology. Project AstroBio activities are rigorously designed to meet national and state education standards.

In 2003–2004 astrobiology researchers and graduate students Jesse Dillon, Jeremy Dodsworth, Monika Kress, John Leigh, and Steve Vance continued with Project AstroBio as new science partners. Director Woody Sullivan continues to visit an elementary school classroom, having begun as an astronomer partner with the original Project ASTRO in 1997. They each visited their classroom between five and seven times, thus having a direct impact on the science education of nearly 200 K–12 students.

Project AstroBio: Annual Training Workshop for Teachers and Science Partners

Project AstroBio workshop: This two day mandatory training session brings the new Project AstroBio partners together for the first time. Partners work together to learn strategies for effective communication between scientists and teachers, and between scientists and students, as well as take part in actual hands–on activities of the sort that they will be conducting with students. Each member of the partnership receives two volumes of activities in astronomy and related sciences, in addition to custom–made and classroom–tested activities in astrobiology. Various additional materials for classroom activities are also supplied.

In August 2004, astrobiology researchers and graduate students John Kirkpatrick and Billy Brazelton joined Project AstroBio as new science partners.

Public Access: Astrobiology Lectures and Presentations

Public presentations and lectures are an important component of UW's astrobiology education/public outreach efforts, and many investigators have been active in a variety of communities.

Microbiologist Jim Staley gave a public lecture on Astrobiology at Skagit Valley College, Washington; Astronomer Woody Sullivan gave a talk to a Seattle area amateur astronomy society on Astrobiology; Atmospheric Scientist David Catling gave a public talk to the Seattle Astronomical Society on the Evolution of Mars; and graduate student Steve Vance (Earth & Space Sciences) gave a talk to an elementary school in Bakersfield, CA on Europa and his trip to the Arctic.

From January 7 to April 2, 2004, Oceanographer Jody Deming served as Chief Scientist for the international CASES (Canadian Arctic Shelf Exchange Study) overwintering project aboard the research icebreaker Amundsen frozen into the

high Arctic. During that time, she and members of her team participated in numerous outreach activities, either remotely via satellite or directly shipboard. Throughout her three−month service as Chief Scientist, Deming prepared near−daily log−book releases for the CASES website for widespread public education of scientific research in the extreme environment of the Arctic winter: go to http://www.cases.quebec−ocean.ulaval.ca/trip/log.asp and click on January, February or March 2004, then any highlighted day of the week. Click on February 8 for a summary of Deming−team research shipboard, featuring Astrobiology Masters Student Eric Collins and his research project.

While on the Arctic ice in February, 2004, Oceanographer Jody Deming lectured on astrobiology and gave laboratory demonstrations in extremophile research to a selected group of high school students, including native Inuit students, and their teachers brought aboard the ship for first−hand experience in the field and shipboard laboratories (go to http://www.cases.quebec−ocean.ulaval.ca/trip/log.asp, and click on February 2004, then 27 or 28).

While shipboard, she also hosted and gave a welcoming lecture to the Game Council, a dozen of the most influential Inuit elders from nearby native villages, who flew to the ship to witness the various scientific operations, including extremophile research aboard a research icebreaker in the Arctic.

The Media Front

UW Astrobiologists are frequently asked to provide interviews to the print and broadcast media. They also produce articles for popular and lay−science publications, as well as summary articles in the science press, for example, the News and Views section of Nature, Vol 429, 17 June, featured Atmospheric Scientist David Catling's article: On Earth, as it is on Mars?

Catling was also filmed and interviewed by PBS TV for the "Space Millennium" series; was interviewed on NPR's "Talk of the Nation" with Neil Conan for a program about Mars science, history, and public perception; and was interviewed by Robert Burnham for an article in Astronomy Magazine concerning research on ice deposits in the Martian tropics.

Paleontologist Roger Buick was an interviewee twice on astrobiology topics for BBC; was interviewed for PBS (NOVA) television; and was interviewed for the newspapers Frankfurter Allgemeine Zeitung, Le Figaro, and the Chronicle of Higher Education.

Astronomer Woody Sullivan was interviewed for four print media articles and three broadcast sessions on astrobiology. In addition, he provided four extended local NPR station interviews.

In March, in her roles as both Chief Scientist and research astrobiologist, Oceanographer Jody Deming was interviewed and filmed extensively over the course of ten days by a CBC film crew, currently preparing a feature−length TV program on icebreaker research in the Arctic to be aired in English−, French− and Japanese−speaking countries in the fall of 2004.

Some of Deming's graduate students were featured in a January 2004 National Geographic Magazine article entitled Breaking the Ice: Probing the Frozen Arctic, contributed by J.S. Holland and P. Nicklen (Vol. 205, no. 1, pp. 100–117). This article features Masters' student David Allen (advised by Deming at the time) and his research during a NOAA–supported expedition to the Canada Basin in August–September of 2002. One of the goals of Deming's shipboard program was to collect potentially novel extremophiles and bring them into culture. Some of the successfully cultured cold–adapted bacteria are now being used in the course of NAI–supported research by Astrobiology Doctoral Candidate Llyd Wells.

Deming was also interviewed shipboard by a film crew for the Canadian TV program "Cool Jobs to help bring prospects in science and especially astrobiology to the attention of high school students."

Astrobiology on the School Front: Interning and Mentoring

UW Astrobiologists are frequently contributing knowledge and expertise to a diverse variety of students in a wide variety of school settings and communities.

Astrobiology Doctoral Candidate Llyd Wells and Research Staff member Shelly Carpenter, while working with Oceanographer Jody Deming during the Arctic research season, worked directly with Inuit high school students in the shipboard laboratory. This Schools on Board program is being touted as a model for engaging high school students directly in the scientific enterprise (see http://www.cases.quebec–ocean.ulaval.ca/school.asp for more information).

In June of 2004, Pierre Monnat, a local high school student in Seattle, began volunteer work with Deming's team in the UW laboratory. He is being trained by Shelly Carpenter and mentored by Llyd Wells to help with media preparation and cultivation tests on the collection of extremophiles to determine their specific carbon and nitrogen requirements. Pierre was inspired to seek experience in the laboratory as a result of an Open House he attended in the School of Oceanography three years ago (when he was 13 years old), when he participated in Deming's demonstrations of pressure effects on microorganisms and other astrobiology–related activities organized by the Deming team.

Mission Education and Public Outreach

After the successful landing of and research by the Mars Exploration Rovers this year, astronomer and science historian Woody Sullivan continued to work on Mars–related EPO, centering on the Mars sundial. A highly successful spin–off from the Mars sundial is the EarthDial project, co–developed with science educator Bill Nye and hosted by the Planetary Society.

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NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

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Team Reports: Virtual Planetary Laboratory

Virtual Planetary Laboratory
Executive Summary
Principal Investigator: Victoria Meadows

THE VIRTUAL PLANETARY LABORATORY

Laying the Scientific Foundation for the Search for Life Beyond the Solar System

Because of the vast distances to even the nearest stars, the search for life outside our solar system will be undertaken using astronomical, or "remote−sensing" techniques. While much can be learned about a planet discovered around another star based on the characteristics of the host star and the planet's position in its solar system, spectroscopy is still our most powerful technique for extrasolar planet characterization. The research of the NASA Astrobiology Institute's Virtual Planetary Laboratory (VPL) uses computer models of terrestrial planets to understand the nature and potential range of remote−sensing spectroscopic signs of planetary habitability and life which might be encountered by future planet detection and characterization missions.

Terrestrial Planet Detection and Characterization Missions

There are several missions currently in the planning stage to search for and characterize extrasolar terrestrial planets, and all have planned spectroscopic capability. These missions include the two NASA Terrestrial Planet Finder (TPF) Missions and the European Space Agency (ESA) Darwin mission. The first TPF mission, TPF−C, slated for launch in 2014, will use coronographic technology to block the considerable light from the parent star and reveal the much fainter orbiting planet. TPF−C is designed to detect and characterize extrasolar terrestrial planets via disk−averaged visible light reflected from the planet, and will be well suited to obtain good estimates of the amounts of atmospheric gases detected at visible wavelengths (e.g. O_2 , H_2O and CH_4), and to discriminate between different planetary surface types. The TPF−I and Darwin missions are slated for launch no later than 2020, and will use free−flying spacecraft to enable an interferometric technique for nulling the light from the central star, to detect and characterize an orbiting planet. TPF−I/Darwin will operate at mid−infrared wavelengths, within the range 6−18 m m, and will be sensitive to thermal radiation emitted by the warm planet. TPF−I/Darwin will be sensitive to the overall trace gas composition of the

atmosphere, including greenhouse gases (CO_2 , H_2O, SO_2) and many potential gas biosignatures (e.g. O_3 , CH_4 , N_2O and a number of sulfur compounds). If the planet's surface is not hidden by clouds, TPF−I can also provide information required to infer atmospheric and surface temperatures. The complementary information provided by TPF−C and TPF−I/Darwin, can provide a robust indicator of the planet's size, and when combined with information on planetary mass provided by the Space Interferometer Mission (to launch in 2009), will provide a powerful dataset for comprehensive characterization of terrestrial planets beyond our solar system, including the search for global planetary characteristics that are signs of life. Beyond the TPF and Darwin missions, NASA envisages an even more ambitious mission, Life Finder, whose goal is to provide even more detailed spectroscopic study of terrestrial planets found by the previous missions.

The VPL Research Goals, Astrobiology, and NASA

The VPL is a suite of computer models for simulating the plausible range of atmospheric and surface compositions and climates for terrestrial planets. The objective of this project is to provide the fundamental research needed to support the remote−sensing detection of life, by improving our understanding of the use of spectra to discriminate between extrasolar planets with and without life. This work is most directly relevant to the Astrobiology Roadmap Goals 1 and 7, on the nature of planetary habitability and the remote−sensing signs of life. However, work undertaken as part of the VPL planetary modeling effort also touches on aspects required to understand the Earth's early biosphere (Goal 4), biochemical adaptation to extreme environments (Goal 5), and environmental changes and the cycling of elements by ecosystems (Goal 6). In addition, the work of the VPL provides valuable results to guide the design and search strategies for future NASA planet detection and characterization missions, and VPL scientists also provide two−way communication between astrobiology and NASA mission concepts in Earth and planetary exploration.

The Virtual Planetary Laboratory – Yr 6 Research Projects

Building the VPL: Tasks 1−7. This year, the VPL team continued its efforts to develop and combine computer models of planetary processes into a series of progressively comprehensive terrestrial planet models, and significant milestones, particularly in model integration, were achieved. The completed VPL model suite will provide the capability to model terrestrial planet environments in a self−consistent fashion, and output the spectral appearance of these environments to remote−sensing observations. The resultant models are being applied to a number of scientific questions on the environments of early Earth and extrasolar terrestrial planets.

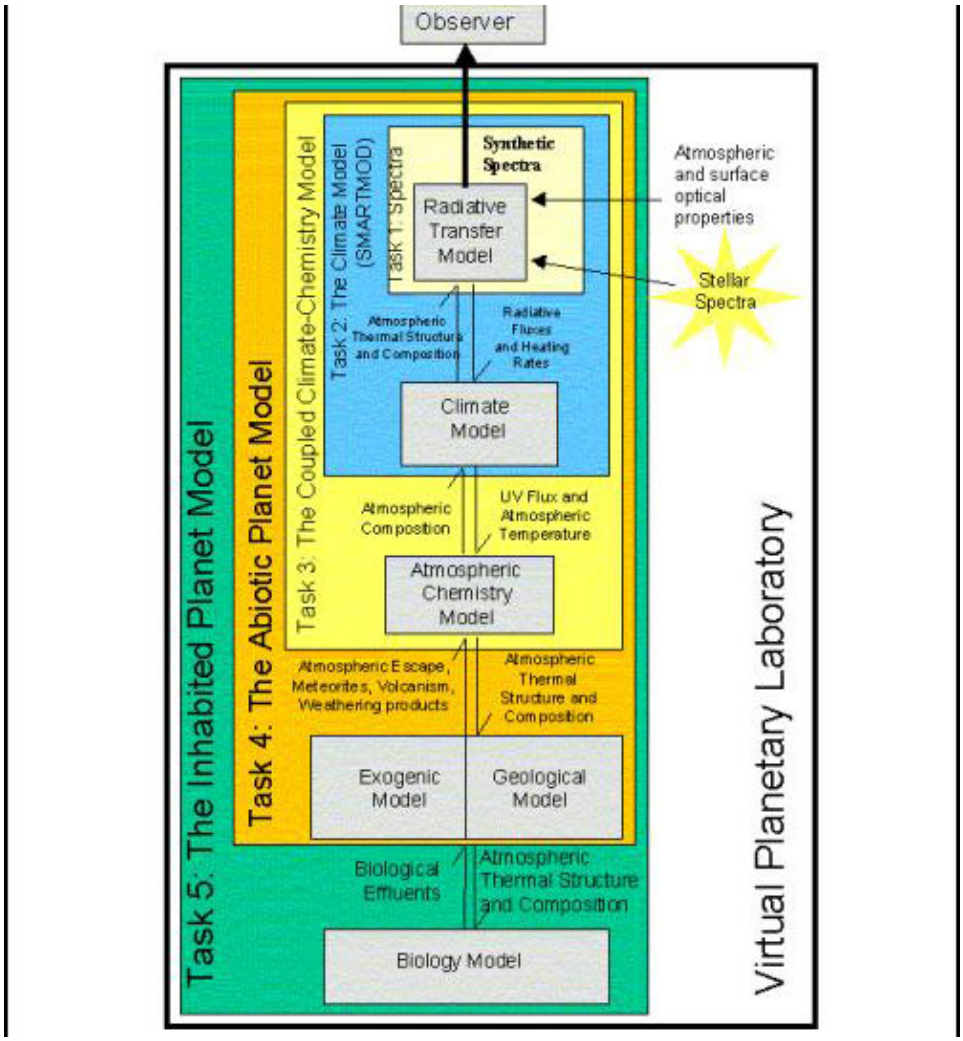

Figure 1: The suite of radiative transfer, climate, chemical, geological, and biological component models are shown as boxes, and their interactions with each other are shown as arrows. The information transferred between these component models is labeled at each interface. The order in which these component models are coupled to each other during the course of building the VPL is specified by the Task number. The radiative transfer, climate and atmospheric chemistry models already exist, and the remaining models are under development by our team. At each task development stage the model can be used to generate synthetic spectra to derive required capabilities for astronomical instrumentation.

This effort is characterized by 5 successive component tasks, the supporting task of spectral database compilation, and the overarching task of model integration. These tasks and highlighted accomplishments are:

Task 1: Spatially–resolved models of terrestrial planets

This task develops sophisticated spatially and spectrally–resolved models of planets in our own Solar System using radiative transfer models, and observed physical properties and environmental data. The reflected solar and emitted infrared spectra generated by models are then averaged across the visible disk

of the planet to produce a “disk−averaged” result, which mimics the type of results anticipated from TPF. Research highlights for this year include completion of the Mars and Earth models, and the production and analysis of disk−averaged 0.1 to 160 µm spectra, light−curves, spectral variability as a function of viewing angle and season, and simulations of an increasingly frozen Mars, and an increasingly cloudy/forested/oceanic Earth.

Task 2: A Climate Model for Extrasolar Terrestrial Planets

This task develops a versatile one−dimensional (1−D) terrestrial planet climate model to yield a globally−averaged description of the surface temperature and vertical temperature distribution that is in thermal equilibrium with the imposed stellar flux from the host star, planetary orbital properties, and the surface and atmosphere composition and optical properties. These temperature distributions are crucial for understanding both the habitability and detectability (at mid−infrared) wavelengths of biosignatures in the disk−averaged spectrum of the planet. Progress this year included the integration of generalized and computationally improved radiative, convective and conductive transport algorithms into the existing climate model to increase computational speed. The resultant model was used to produce annual cycles of soil and atmospheric temperature for a Mars−like planet.

Task 3: A Chemistry Model for Extrasolar Terrestrial Planets

This task focuses on the development of a generalized, yet comprehensive, photochemical model for terrestrial planet atmospheres. This model will interact with the climate model described in Task 2, to create a self−consistent climate−chemical model. This year the model was updated to operate in our Linux test environment, and work was started on the creation of a master reaction file for terrestrial planets and the software to access user−specified reaction sets to describe different classes of planetary atmospheres .

Task 4: The Abiotic Planet Model: The Upper and Lower Boundary Conditions on the Atmosphere

This task develops models of processes at the upper and lower boundaries of the coupled climate−chemical model, including exogenic mass fluxes (dust/meteors/asteroids, atmospheric loss) and surface−atmosphere interactions (chemical weathering, outgassing). When integrated with the climate−chemical model, this module will produce a self−consistent model of a terrestrial planet without life. This past year saw the addition of melt−generation (for predicting mantle volatile loss to the atmosphere) into the planetary interior/plate tectonics model. Progress was also made on reactive transport models for rock weathering, to help constrain the evolution of mineralogies of other habitable planetary surfaces and their volatile fluxes. Work also continued on a model for hydrodynamic loss processes from planetary atmospheres. Research results included the use of kinetics to predict formation of siderite in soils that develop under slightly oxic conditions, which is contrary to thermodynamic predictions. These results reinforce the conclusion that paleosols formation before 2.4Gya occurred under an atmosphere with less than 30 times the present level of CO_2 . Reactive transport modeling also

showed that black shale weathering is an important factor in regulating Earth's atmospheric oxygen composition during the Phanerozoic.

Task 5: The Inhabited Planet Model: The Life Modules

This task provides computer models of life's interaction with the planetary environment for integration with the Task 4 model. Progress this year includes the completion of life module components, including microbial mats and Archean ecosystem models, and initial improvements to existing Earth land surface models to predict vegetation albedos. Our Archean ecosystem modeling indicates that the Archean biosphere was capable of generating methane surface fluxes comparable to those of modern Earth, which would have been large enough to keep the early Earth warm. These results emphasize that life can affect the climate and atmosphere of extrasolar planets in ways that can be detected by instruments such as TPF, even in the absence of oxygenic photosynthesis.

This task also includes a field trip component to analyze life in highly alkaline aquifers and springs that are associated with terrestrial serpentinizing bodies, providing a model system for life at the surface of young terrestrial bodies. Research highlights this year include completion of the initial survey of the genetic diversity of microbes, which show considerable diversity, despite the extreme lack of nutrients and high pH (>11.5).

Task 6: Spectroscopic Databases to Support Extrasolar Planet Modelling: Stellar and Molecular

This task focuses on collecting and preparing full−wavelength, continuous stellar spectra for use by planetary climate and chemistry models. This year we worked on spectra of quiescent and active M stars, with spectra now available for two M stars, AD Leo and GJ643. These spectra are currently being used to simulate the nature and detectability of characteristics of Earth−like planets around quiescent M stars. Future work will include the less active M dwarf spectra, and a full time−dependent characterization for a more active M−star.

We also continued development of the molecular spectra database, which is a collection of line lists and absorption cross−sections for 61 molecules of interest to astrobiologists and planetary scientists. The database was made public this year at http://vpl.ipac.caltech.edu/spectra/ .

Task 7: The Virtual Planetary Laboratory: Synthesis and Architecture

This task focuses on interfacing and integration of the core model components to produce the VPL planetary models described in Tasks 3−5. This year, significant progress was made on interface design, with the development of an Application Programming Interface (API) and a central VPL model database. This allows current code components (and all future components) to access model results from the full range of VPL tools, especially those that operate on very different planetary timescales. As a major milestone, the first full VPL coupled−climate−chemical model run was executed at the very end of this reporting period. As our first step toward the community tool that VPL is

intended to be, we also developed a structured data format and a web front end for the Task 2 climate code to allow the user to enter a planetary “state” of parameters for configuring the climate model runs, and to enable execution of VPL models from centralized databases over the Internet.

In addition to work on the VPL modeling suite, we have also worked to improve our understanding of the characterization of terrestrial planets from disk−averaged spectra. This work has been undertaken in three distinct research areas:

Sensitivity to Planetary Characteristics in Disk−Averaged Spectra

The completion of the Mars and Earth Task 1 models allowed us to explore the detectability of local features in the disk−averaged spectrum, as a function of viewing angle, solar illumination, and surface type. First results from the Mars model indicate that the presence of the Martian poles, and seasonal changes in polar ice coverage, could be detected in disk−averaged spectra at both visible and Millimeter Imaging Radiometer (MIR) wavelengths. Simulations with an increasingly frozen Mars indicated that the effect of the ice cap is most easily detected in the wavelength range 8−13.5 m m, where the wavelength dependent emissivity of CO_2 ice produces a strong spectral feature.

Earth−like Planets Around Other Stars

Building on last year's coupled climate−chemical modeling of Earth−like planets around F, G and K stars, we are now using similar models to explore the detectability of characteristics for Earth−like planets orbiting M stars, which are typically highly variable. Our current simulations use the observed time−averaged spectra of two M stars and a quiescent, modeled M star. For 1PAL Earth−like atmospheres, our results show that planets with the modern day Earth surface methane flux show an atmospheric abundance that is relatively high due to reduced tropospheric OH densities, which increases the atmospheric lifetime, even in these O_2 −rich atmospheres. Consequently even small surface fluxes of methane could be highly detectable around M stars. Our models also show that ozone, photochemically derived from O2, is detectable in Earth−like planets around non−active M stars with photospheric temperatures in excess of 3400K. Below that stellar temperature threshold, O3 is not detectable. We are currently developing a time−dependent climate−photochemical model to determine how the flux variability of M stars would affect the lifetime and detectability of planetary biosignatures.

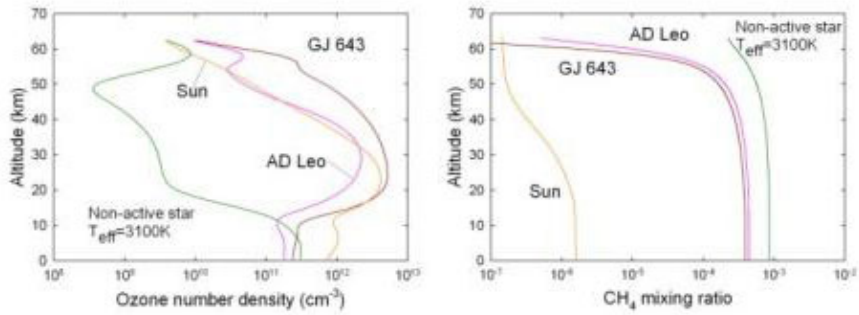

Figure 2: Coupled climate–chemsitry model simulations of the atmospheric vertical distribution of ozone and methane in Earth–like planets around the active, but time–averaged M–stars AD Leo and GJ 643, compared with the value for the Earth (around the Sun) and a non–active modeled M star with an effective temperature of 3100K. While the ozone show similar abundances and distribution to the Earth, except in the case of the planet around the 3100K star, all the M–stars show enhanced atmospheric CH_4.

Analysis and Discrimination of TPF Planetary Spectra Using Artificial Neural Network Techniques.

To determine the scientific impact of trade–offs in instrument characteristics (e.g. wavelength coverage, spectral resolution, and signal–to–noise (S/N)) for spectral characterization of terrestrial planets, this task focuses on using Artificial Neural Networks (ANNs) to determine instrumentation limits for reliable classification of spectra. As the test set, we have used UV–FIR planetary spectra generated by the VPL and convolved these with slit functions and a simplistic noise model to produce spectra with a range of spectral resolutions and S/N levels. With our simplistic noise model, the ANNs clearly discriminate spectra at very modest resolutions and S/N. Ongoing work involves expanding the test set to other planetary types, and working with the TPF design teams to get more realistic noise models.

VPL Education and Public Outreach

VPL is providing budget and scientist support to develop the “Create a Planet” module of the AstroVenture interactive website for middle school students. AstroVenture highlights NASA careers and astrobiology research. VPL is also funding in–service teachers to earn graduate credits taking the “Astrobiology On–line Course for Teachers” in informal education, and providing support for the California Academy of Science. We delivered field photos and a profile of Dr. Kress for the museum's astrobiology exhibit. Additionally, there are numerous E/PO efforts by Dr. Meadows and VPL scientists, and an online astrobiology course provided by Dr. Siefert at Rice University.

Project Report: Characterization of Terrestrial Planets From Disk–Averaged Spectra: Spatially and Spectrally Resolved Planetary Models

Project Investigators:	***Victoria Meadows , Giovanna Tinetti , David Crisp***

Project Progress

This task uses sophisticated spatially and spectrally–resolved radiative transfer models and data from planets in our own Solar System to explore the detectability of surface and atmospheric properties of terrestrial planets from disk–averaged spectra at a number of different spectral resolutions. These models, which simulate both surface and atmospheric properties for a variety of viewing angles, illuminations, surface type, and cloud coverage, provide tools to better understand the likely sensitivity of planet detection and characterization missions such as TPF/Darwin to both local and global planetary properties.

This year, we completed the Mars and Earth models, and validated the resultant disk–averaged spectra against observations acquired by approaching or orbiting spacecraft, and Earthshine measurements from ground–based observations of the Moon. The validated planetary models, and TPF instrument simulator models were used to explore the detectability of features for Mars–like (likely abiotic) and Earth–like (life–supporting) planets. The resultant products include: 1) globally averaged synthetic spectra from 0.1 to 160 µm for both planets, 2) light–curves and the spectral variability at visible and infrared (IR) wavelengths as a function of viewing angle and season, and 3) simulations of an increasingly frozen Mars, and an increasingly cloudy/forested/oceanic Earth.

From the Mars modeling, we found that although disk–averaging clearly reduced the influence of localized features, we were able to detect differences in the observed spectra as a function of season at all wavelengths, as either changes in observed intensity or spectral shape. These seasonal variations were related either to changes in atmospheric density, surface temperature, or aerial coverage of surface ice, and were most pronounced for the millimeter imaging radiometer (MIR) spectra. Our Mars results have been submitted for publication, and our Earth results are currently being prepared for publication. Ongoing work on this project in the coming year will also include similar models for Venus and Titan.

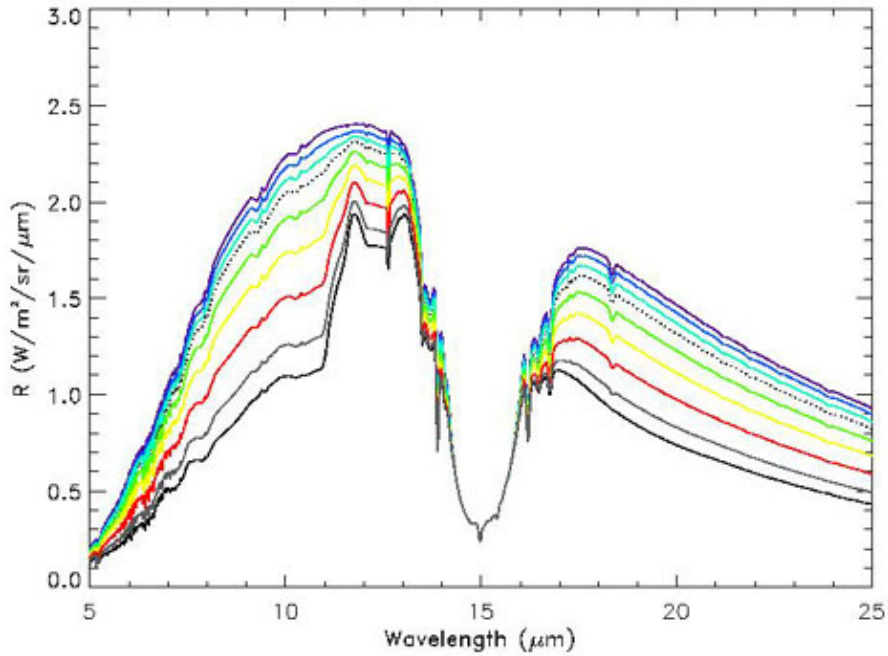

Figure 1.

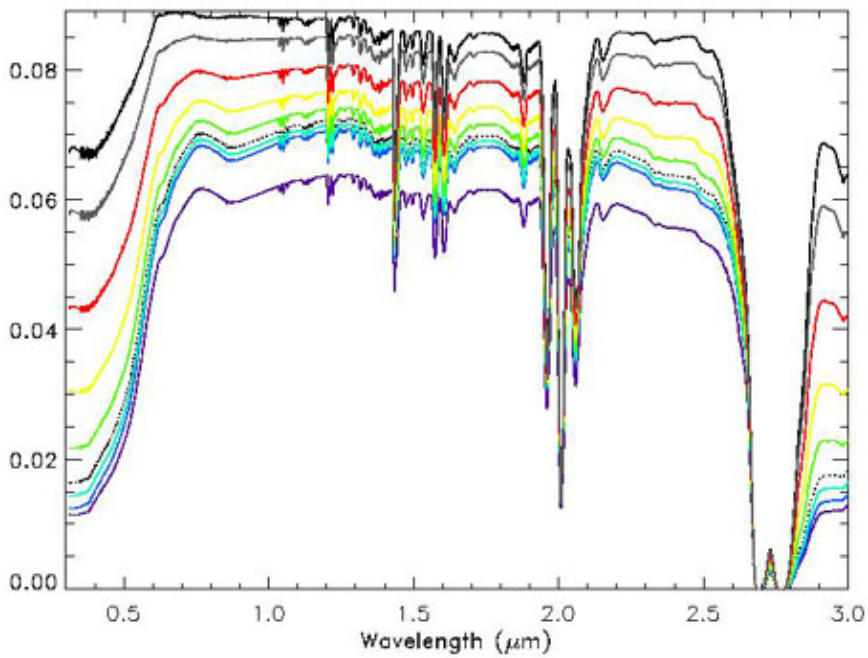

Figure 2.

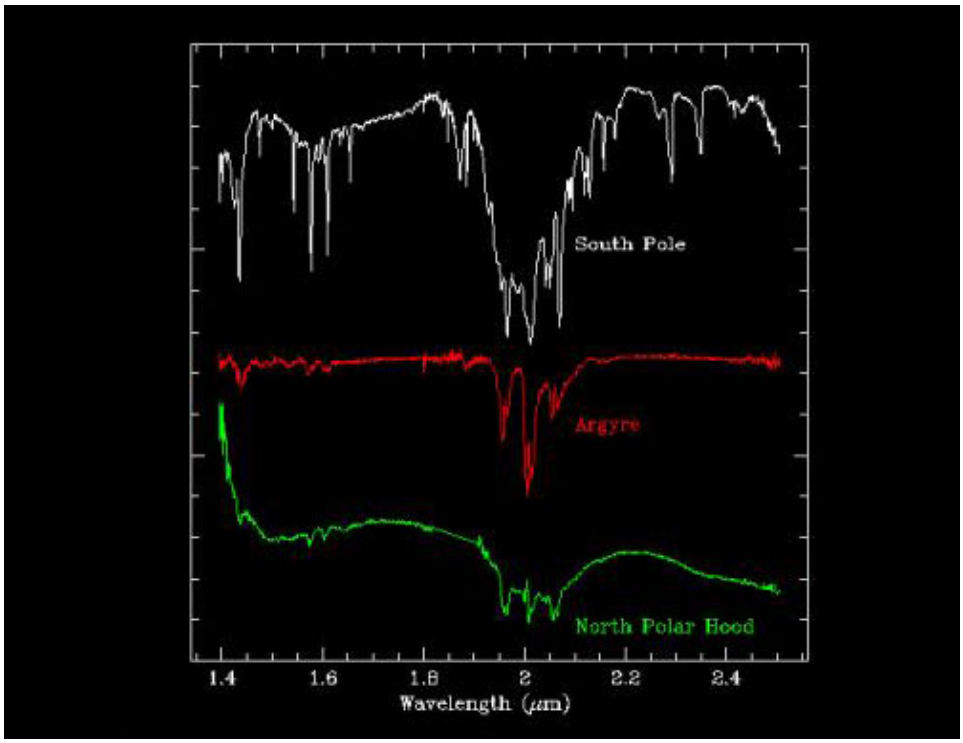

Figure 3. The top (white) spectrum is from the South polar cap and is dominated by CO_2 ice absorption. the middle (red) spectrum is from the Argyre impact basin and shows atmospheric CO_2 features. The bottom (green) spectrum is from the north polar regions and shows water ice absorption. All spectra have been ratiod to a reference region on the Martian surface which removes terrestrial absorption features as well as much of the absorption due to the Mars atmosphere.

Highlights

- The Mars and Earth spatially– and spectrally–resolved models were completed this year, and the Mars model results were submitted for publication. These results provide the first thorough exploration of the likely range of observed brightness and spectral features as a function of season for the disk–averaged spectrum of a Mars–like planet, and should prove useful to planet detection and characterization missions such as NASA's TPF and theESA's Darwin missions.
- First results from the Mars model indicate that the presence of the Martian poles, and seasonal changes in polar ice coverage, could be detected in disk–averaged spectra at both visible and MIR wavelengths. The effect of the ice cap is most easily detected in the wavelength range 8–13.5μm, where the wavelength dependent emissivity of CO_2 ice produces a strong spectral feature.
- Model runs for an increasingly frozen Mars showed that a sub–observer polar ice cap is detectable in the MIR disk–averaged spectra once the ice cap extended 30° equatorward. A pure CO_2 ice cap has no distinct absorption features at visible wavelengths, but a "dusty" CO_2/water ice cap like that on Mars does have weak absorption at wavelengths shorter than ~0.6 microns. In principle, the spectral signature of such an

ice cap would be detectable once the ice cap had extended 60° toward the equator, but such a feature would be difficult, if not impossible to discriminate from weak iron absorption on an ice–free rocky surface. So, although visible is generally better for surface characterization, the MIR appears to be more efficient at detecting surface ice, provided that the planetary atmosphere is extremely thin.
- Using instrument simulator models for representative TPF interferometer and coronograph designs for Mars, and a model of a CO_2 ice–covered Mars–sized object, we confirmed that it is relatively easy to detect gaseous CO_2, and determined that the 0.5–0.6 and 11–13 µm CO_2 ice features might be detectable in the ice–covered case, with sufficient integration, even at the relatively low spectral resolutions that are likely to characterize TPF instrumentation.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Planning Support,Background Research,Instrument/Payload Development

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This project work supports the development of the Virtual Planetary Laboratory modeling suite, which will be used to identify and estimate the detectability of terrestrial planet characteristics to determine whether astronomical remote–sensing techniques will be valide for determining if a detected terrestrial planet is habitable or already supports life. This work is therefore

background science for the TPF mission and will provide information that will be valuable for mission planning, including estimates of the minimum and optimum sensitivity, wavelength range and spectral resolution required for both TPF−I and TPF−C

Field Expeditions

Field Trip Name: UKIRT Obervations of Mars	
Start Date: August 16, 2003	***End Date:*** August 18, 2003
Continent: North America	***Country:*** USA
State/Province: Hawaii	***Nearest City/Town:*** Hilo
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): Mauna Kea Observatories	***Keywords:*** Astronomical Observing
Description of Work: Our collaborators at the Australian Center for Astrobiology, Jeremy Bailey and Sarah Chamberlain, obtained a new set of spatially resolved near−IR spectra of Mars using the United Kingdom Infrared Telescope at Mauna Kea during the planet's close approach to Earth in August 2003. The data have higher spatial resolution (~100km) than any previous ground−based studies and provide the most complete global coverage of the near−IR properties to date.	
Members Involved:	

Project Report: Climate Model For Extrasolar Terrestrial Planets

Project Investigators: ***David Crisp , Giovanna Tinetti***

Project Progress

Results from Virtual Planetary Laboratory (VPL) Task 1 indicate that both the habitability and the detectability of biosignatures in the disk averaged spectrum of a terrestrial planet depend crucially on the planet's surface temperature and the vertical distribution of temperatures in its atmosphere. Hence, as the first step in our efforts to simulate a broad range of plausible extrasolar terrestrial planetary environments, we have implemented a simple, but versatile one−dimensional climate model to provide a globally−averaged description of their vertical temperature distributions. Given assumptions about a planet's stellar type, orbital properties (mean distance, eccentricity, obliquity), and the composition and optical properties of its surface and atmosphere, the climate model yields a globally−averaged description of the vertical temperature distribution that is in thermal equilibrium with these imposed conditions. This model includes all of the major physical processes that contribute to the deposition and vertical transport of heat in the planet's atmosphere, surface, and near sub−surface. These processes include stellar radiative heating, thermal radiative cooling, vertical convective and conductive heat transport within the sub−surface and atmosphere, and latent heat transport associated with the evaporation, condensation, and transport of volatile species.

The radiative heating and cooling rates are simulated using the same spectrum−resolving atmospheric radiative transfer model (SMART), used to generate the high−resolution spectra in VPL Task 1. Vertical convective heat transport in the atmosphere is simulated using a formulation adapted from a 1−dimensional boundary layer model (Savijarvi, 1991). This model incorporates classical mixing length theory, Ekman pumping, and Richardson−number−dependent eddy mixing to provide an explicit physical link between the surface−atmospheric thermal structure and the vertical transport of heat and volatile species. Vertical diffusive heat transport within the near−surface layer is simulated by solving the one−dimensional heat diffusion equation using a time−dependent 4th−order Runge−Kutta scheme (Sertorio and Tinetti, 2002). Cloud and aerosol particle nucleation, condensation, evaporation, transport, and the associated latent heat transport are modeled using a formulation originally developed for simulations of the Martian climate (A. Inada personal communication, 2002). These processes are incorporated

into the time−dependent thermodynamic energy equation of the system, which is solved numerically as an initial value problem using time stepping.

References Cited:
Savijarvi, H. 1991, “A Model Study of the PBL Structure on Mars and Earth, Contrib. Atmos. Phys., 64, 103−112.

L. Sertorio and G. Tinetti, Constraints in the Coupling Star−Life, Il Nuovo Cimento, 25 C, N. 4, 457−499 July−August 2002

Highlights

- A substantial amount of progress has been made in the implementation of the climate model over the past year.
- The SMART model has been revised to dramatically increase its speed and accuracy.
- The radiative, convective, and conductive transport algorithms have been integrated into the climate model, and tested for stability and accuracy.
- The cloud and volatile transport models are currently under development.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 5.1:*** Environment−dependent, molecular evolution in microorganisms
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Planning Support,Background Research,Instrument/Payload Development
2	Orbiting Carbon Observatory	Project Investigator
2	ESA Venus Express	Science Team Member
2	Planetary Fourier−transfrom Spectrometer	Project Investigator

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This project work supports the development of the Virtual Planetary Laboratory modeling suite, which will be used to identify and estimate the detectability of terrestrial planet characteristics to determine whether astronomical remote−sensing techniques will be valid for determining if a detected terrestrial planet is habitable or already supports life. This work is therefore background science for the TPF mission and will provide information that will be valuable for mission planning, including estimates of the minimum and optimum sensitivity, wavelength range and spectral resolution required for both TPF−I and TPF−C.

Orbiting Carbon Observatory (OCO): D. Crisp is the Principal Investigator of the Earth System Science Pathfinder Orbiting Carbon Observatory (OCO). This mission will make the first space−based measurements of atmospheric CO2 with the spatial and temporal resolution and precision needed to characterize surface sources and sinks of this important greenhouse gas. These observations will improve our understanding of the Earth's carbon cycle, and facilitate improved predictions of future atmospheric CO2 concentrations and their effect on the Earth's climate. There is strong synergy between the NAI VPL radiative transfer and climate modeling activities and the analysis tools being developed for OCO.

Venus Express: D. Crisp is a member of the PFS and VMC science teams. In those roles, he is responsible for remote sening retrieval and thermal balance studies of the Venus atmosphere. The tools being developed as part of the VPL climate modeling task will be used in those investigations.

Project Report: Chemistry Models for Extrasolar Planets

Project Investigators:	***Mark Allen , Yuk Yung***

Project Progress

This task focuses on the development of a generalized, yet comprehensive photochemical model for terrestrial planet atmospheres. This model is to interact with the climate model described in Task 2, to create a self–consistent climate–chemical model.

This year we completed the implementation and testing of the Caltech/JPL generalized planetary chemistry/transport model, KINETICS, using the Absoft FORTRAN compiler on a Linux computer, a similar computing environment as planned for Virtual Planetary Laboratory (VPL). Originally developed on a VAX/VMS computer with a VMS FORTRAN compiler, KINETICS was tested for portability on a Unix computer and with two different FORTRAN compilers on a Linux computer. When executed in all the different computing environments, both simple and relatively complex simulations gave the exact same results. The simple simulations were chosen for comparison with analytic solutions and reproduced these analytic solutions to better than 1%.

Current work continues on creating a master reaction file for terrestrial planets, and designing the software to access user–specified reaction sets to describe different classes of planetary atmospheres. We are also working with John Armstrong and Giovanna Tinetti to interface the chemistry model with the central VPL database and the climate model.

Highlights

- The VPL chemistry model is now working on the VPL test and development architecture and is currently being interfaced with the climate model through the VPL central database.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	Mars Scout Proposal	Project Investigator
2	MARVEL Mars Mission	Science Team Member

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
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** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Dr. Mark Allen served as the Principal Investigator, and Prof. Yuk Yung and Dr. Mark Richardson were Co–Investigators on the Mars Scout Mission concept MARVEL. This mission concept focused on understanding the detailed chemistry of the Martian atmosphere as a first step to understanding the context for potential subsurface life on Mars, and consequently had a strong astrobiological focus. This mission concept was selected to go forward to the second proposal round but did not make it to final selection.

Project Report: The Abiotic Planetary Model: The Upper and Lower Boundary Condition on the Atmosphere

Project Investigators:	***Robert Rye , Mark Richardson***

Project Progress

Work related to this task moved forward on several fronts, from the deep interior of planets to the top of planetary atmospheres. Nimmo took the lead in the interior, adding melt generation to his existing parameterized thermal evolution code. This model simulates the transport of heat and materials between the interior and surface of planets with or without plate tectonics. The model now allows melting to occur at both mid–ocean ridges and upwellings. Melt extraction removes incompatible elements from the mantle; these elements return to the mantle if there are subduction zones, or are lost to the system if they are volatile. The removal of incompatible radiogenic elements from the mantle results in a reduction in the amount of internal heating.

We are incorporating the dominant rock–forming minerals into our models that simulate kinetically controlled weathering. Our general models will help constrain the evolution of mineralogies of other habitable planetary surfaces and their volatile fluxes. We have used such a model to show that with >1 ppm atmospheric oxygen, (Rye et al. 1995), constraints on pre–2.2–billion–year–ago carbon dioxide levels using paleosol chemistry and mineralogy remain applicable. Incorporation of microbially enhanced kinetic rates of reactions will allow future models to assess changes on volatile exchange expected due to life.

Kasting and Parkinson worked on a new model of hydrodynamic loss processes from planetary atmospheres. Their method seeks to overcome the instabilities inherent in modeling transonic conditions by solving the coupled, time–dependent mass, momentum, and energy equations, instead of integrating time–independent equations. Several model modules are largely working, including the core solver, atmospheric setup, gravitation, heating, thermal conductivity, viscosity, tidal forces, and geometrical considerations. Work continues on the problem of damping in the top layers of the model amosphere.

Highlights

- Rye and Steefel can now show that when kinetics is taken into account, siderite can form in soils that develop under slightly oxic conditions, contrary to the thermodynamic predictions of Ohmoto et al. (2004) recently published in *Nature*. These results show that even at >1 ppm atmospheric oxygen, the presence of Fe−rich chlorite (metamorphosed from smectite), and the absence of siderite, indicates that paleosols that formed before 2.4 billion years ago formed under an atmosphere with less than 30 times the present level of carbon dioxide.
- Team member Bolton has collaborated with others on the characterization and modeling of black shale weathering as an important factor in regulating Earth's atmospheric oxygen composition during the Phanerozoic (Wildman et al., 2004).

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Planning Support,Background Research,Instrument/Payload Development

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3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

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background science for the TPF mission and will provide information that will be valuable for mission planning, including estimates of the minimum and optimum sensitivity, wavelength range and spectral resolution required for both TPF−I and TPF−C

Field Expeditions

Field Trip Name: The Cedars

Start Date: 9/12/03	***End Date:*** 9/14/03
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Cazadero
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): The Cedars	***Keywords:***

Description of Work: Collected water samples from hyperalkaline springs for ICP−MS analysis. Collected dissolved gas samples for GC analysis. Analysis of these samples will help define this site as a potential early Earth surface analogue.

Members Involved:

Field Trip Name: The Cedars

Start Date: 10/17/03	***End Date:*** 10/18/03
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Cazadero
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): The Cedars	***Keywords:***

Description of Work: Collected water samples from hyperalkaline springs for geochemical and microbiological analysis. Geochemical samples collected for comparison to earlier samples in order to assess local short term variability in water composition.

Members Involved:

Field Trip Name: The Cedars

Start Date: 3/5/04	***End Date:*** 3/7/04
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Cazadero
Latitude:	***Longitude:***
	Keywords:

Name of site(cave, mine, e.g.): The Cedars	

Description of Work: Collected water and rock samples for geochemical and microbiological analysis. Water samples collected for comparison with previous samples to assess local temporal variability of water chemistry.

Members Involved:

Field Trip Name: The Cedars

Start Date: 5/21/04	***End Date:*** 5/23/04
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Cazadero
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): The Cedars	***Keywords:***

Description of Work: Collected water samples for geochemical and microbiological analysis, including samples for organic geochemical analysis. This sample set will provide continuing coverage of temporal variability of water chemistry and will also provide information on abiogenic and biogenic gas fluxes from, and organic compounds in, the water.

Members Involved:

Project Report: The Virtual Planetary Laboratory – The Life Modules

Project Investigators:	***Robert Rye , Nancy Kiang***

Project Progress

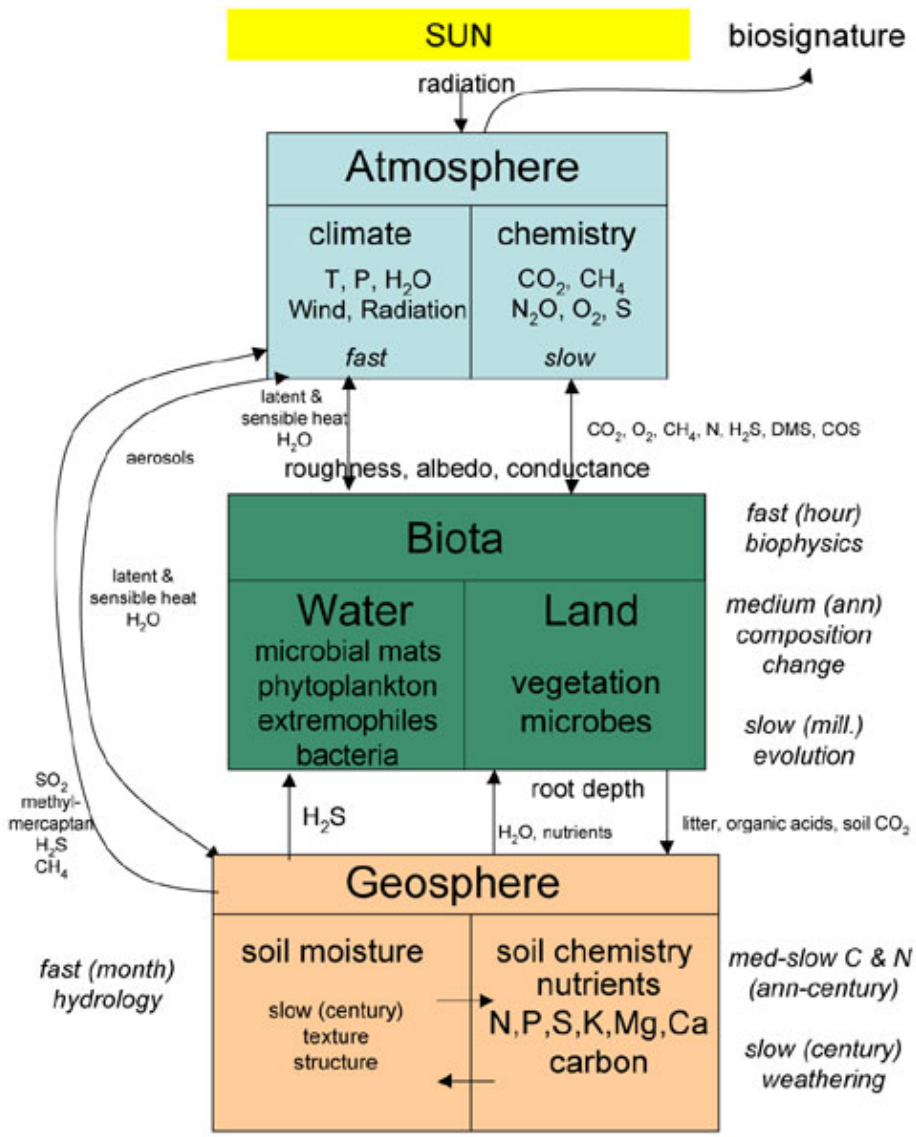
Progress has been made with submodels and fieldwork toward supporting a coherent model of how detectable biosignatures may be produced on extrasolar planets:

Architecture of the coupling between the Life Modules and the geosphere and atmosphere (Kiang, Rye , Bolton , Armstrong, and other NAI teams). The Life Module components from cross–team collaborations have been completed (microbial mats, Archean ecosystem), and links have been forged with NASA Earth Sciences for simulating a planet at different stages of its history, and for validating the model compared to the modern Earth. Improvements to existing Earth land surface models have commenced to predict the currently prescribed albedoes of vegetation. The architecture for interfacing these Life Modules with the geosphere and atmosphere is now in intensive development.

Analysis of life in aquifers and springs associated with terrestrial serpentinizing bodies (Rye and Johnson). We now have preliminary data on microbial community structure, and have begun to develop clone libraries. Detailed geochemical analysis has allowed us to develop better targeted media for culture work. Despite extremely dilute inorganic chemistry (<100 ppm total dissolved solids) and very simple mineralogy, we find that there is complex organic chemistry present in this system. This site is already serving as a model system for life at the surface of young terrestrial bodies and how it may be simulated.

Process–based, one–dimensional reactive transport models of the interactions between surface rocks, water, atmospheric gases and life (Rye , Bolton , and Steefel) . The models developed thus far primarily simulate abiological processes, but we have shown that such models can reproduce weathering profiles on black shales, sediments that preserve ancient (dead) biological matter. Such weathering is likely a key part of the biologically driven portion of the carbon cycle as oxygen levels in atmospheres are strongly controlled by the imbalance between carbon fixation and carbon respiration/weathering.

Archean ecosystem model (Kasting and Kharecha) . The investigators have found that hydrogen fluxes and the carbon cycle of the Archean would have readily supported biogenic methane fluxes of the same magnitude as today's. Previous results suggested that such a flux would allow methane levels to rise to ~350 ppmv, thereby averting massive glaciation. This is more evidence that life can profoundly, and potentially detectably, affect the climate and atmosphere of extrasolar planets, even in the absence of oxygenic photosynthesis.



Figrure 1. Interface between the Life Modules (Biota) and the atmosphere and geosphere components of the VPL.

Highlights

- We have completed an initial survey of the genetic diversity of microbes in springs and sediments associated with a terrestrial serpentinizing

peridotite. Life appears to be diverse there despite the extreme lack of nutrients and high pH (>11.5)
- A simple ecosystem model has shown that the biosphere was probably capable of generating methane fluxes large enough to keep Earth warm during the Archean.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Planning Support,Background Research,Instrument/Payload Development

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Field Trip Name: The Cedars	
Start Date: July 1, 2003	***End Date:*** July 2, 2003
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Cazadero
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): The Cedars	***Keywords:***
Description of Work: Water collection for genetic analysis	
Members Involved:	

Field Trip Name: The Cedars	
Start Date: September 12, 2003	***End Date:*** September 14, 2003
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Cazadero
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): The Cedars	***Keywords:***
Description of Work: Collected water samples from hyperalkeline springs for ICP−MS analysis. Collected water samples for genetic analysis. Collected sediment and water samples in order to culture microbes present in springs. Collected dissolved gas samples for GC analysis.	
Members Involved:	

Field Trip Name: The Cedars	
Start Date: October 17, 2003	***End Date:*** October 18, 2003
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Cazadero
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): The Cedars	***Keywords:***
Description of Work: Collected water samples from hyperalkeline springs for geochemical and microbiological analysis.	
Members Involved:	

Field Trip Name: The Cedars	
Start Date: December 17, 2003	***End Date:*** December 19, 2003
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Cazadero
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): The Cedars	***Keywords:***
Description of Work: Installed our weather station.	
Members Involved:	

Field Trip Name: The Cedars	
Start Date: March 5, 2004	***End Date:*** March 7, 2004
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Cazadero
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): The Cedars	***Keywords:***
Description of Work: Collected water and rock samples for geochemical and microbiological analysis.	
Members Involved:	

Field Trip Name: The Cedars	
Start Date: May 21, 2004	***End Date:*** May 23, 2004
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Cazadero
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.): The Cedars	***Keywords:***
Description of Work: Collected water and rock samples for geochemical and microbiological analysis, including samples of organic geochemical analysis	
Members Involved:	

Cross Team Collaborations

Work on modeling the Archean ecosystem with co–investigators Kasting and Kharecha is on ongoing cross–team collaboration with Penn State.

The team of DesMarais at NAI NASA Ames has contributed a model of the surface fluxes from microbial mats for modeling the Proterozoic.

Project Report: Characterization of Terrestrial Planets From Disk–Averaged Spectra: Earths Around Other Stars

Project Investigators:	***James Kasting , Antigona Segura***

Project Progress

In this task, we have attempted to understand the nature and detectability of biosignatures and planetary characteristics for Earth–like planets around other stars. In our initial experiment, we used a coupled climate–photochemical model to simulate Earth–like planets with different amounts of atmospheric oxygen, in orbit around the Sun (a G2V star), an F2V star, and a K2V star. For the solar case, Proterozoic Earth was also included in the simulations. Three significant results were derived from this research: 1) O_2 can be detected at visible wavelengths (~0.765 microns) in disk–averaged spectra at atmospheric concentrations as small as 10^{-2} present atmospheric levels (PAL) and O_3 can be detected at O_2 concentrations as low as 10^{-3} PAL at millimeter imaging radiometer (MIR) wavelengths; 2) Mid–Proterozoic Earth–like atmospheres show strong signatures from both CH_4 and O_3, and it is potentially easier to detect life remotely in a mid–Proterozoic–type atmosphere than a modern Earth; and 3) The critical threshold for atmospheric oxygen to provide a planetary ultraviolet (UV) shield for host stars of different spectral types is typically ~10^{-2} PAL. We also discovered that planets with high–O_2 atmospheres orbiting K2V and F2V stars were better protected from surface UV radiation than Earth, but O_2 levels below ~10^{-2} PAL were insufficient to provide adequate surface protection. (Segura et al., *Astrobiology*, 2003, vol. 3, pp. 689–708).

Our second, ongoing, experiment is focused on detectability of characteristics for planets orbiting M dwarf stars, which are typically highly variable. As a first step, the observed time–averaged spectra of two M stars and a quiescent, modeled M star were used (Figure 1). The planets modeled in this case contained 1PAL Earth–like atmospheres. Our results show that methane could be an excellent biosignature, along with ozone (Figures 2 and 3). We are currently developing a time–dependent climate–photochemical model to determine how the flux variability of M stars would affect the lifetime and detectability of planetary biosignatures. We also show that CH_4 is potentially observable along with O_2 (or O_3). The CH_4 abundance is relatively high in these systems because the enhanced ozone shield at near–UV wavelengths between 200–300 nm produces reduced tropospheric OH densities. Hence,

methane is long−lived even in O_2−rich atmospheres of M−star planets.

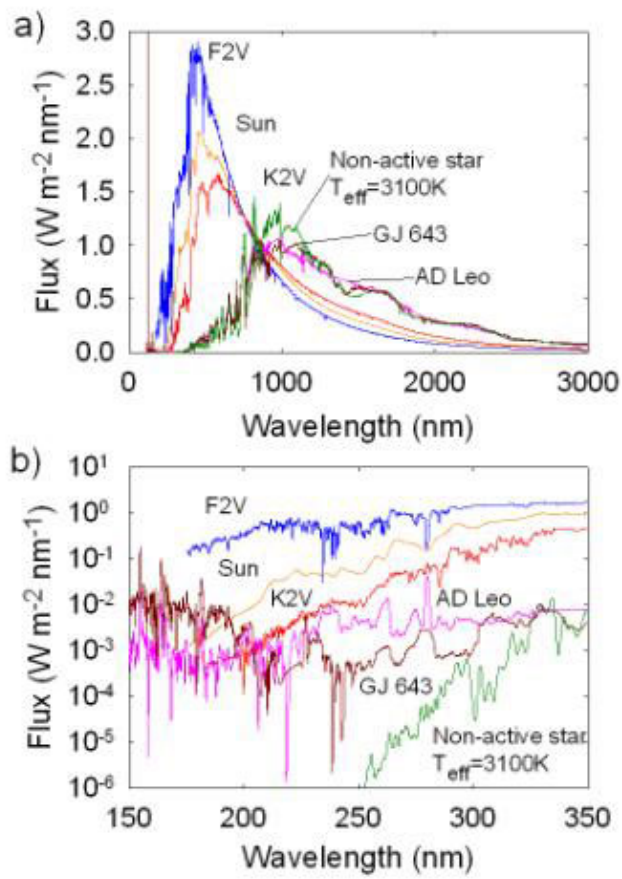

Figure 1. Complete (a) and UV (b) spectra for various stars. The F2V and K2V spectra are from Segura et al. (2003). The data for the two M stars, AD Leo and GJ 643, are from International Ultraviolet Explorer, observations in the UV and from Kurucz models convolved to fit photometric measurements in the visible. The non−active M−star spectrum is from a theoretical model downloaded from the BaSeL website (http://www.astro.mat.uc.pt/BaSeL/).

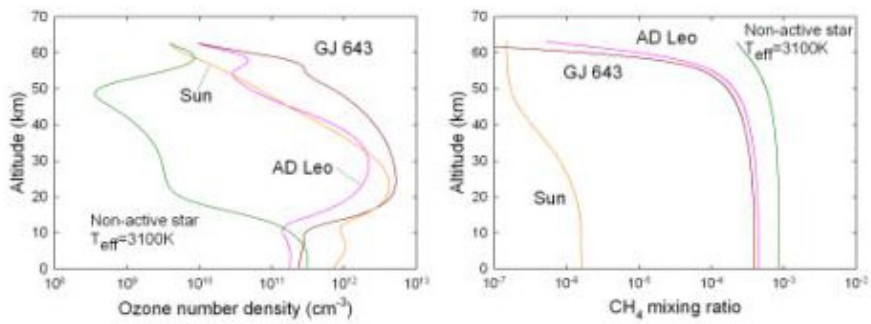

Figure 2. Left panel: Ozone number density profiles for Earth−like planets (1 PAL O2) around the Sun and the three different M stars shown in Fig. 1. Right panel: Vertical mixing ratio CH4 (bottom panel) on Earth−like planets around the three M stars shown in Fig. 1.

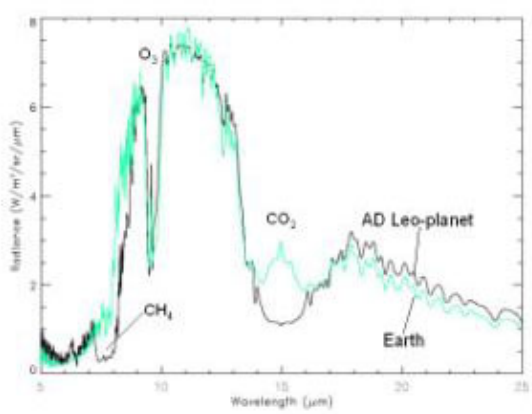

Figure 3. Comparison of the mid−infrared spectrum for Earth (aqua−colored line), and an Earth−like planet orbiting the star AD Leo (black line). For Earth, the strong CO_2 band at 15 mm shows a central emission peak, indicative of a hot stratosphere. For the AD Leo planet, this feature is missing, implying an atmospheric temperature structure that is quite different from Earth's. At 7.7 mm, the AD Leo planet shows strong absorption from CH_4, which is weak in the Earth spectrum. AD Leo also shows weak, yet enhanced absorption from N_2O between 8.5−8.8μm, and from 17−18μm, when compared to the far weaker Earth case. Both planets show a strong absorption from ozone at 9.6 mm. These results are preliminary and still under analysis, but give an indication of the effect on the observable spectrum for an Earth−like planet orbiting stars of different spectral type

Highlights

- Earth−like planets were simulated around F, G, and K stars. Our results

indicate that O_2 is potentially observable remotely in the visible for atmospheres containing at least 10^{-2} PAL of O_2, and in the thermal infrared (IR) for atmospheres containing at least 10^{-3} PAL of O_2, around all three types of stars.

- Mid–Proterozoic–type atmospheres show strong signatures from CH_4, which is elevated compared with the present day, and O_3, which despite the reduction of the atmospheric oxygen to ~10^{-1} PAL, is still just as detectable as for the 1PAL case. Thus, the simultaneous detection of both O_3 and CH_4—considered a reliable indication of life—is easier for Proterozoic–type atmospheres than for modern Earth.
- Planets with high–O_2 atmospheres orbiting K2V and F2V stars are better protected from surface UV radiation than modern Earth. For the F2V case the high intrinsic UV luminosity of the star is more than offset by the much thicker ozone layer. However, at O_2 levels below ~10^{-2} PAL, planets around all three types of stars are subject to high surface UV fluxes, with the F2V planet exhibiting the most biologically dangerous radiation environment.
- Earth–like planets circling M stars may have high atmospheric concentrations of CH_4, in addition to O_2 (or O_3). The simultaneous observation of O_2 and a reduced gas like CH_4 is considered the best remote spectroscopic evidence for life.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Science Team Member,Planning Support,Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload

development, research or analysis techniques, other (specify).

This project work is specifically being used to identify and estimate the detectability of terrestrial planet characteristics in disk−averaged spectra for Earth−like planets orbiting other stars, as an aid to understanding what can be learnt about extrasolar terrestrial planets from astronomical observations. This work is therefore background science for the TPF mission and will provide information that will be valuable for mission planning, including estimates of the minimum and optimum sensitivity, wavelength range and spectral resolution required for both TPF−I and TPF−C, especially when attempting to characterize terrestrial planets around TPF target stars of different spectral type.

Project Report: Analysis of and Discrimination of TPF Planetary Spectra using Bayesian and Artificial Neural Network Techniques

Project Investigators:	***Victoria Meadows , Ted von Hippel , Thangasamy Velusamy***

Project Progress

The Terrestrial Planet Finder (TPF) mission will use low−resolution, low−sensitivity data to detect and characterize extrasolar terrestrial planets. This task focuses on mathematical techniques to maximize the return from TPF data.

Image Reconstruction and Planet Signal Extraction for TPF−I nulling interferometer Velusamy (with Ken Marsh) has developed an algorithm based on Richardson and Marsh (1983) to reconstruct the image from the SINE/COS chopped output of dual nulling interferometer. This algorithm treats the ensemble of possible images as a Gaussian random process, subject to a positivity constraint, and contains no limitations on the presence of negative lobes in the null response pattern with the chop. The Bayesian procedure maximizes the probability density of the image conditioned on the data. This algorithm will have application in analyzing the spectral features detectable by TPF−I

<u>Using Artificial Neural Networks to Discriminate TPF Spectra</u>
To determine the scientific impact of trade−offs in instrument characteristics (e.g., wavelength coverage, spectral resolution, and signal−to−noise (S/N)) for spectral characterization of terrestrial planets, this task focuses on using Artificial Neural Networks (ANN) to determine instrumentation limits for reliable classification of spectra. As the test set, we have used UV−FIR planetary spectra generated by the Virtual Planetary Laboratory (VPL) and convolved these with slit functions and a simplistic noise model to produce spectra with a range of spectral resolutions and S/N levels. Thousands of ANNs have been run to discriminate these spectra in four wavelength regions, at multiple resolutions (millimeter imaging radiometer (MIR): R = 5 to 100, vis: R = 20−200), and for S/N from 3−100. Multiple versions of the same ANNs have also been run to test for consistency of results. With our simplistic noise model, the ANNs clearly discriminate spectra at very modest resolutions and S/N. Ongoing work involves expanding the test set to other planetary types and working with the TPF design teams to build more realistic noise models.

Highlights

- Based on our preliminary noise model and our ANN analyses, Meadows, Von Hippel, and Tinetti estimate that at S/N ≥5 at R = 25 for 6–17 µm (TPF–I) and a S/N ≥8 at R = 75 for TPF–C 0.5–1.0 µm (TPF–C) the ANNs will provide a certainty of 90% for a correct classification among a basic family of 6 hypothetical, but realistic planets: Earth, Mars, Ancient Earth, Frozen Mars, and Jovian planet at 1 AU. (We do caution, however, that this result is based on a simplistic noise model and these results represent the most optimistic case.)
- Project Scientist Velusamy was a co–I on a successful Spitzer proposal to search for debris disks around nearby stars to characterize likely Space Interferometry Mission (SIM) and TPF target stars in the mid–infrared. These data will help characterize the evolution, amount, structure, and composition of the dust associated with Kuiper and asteroid belts around many types of stars. This characterization of exo–zodiacal light around nearby stars will provide observational input for more realistic noise models for TPF data.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Planning Support,Data Analysis,Background Research,Research or Analysis Techniques
2	Spitzer	Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member,

planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This project work is specifically being used to identify and estimate the detectability of terrestrial planet characteristics in disk−averaged spectra for Earth−like planets orbiting other stars, as an aid to understanding what can be learnt about extrasolar terrestrial planets from astronomical observations. This work is therefore background science for the TPF mission and will provide information that will be valuable for mission planning, including estimates of the minimum and optimum sensitivity, wavelength range and spectral resolution required for both TPF−I and TPF−C, especially when attempting to characterize terrestrial planets around TPF target stars of different spectral type. Vikki Meadows is a member of the TPF Science Working Group and has served as an advisor and reviewer for specific tasks related to developing TPF science requirements. The Spitzer work successfully proposed by team member Velusamy and colleagues uses a NASA Origins mission to support the search for life beyond the solar system by starting the detailed characterization of nearby stars that are potential targets for SIM and TPF. This information is crucial not only to allow us to chose the target stars that are most likely to provide optimum detectability and habitability for orbiting terrestrial planets, but to provide valuable input on levels of exo−zodiacal light, which is likely to be a significant noise source for the detection and characterization of terrestrial planets, and must be accounted for in realistic models for planetary spectral discrimination.

Project Report: Spectroscopic Databases to Support Extrasolar Planet Modeling

Project Investigators:	***Linda Brown , Martin Cohen***

Project Progress

To support efforts to understand the nature and detectability of terrestrial planet characteristics for planets around stars of different spectral type, this task focuses on collecting and preparing full wavelength, continuous stellar spectra for use by the planetary climate and chemistry models (c. f. Task 6). Last year, we collected F and K spectra, and this year we worked towards providing spectra of quiescent and active M stars. We sought and recalibrated International Ultraviolet Explorer UV spectra for between 15 and 20 M−dwarfs. Analysis of the UV spectra for AD Leo, a well−known flare star with abundant UV data revealed five guises: flare, post−flare, non−flaring, “typical,” and no emission lines. The averaged “typical” UV spectra for both AD Leo, and GJ643, were appended to absolutely calibrated optical+infrared (IR) energy distributions to generate complete FUV−FIR “quiescent” spectra. Future work will include producing early−M to mid−M dwarf spectra, which are much less active cool stars, prior to tackling the full time−dependent situation for the more active M−stars. These collated, full−wavelength−range stellar spectra are being publicly archived.

We also continued development of the molecular spectra database, http://vpl.ipac.caltech.edu/spectra/ , which is a collection of line lists and absorption cross−sections for molecules of interest to the Virtual Planetary Laboratory (VPL). There are currently 61 molecules with entries in the database, with more being added as information becomes available. Data can be absorption cross sections and/or actual line lists, and may come from multiple sources. The most common sources are infrared absorption cross−sections from Pacific Northwest National Lab (PNNL), infrared line lists from the High Resolution Transmission Molecular Absorption (HITRAN) database, and UV cross−sections from personal collections of VPL personnel. Images of the data are provided on the website, although the actual data is not yet linked, but is available on request. Work is underway to make the source data available for download from the VPL server.

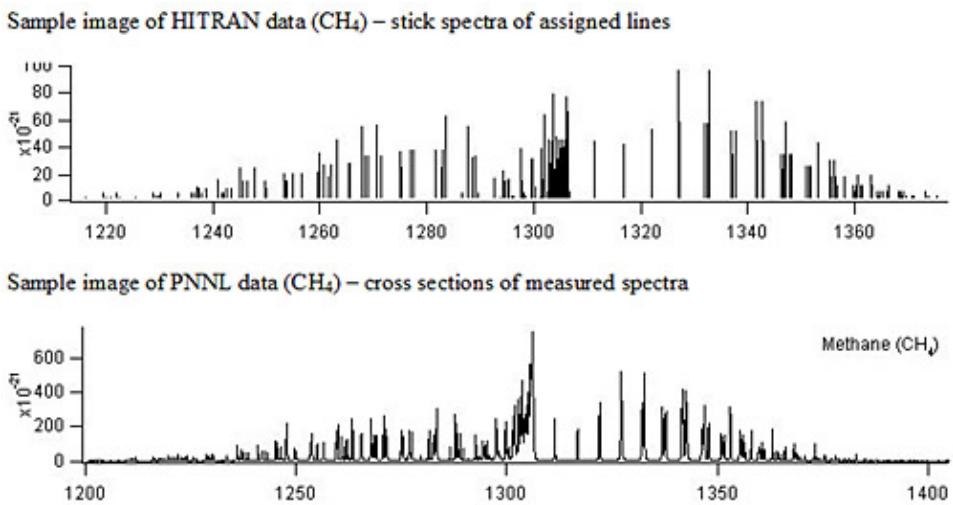

Figure 1. CH_4 Spectra

Highlights

- Full–wavelength–range spectra are now available for two M stars, AD Leo and GJ643, and these spectra are currently being used to simulate the nature and detectability of characteristics of Earth–like planets around quiescent M stars.
- The VPL Molecular Spectra Database was made publicly available this year. The database now holds information on 61 molecules of interest to astrobiologists and planetary scientists.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Planning Support,Background Research,Instrument/Payload Development

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF,

Mars Lander 2009)
3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This project work supports the development of the Virtual Planetary Laboratory modeling suite, which will be used to identify and estimate the detectability of terrestrial planet characteristics to determine whether astronomical remote−sensing techniques will be valid for determining if a detected terrestrial planet is habitable or already supports life. This work is therefore background science for the TPF mission and will provide information that will be valuable for mission planning, including estimates of the minimum and optimum sensitivity, wavelength range and spectral resolution required for both TPF−I and TPF−C.

Project Report: The Virtual Planetary Laboratory – Synthesis and Architecture

Project Investigator:	***John Armstrong***

Project Progress

With many of the core components operating independently or near completion, this past report period focused on interface design, with focus on development of an Application Programming Interface (API) in Fortran to facilitate communication between different model components. Since many of the core components operate independently at radically different timescales, it is necessary for all common data and calculations to be stored in an accessible format with well–specified methods for retrieving information. Each code component accesses this information through a set of common subroutines, and stores the results for use by other programs.

Progress includes:

- ***Data structure design:*** This has now been fully specified in the draft API document. The initial structure has been designed for XML, but the overall format can be used for any structured database.
- ***Data structure function library:*** The function library is now fully specified in the draft API, and a modest, VPL–specific XML library now exists for Fortran 95.
- ***Interface scheme:*** The interface model assumes that a database exists containing relevant parameters, and data sets are accessed through a well–specified API. A given code component, rather than handing material off to another component in sequence, registers the results in the database, and sets relevant flags informing other code components that new calculations exist.

Testbed web interface for climate: The main benefit of the XML/Database model is the ease by which models can be run and results displayed over the Internet. As a full test, using an XML web interface, we developed a web front end for Giovanna Tinetti's climate code. This allows the user to enter planet parameters (or develop a planet ‘state' file) and generate model temperature profiles that can be imported into other core components. This is the first step towards a true community tool.

Highlights

- The development of a VPL Application Programming Interface allows current code components (and all future components) to access model results from the full range of VPL tools.
- The adoption of a structured data format gives us the ability to run VPL core components from centralized databases over the Internet. This is the first step towards a true planet simulation community tool.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
2	TPF	Planning Support,Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Individual VPL tools already produce simulated spectra for Earth, Venus, and Mars that support the design of TPF. The integration of the VPL core components will allow us to extend this work to other types of worlds that may have different atmospheric structures and formation histories than that of the known terrestrial worlds. This will provide a more detailed set of simulations to inform TPF design and to help analyze the results from TPF.

Fellowships: Virtual Planetary Laboratory

The NAI–NRC Postdoctoral Fellowship recipients for this team are below.

Recipient: Giovanna Tinetti
Project Title: Light–curves and disk–averaged spectra for terrestrial planets
Advisor: Victoria Meadows, Project Investigator
NAI Lead Team: Virtual Planetary Laboratory
Fellowship Began In:

Project Report: Light–curves and disk–averaged spectra for terrestrial planets

NAI–NRC Postdoctoral Fellow :	***Giovanna Tinetti***

Project Progress

Any planets found by the Terrestrial Planet Finder Mission will be spatially unresolved. Basic information can be gleaned from the object's distance from the star and its apparent brightness, but the presence of a planetary atmosphere of unknown composition will complicate simplistic determinations of planetary properties. Disk–averaged spectroscopy will be our best tool for discriminating between Jovians and Terrestrials, and between Terrestrials of different types.

Spectrally–dependent light–curves and disk–averaged spectra of extrasolar terrestrial planets can be generated to determine the detectability of biosignatures by proposed space–based observatories. The seasonal and annual climate variations of plausible terrestrial planets with a range of orbital distances, eccentricities, and obliquities can be simulated using a versatile climate model, developed in collaboration with part of the Virtual Planetary Laboratory (VPL) during this reporting period, and currently under testing. A surface/atmosphere radiative transfer model (SMART, by D. Crisp) can then be used to generate time–dependent spectra of these environments throughout the annual cycle.

In collaboration with part of VPL, we completed the Mars and Earth models, and validated the resultant disk–averaged spectra against observations. This work will be expanded by extending the investigation to planets with realistic surfaces and atmospheres to explore how astronomical parameters such as orbital eccentricity and obliquity can influence the global climate and atmospheric surface signature and hence the disk–averaged spectra. This set of high–resolution spectra can be used to identify potential biosignatures from the atmosphere and surface, and then successively be degraded to note at which spectral resolution and signal–to–noise (S/N) these features can no longer be detected (collaboration with V. Meadows and T. Von Hippel, University of Texas, on Neural Network Analysis as a possible technique to better interpret and discriminate these spectra).

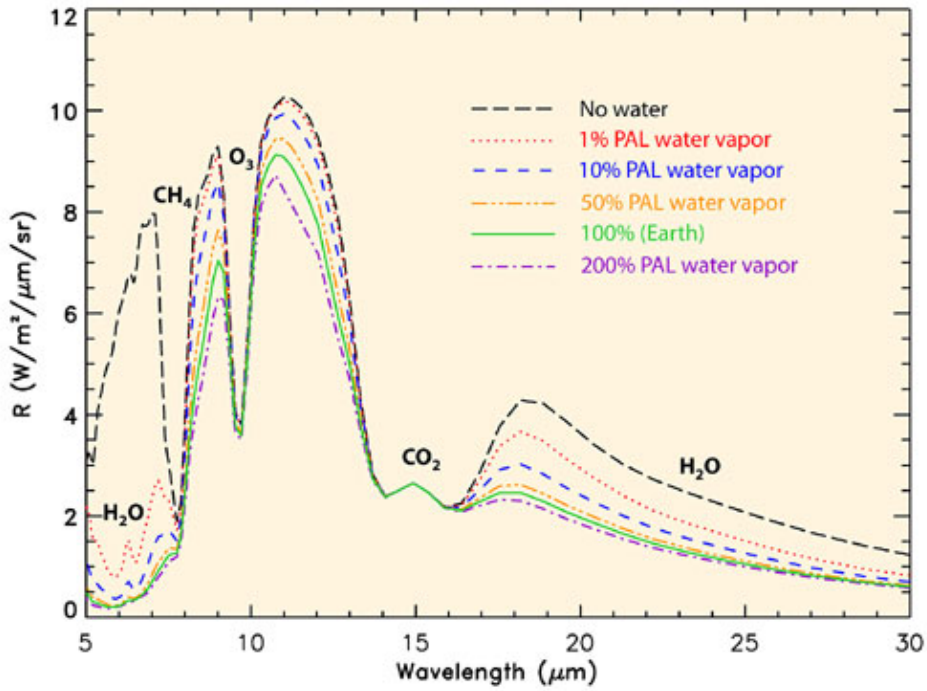

Figure 1.

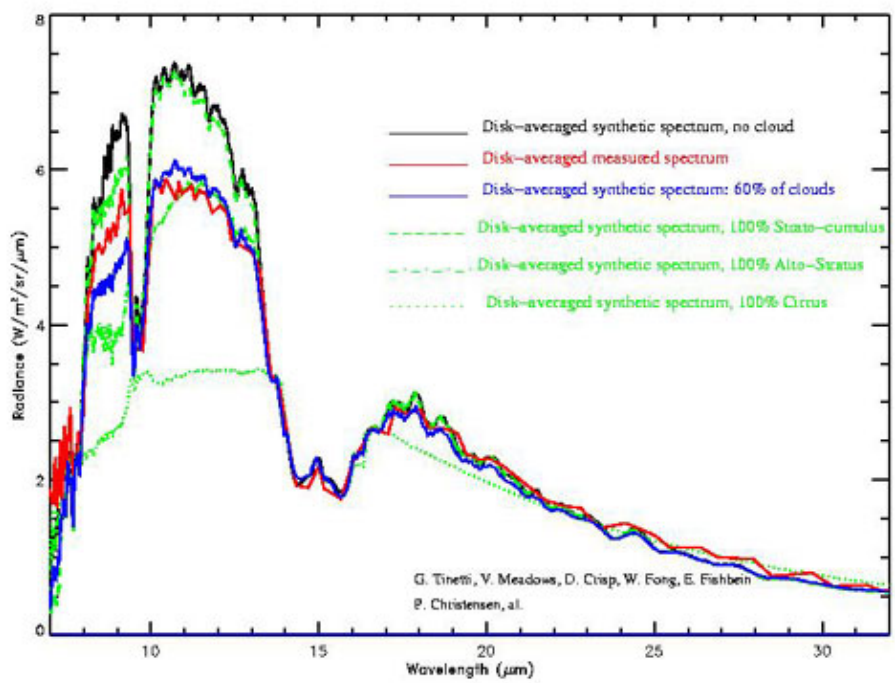

Figure 2.

Highlights

- ***Detectability of surface and atmospheric properties of Earth−like and Mars−like planets from light−curves and disk averaged synthetic spectra***

(with Vikki Meadows (NAI−IPAC) and David Crisp (JPL), et al.)

We have already completed the model for Mars (a good example of a likely abiotic planet) and Earth (the only example of life supporting planet known, so far...). The Earth model has been validated against observations of the Earth by the Mars Global Surveyor Thermal Emission Spectrometer (MGS TES) and Earth−shine spectra, and the Mars model has been validated against spectra recorded by Mariner 9 Interferometer Spectrometer (IRIS).

The results include globally averaged synthetic spectra light−curves and the spectral variability at visible and infrared (IR) wavelengths as a function of viewing angle, simulations of an increasingly frozen Mars, an increasingly cloudy/forested/oceanic Earth and detectability of biosignatures on an Earth−like planet.

These results have been processed with an instrument simulator to improve our understanding of the detectable characteristics as viewed by the first generation extrasolar terrestrial planet detection and characterization missions (by T. Velusamy). The results for Mars are submitted for pubblication.

- ***A comprehensive Climate Model for Extrasolar Terrestrial Planets***

  with David Crisp (JPL), John Armstrong (NAI−Weber State University), Chris parkinson (Caltech)

  In support of the NAI Virtual Planetary Laboratory we are developing and testing a climate model to simulate the environments of extrasolar terrestrial planets. We have adopted the vertical transport scheme from the University of Helsinki 1−D planetary boundary layer model (Savijarv i 1999). The soil temperature is described with a 20−layer soil thermal diffusion scheme in order to include daily and annual variations (G. Tinetti). The Spectral Mapping Atmospheric Radiative Transfer (SMART by D. Crisp) algorithm has been installed. A cloud model has been added, so that clouds could form and dissipate as the atmospheric thermal structure evolved toward equilibrium. Precipitation as well as condensation and evaporation are taken into account (Imamura and Hashimoto, 2001). In addition, a horizontal energy balance (EB) model is being developed to integrate the planetary temperature distribution with the specific atmospheric structure.

- ***Using Artificial Neural Networks for Analysis and Discrimination of Terrestrial Planet Finder (TPF) Planetary Spectra***

  with Vikki Meadows (NAI−IPAC) and Ted Von Hippel (University of Texas)

  The TPF mission will use low−resolution spectra to characterize extrasolar terrestrial planets, with the ultimate goal of finding global signs of life in their atmospheres or surfaces. To help understand the trade−offs for spectral characterization of terrestrial planets, we are using Artificial Neural Networks to discern the degree to which planetary

spectra can be reliably classified as a function wavelength coverage, spectral resolution, and signal–to–noise.

To do this, we have generated synthetic spectra in both the optical and mid–infrared for a range of plausible terrestrial planets, from frozen to more Earth–like worlds. These spectra are produced for a range of spectral resolutions and S/N levels. The results indicate that Artificial Neural Networks can make important distinctions between atmospheric types at the modest resolutions and signal–to–noise likely to be characteristic of TPF planetary spectra..

Based on our preliminary noise model and our ANN analyses, we estimate that S/N = 8 at R = 75 for a visible TPF (full range) will provide a certainty of = 90% for a correct classification among a basic family of 6 hypothetical, but realistic planets (Earth, Mars, Ancient Earth, Frozen Mars, Jovian planet at 1 AU, and Titan).

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
2	NASA Terrestrial Planet Finder	Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

This type of research, even if theoretical and mostly based on mathematical and numerical modeling, can be very useful to better address and constraint a

large number of TPF requirements: " Terrestrial planet definition " Orbit Phase Space " Types of Stars " Habitable Zone " Spectral Range " Color " Spectrum " Visitations " Detectability of biosignatures " Detectability as a function of S/N and resolution

EPO: Virtual Planetary Laboratory

These are the Education and Public Outreach activities for the Virtual Planetary Laboratory.

Teaching Astrobiology

Dr. Janet Siefert from Rice University taught a course for masters teachers and professional development, which was webcast and held Spring 2004 semester. This course is comprised of a year long, integrated science curriculum: Voyages Through Time, which provides the basis of the course including six modules, Cosmic Evolution, Planetary Evolution, Origin of Life, Hominid Evolution and Evolution of Technology. This curriculum was developed by practicing scientists, teachers, science educators, and curriculum specialists. The content and instructional approach is based on the National Science Education Standards and on the Benchmarks for Science Literacy. This course was taught by a number of local scientists as well as several principle investigators who are actively involved in Astrobiology and Exobiology research efforts in the United States and Mexico.

Dr. Monika Kress from San Jose State University taught a course at Seattle University entitled: ?Astrobiology?, for liberal arts and non–science majors. This course fulfills the core science requirement for all non–science majors. This course, explores the scientific reasons behind why our solar system harbors a living planet. Students learned the factors that allow the Earth to support life, while other planets appear lifeless (currently).

On–Line Course

Ms. Doris Daou, E/PO lead, initiated the collaboration and set the contract for The Virtual Planetary Laboratory, which is providing moderate funds to subsidize the costs for offering 25 in–service teachers the opportunity to earn three graduate semester credits in an Internet–delivered ASTROBIOLOGY FOR TEACHERS course. The courses will be offered in the fall of 2004 and clearly indicate funding support from VPL as part of the National Science Teachers Association Professional Development Institute and the National Teachers Enhancement Network (http://www.scienceteacher.org).

The ASTROBIOLOGY FOR TEACHERS course was developed and is taught by teams of scientists, high–school teachers, and science educators. Over a 16–week period, participants use a personal computer and modem to connect to their classes interacting with each other and with the instructor through

conferencing software that allows for both structured public discussions and private messaging. Most aspects of the courses are unsurprising; textbooks, homework exercises, computer software, and evaluation activities are still utilized – but there are no lectures. Instead, instructors and students work through the material together in a structured and scheduled format, which requires almost daily interaction on behalf of the students and instructors. These are far from "independent study" experiences – indeed, participants report that discussion and networking is a major factor in their learning. Nonetheless, the fact that the discussions are not conducted in real time means that teachers can participate in the class at times of day most convenient for them.

Public Astrobiology Talks

Dr. Antigona Segura from Pennsylvania State University was invited to present a talk at a private middle school in Aguascalientes, Mexico, Universidad del Valle. The title of the talks was: ?Vida En Otros Planetas? (Life in other planets).

Dr. Monika Kress from San Jose State University gave a talk entitled "searching for relics from the birth of our living universe" to a retirement community in Washington State. Dr. Kress also shared her experience from her travel to Antarctica in search of meteorites with the following groups: Green Lake Elementary School, French American School, Bernice Curren elementary school, Seattle University, Women in science and Engineering Club at the University of Washington, and at the Juan de Fuca festival of the Arts in Port Angeles, Washington.

Dr. Vikki Meadows, VPL Principle Investigator, gave a talk at the Adler Planetarium in in Chicago entitled, "The Search for Habitable Worlds?.

Dr. Chris Parkinson, gave a talk entitled, ?The Search for Habitable Worlds" to an Astronomy Group in Santa Clarita, Ca.

Scientific Talks, Presentations, and Seminars

Dr. Giovanna Tinetti, NAI/NRC Postdoctoral Fellow, was invited to give a talk ?Detection and Characterization of Extrasolar Terrestrial Planets to the Astronomical Observatory of Torino and at the University of Pisa. Dr. Tinetti was also invited to give a seminar at California Institute of Technology, entitled: ?Characterizing Extrasolar Terrestrial Planets by Light Curves and Disk Averaged Spectra?.

The 32nd Harry Messell International Summer School was held at St. John?s College, which is on the main campus of the University of Sydney. The invited lecturers are considered of International renown in the scientific community. All matters of scientific study are considered during a two week intensive study period. Dr. Victoria Meadows was invited to develop and teach two courses at this summer school: ?The Search For Planets Around Other Stars: Dancing in the Dark? and ?The Search for Habitable Worlds: How Would We Know One if We Saw One??

Dr. Meadows also developed and taught the following courses at the NAI Insight Course hosted in Flagstaff, AZ: "The Jovian Planets" "Terrestrial Planet Atmospheres: Climate and Evolution" "The Composition, Origin, and Evolution of Terrestrial Planet Atmospheres" and "Finding Life Beyond The Solar System" .

Dr. Chris Parkinson presented a talk entitled: ?The Search for Habitable Worlds" at the Institut d?Astrophysique de Paris and at the Laboratoire de Planetologie de Grenoble

Dr. Rob Rye from USC gave a 50 minute lecture delivered entitled: ?How Life Shapes Planets: From VPL to the Cedars and Back? at Caltech and at the University of California, Davis, Department of Geology.

Dr. Frances Nimmo from UCLA and a member of the Royal Society gave the following scientific talks:

Lunar Planetary Institute (Europa's Icy Shell workshop) – "Lateral and vertical motions in Europa's Ice Shell" and "What is the Young's modulus of ice?". UC Berkeley – "Heat fluxes and deformation on icy satellites". UC Santa Cruz – "Flexure and topography on icy satellites". Scripps Institute (CSEDI) – "Potassium in the Earth's core". LPSC – "Thermal and topographic tests of Europa chaos formation models?. SWRI – "Heat fluxes and deformation on icy satellites"

An idea born at the 2003 NAI General Meeting during a conversation between VPL members Dr. Maggie Turnbull (Carnegie Institute) and Dr. John Armstrong (Weber State University) became a reality in January 2004 with the Astrobiology Graduate Conference, held in Tucson at the University of Arizona. At this international conference, junior scientists from all subfields of Astrobiology had the opportunity to discuss their work and get to know one another. Seventy–three graduate and postdoctoral students from 41 institutions attended (including 10 current and former NAI member institutions), and they gave 20 excellent oral presentations and 20 poster presentations. This conference was the first meeting of a new community of scientists: the first generation of "native" Astrobiologists.

Popular Publications

Dr. Victoria Meadows submitted two chapters for the publication, "From Zero to Infinity", Sydney University Press, ed. J. Nicholls. The chapters were entitled: The Search For Planets Around Other Stars: Dancing in the Dark? and ?The Search for Habitable Worlds: How Would We Know One if We Saw One?? These chapters were in conjunction with two courses taught at the 32nd Harry Messell International Summer School, which is held at St. John?s College at the University of Sydney.

Interactive Astrobiology

Dr. Meadows served as both a live panel participant and did a pre–interview for supporting edited footage for the Venus Transit Webcast. This webcast was

presented on the JPL Navigator Program and the Sun−Earth Connection Education Forum in Pasadena, Ca. She also worked with the London Science Museum to review the scientific likelihood and accuracy of hypothetical extrasolar planets that they Museum had proposed for an exhibit on life beyond the solar system. She also provided scientific input for the ?Lifefinder? game which will be hosted by JPL?s Navigator as well as collaborating with Scholastic Publishing towards the release of this game to the general public.

Ms. Doris Daou, EPO Lead, is coordinating efforts to assist The Virtual Planetary Laboratory providing budget as well as scientists support for the AstroVenture developing group to create the last module: ?Create Your Own Planet?. Ms. Daou initiated the collaboration, set the contract and is overseeing the direction, schedules and deliverables.

Astro−Venture (http://astroventure.arc.nasa.gov) is an educational, interactive, multimedia Web environment highlighting NASA careers and astrobiology research in the areas of Astronomy, Geology, Biology and Atmospheric Sciences. Students in grades 5−8 role play NASA occupations and use scientific inquiry, as they search for and design a planet with the necessary characteristics for human habitation. Supporting activities include, classroom lessons, career fact sheets and online challenges supported by scientist chats and webcasts.

The Virtual Planetary Laboratory is providing support for the California Academy of Science during their redesign of the Museum and grounds. Images and Content from VPL will be used in the new exhibits. Ms. Daou E/PO lead initiated the collaboration and is overseeing the direction, schedules and deliverables from VPL to the CAS. We already delivered field photos of scientist Dr. Monika Kress during her trip of meteorite search as well as her profile for inclusion in the museum?s astrobiology exhibit. They will be incorporated into our "How do we study it?" component.

Media

Dr. Meadows provided live interviews for radio and TV on TPF and VPL and the search for life beyond the solar system to the following: Australian Broadcasting Commission, Sydney, Australia. This was a 10 minute radio interview.

Dr. Meadows was interviewed for the following journals regarding topics that ranged from the current status of astrobiology to data relating specifically to Mars: Internationally − GEO, a German science and Nature magazine; Astronomy Now, a British magazine; Politika, a Polish magazine that touches on current issues and events. Nationally − Nature; American Geophysical Union?s Eos Newspaper (Interview for an article on Spitzer and planetary science for the AGU's Eos newspaper); Magellanic Times (Worked with Michael Bicay to write an article on the SIRTF launch); National Geographic (Two research interviews for an upcoming story on Solar Systems, which will explore the scientific links between recent discoveries in our own solar system, and the newly discovered extrasolar planetary systems. Provided conceptual graphics for the article as well); JPL?s on−line publication, Navigator

(Interviewed for an article on TPF and TITAN. Also, edited and corrected for publication);

Dr. Meadows also provided two research interviews and a 4 hour TV interview on remote−sensing biosignatures for the NOVA series. She also supplied scientific input and synthetic spectra to Matt Bobrowkski of STScI for participation in EPO products as tie−ins to the series.

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Focus Groups: Focus Groups Introduction

The program of NAI Focus Groups was established as a way to mobilize expertise from across the Institute and the wider scientific community towards the rapid advancement of a defined area of research, mission planning, or other activity of particular importance to astrobiology. Novel, timely, and multidisciplinary efforts achieving synergy among various research fields are particularly encouraged.

Towards its objective of influencing future space missions, and reflecting its strengths in this area, the NAI established during this past year the Astronomy Focus Group (September, 2003). The formation of this Focus Group capitalized on existing expertise and ambition in this area, as many of the founding members were instrumental in organizing the "Astrobiology and the James Webb Space Telescope (JWST)" workshop which was held earlier in 2003 at the Carnegie Institution of Washington. A white paper report was produced from this workshop making recommendations on the technical and science requirements for the JWST. Two similar workshops are being planned by the Astronomy Focus Group for the coming year, the first of which will concentrate on Atmospheric Biomarker Signatures.

Similarly, to further increase the NAI's role in planning for future space missions, the NAI also approved this past year the Astrobiotechnology Focus Group (December, 2003). Planning is already well underway by this diverse group for a major workshop dedicated to the definition of the most advanced biotechnology available for upcoming Mars exploration missions (September, 2004; CIW).

The Virus Focus Group was also renewed this past year for a three−year term. This Focus Group organized two significant activities during this past year, including a field expedition and workshop at Mono Lake and the Long Valley caldera region near Mammoth Lakes in eastern California. An important component of this expedition was to collect a variety of microbial, viral and environmental samples from this suite of unique environments which provide a diversity of habitats exhibiting extremes in temperature, pH, salinity and chemical composition. Individual investigators will examine the carbon metabolism, ecology, and community structure of the sites and conduct metagenomic studies of the viruses, as well as bacteria and archaea. Since samples are being distributed among researchers, the results of specific analyses will be able to be integrated in ways not previously possible.

These are just a few highlights of the NAI Focus Groups' accomplishments from this past year – you are invited to read more about each of the group's individual activities elsewhere in this annual report.

Astrobiotechnology

Astronomy

Early Earth

Europa

Evogenomics

Impacts

The Astrobiological Exploration of Titan Focus Group

Virus

Focus Groups: Astrobiotechnology

Chairs: ***Bruce Jakosky*** **,** ***Andrew Steele*** **,** ***Greg Bearman***

Project Progress

EXECUTIVE SUMMARY

Focus Group on Astrobiotechnology

The NAI formally chartered an Astrobiotechnology Focus Group, in order to provide oversight in this area, to enhance interactions and communications between science and technology, and to encourage new technologies to become integrated into the astrobiology science and missions. The initial efforts will emphasize the incorporation of terrestrial biotechnology into in situ astrobiology science and instrumentation, but the long–term emphasis is on all aspects of astrobiology; this includes telescopic analysis, remote–sensing from spacecraft, in situ analysis on planetary surfaces, and sample–return missions. Detailed planning is being carried out for a first workshop, dealing with Mars astrobiotechnology, to take place in September 2004.

FOCUS GROUP DESCRIPTION & ACTIVITIES

The Astrobiotechnology Focus Group (ABTF) of the NAI was formally chartered this year. Its goals are to provide oversight in the area of technology, to enhance interactions and communications between science and technology, and to encourage new technologies to become integrated into the astrobiology science and missions. The three co–leaders of the group (Greg Bearman at Jet Propulsion Laboratory (JPL), Bruce Jakosky at University of Colorado, and Andrew Steele at Carnegie Institution of Washington) have begun a broad effort to involve science participation from across the NAI and technology participation from the aerospace corporations that are involved in astrobiology–related activities and from biotechnology companies. Nearly 100 people from the biotechnology companies have been added to our mailing list, and a web site has been created to keep them informed.

The first major activity of the ABTF is to sponsor and organize a workshop on Mars Astrobiotechnology. The goal is to bring together scientists and technologists in order to promote the development of the next generation of in situ instruments for Mars missions. Without an effort such as this, the community will find itself in the position of having missions scheduled to fly but not having instruments ready that can address the science goals. The

workshop is scheduled for 8–10 September 2004, in Washington DC , is open to participation by anybody who is involved in relevant activities, and will include participation from the appropriate personnel at NASA Headquarters.

Follow–on activities will involve a workshop on “how to build a flight instrument,” aimed at biotech industry partners and at astrobiologists who are new to the NASA programs.

Highlights

- The NAI has formally chartered an Astrobiotechnology Focus Group. This group fills a tremendous gap that existed in planning development for future spacecraft missions.
- A major workshop on Mars Astrobiotechnology is being planned for 8–10 September 2004.

Roadmap Objectives

- ***Objective No. 1.2:*** Indirect and direct astronomical observations of extrasolar habitable planets
- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Focus Groups: Astronomy

Chairs:	***Sara Seager , Jonathan Lunine***

Project Progress

The Astronomy Focus Group aims to ensure that there is a strong astronomical component to astrobiology, and also that there is a strong astrobiology component to astronomy. The Astronomy Focus Group became an official NAI focus group in September, 2003. Sara Seager (Carnegie Institution of Washington) serves as chair, and the focus group currently has approximately 60 members from 20 NAI and non–NAI institutions.

The major activity during 2003–2004 was completion of “Astrobiology and JWST,” a report to NASA. In this report the focus group addressed the question of how to maximize the astrobiology science return from NASA's James Webb Space Telescope (JWST) by the addition or optimization of current capabilities. JWST is an optical–infrared telescope with a 6.5–m mirror now under development for launch in 2011. The Astronomy Focus Group made several specific recommendations, including: implementation of moving target software (to measure the deuterium–to–hydrogen ratio in Solar System comets); inclusion of a capability to observe bright stars with high cadence (to study transiting extrasolar planet atmospheres); and incorporation of a set of filters for the near–infrared camera, which also hosts a coronagraph (to study protoplanetary disk chemistry). Meeting these recommendations is critical if the mission is to serve the interests of astrobiology, because JWST was initially designed for cosmology ¾ observing very faint, distant galaxies. The report was co–chaired by Seager and Jonathan Lunine (University of Arizona), and participants included those from a number of different NAI teams as well as non–NAI members.

Plans of the Astronomy Focus Group for the near future include two workshops similar to the one that spawned the Astrobiology and JWST report: one on astrobiology and the Atacama Large Millimeter Array (ALMA) and one on astrobiology and a 20– to 30–m ground–based optical telescope. The Astronomy Focus Group plans three additional workshops on processing material through disks to planets, astronomy biomarkers, and a definition of astronomy–related astrobiology.

Focus Groups: Early Earth

Chairs:	***Ariel Anbar , Roger Buick , Stephen Mojzsis***

Project Progress

EXECUTIVE SUMMARY: MISSION TO EARLY EARTH FOCUS GROUP

The search for life beyond Earth requires understanding the conditions under which life originates and evolves, the factors influencing the emergence of complex life, and the ability to interpret the “fingerprints” left by primitive biospheres on the geologic record or in the atmospheres of extrasolar planets. Such understanding must be informed by examination of the history of the only planet on which life is known to exist—the Earth. Hence, study of life and the environment on the early Earth is a critical aspect of astrobiology research.

The aim of the Early Earth Focus Group is to facilitate collaborative activities centered on this topic that bring together researchers from multiple NAI teams as well as researchers from outside the NAI (including researchers based outside the U.S.). To this end, the group currently includes approximately 120 researchers (roster submitted in previous years' reports). These individuals all actively requested membership in the group.

The primary activity of the group over the past four years has been to develop the case for organized stratigraphic drilling of ancient sedimentary intervals of unique astrobiological interest—a “mission to early Earth.” To this end, the group sponsored a series of meetings and a field expedition, and ultimately proposed a “Deep Time Drilling Project” to begin with a set of three pilot drill cores in the Archean stratigraphy of Western Australia . These activities helped spur the creation of the NAI's Astrobiology Drilling Program (ADP) in Fall, 2003.

Major ongoing activities coordinated by the focus group include:

• Advising the NAI Director and the ADP Steering Committee in the development of guidelines for the acquisition, curation, and distribution of samples acquired under the auspices of the ADP.

• Planning the recovery of cores from Western Australia in Summer, 2004, with support from the NAI under the aegis of the ADP.

• Leveraging NAI support by seeking funds from other agencies. Most notably, the investigators leading the Western Australia project prepared a successful

$500,000 proposal to the Geology & Paleontology program at the National Science Foundation (NSF) to support research on the km−long Hamersley Basin drill core that will be recovered in Summer, 2004.

With the creation of the ADP, the “operational” aspects of the focus group are being relocated to an administrative committee (the Astrobiology Steering Committee) overseen by the NAI Director. This is an appropriate evolution, the net result of which will be that the future activities of the focus group will center on advisory/outreach functions rather than “mission planning”. Consequently, it was proposed that the name of the group change from “ Mission to Early Earth Focus Group” to “Early Earth Focus Group.” The future activities of this refocused focus group remain to be developed.

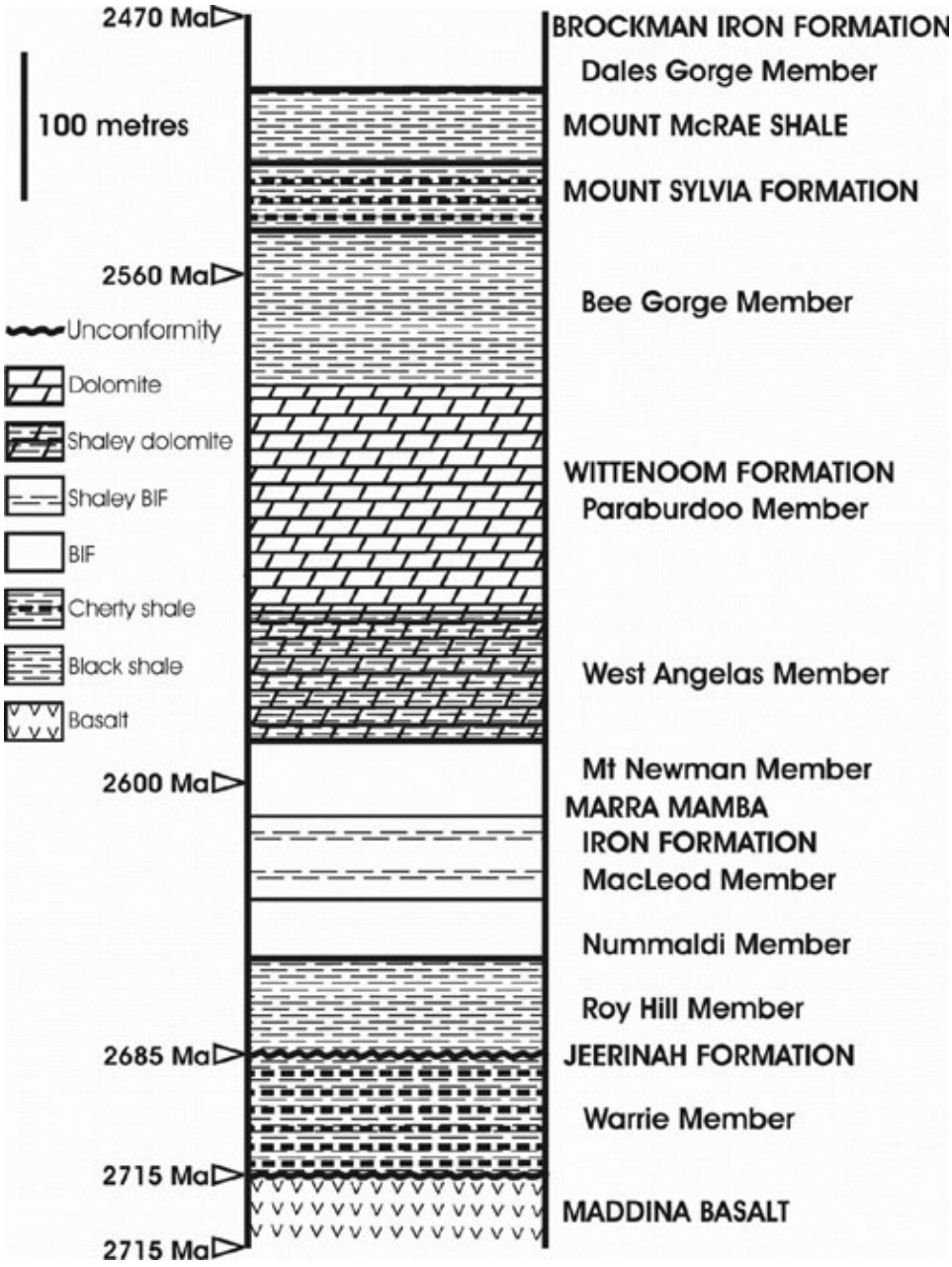
FOCUS GROUP DESCRIPTION & ACTIVITIES

Year 6 activities were dominated by preparation for the Summer, 2004, drilling activities of the Deep Time Drilling Project that emerged from the Focus Group. This project is described in considerable detail in the Year 5 report, and so will not be repeated here. The primary activities involved budgeting and fund raising.

In late 2003/early 2004, a detailed proposal for funding recovery of three drill cores was prepared by Roger Buick, submitted to and approved by the NAI. The total amount requested and allocated was $275,000. A collaborative model was developed in which the Deep Time Drilling Project would work jointly on some of these cores with the Archean Biosphere Drilling Project led by Munetomo Nedachi and Hiroshi Ohmoto.

In early 2004, a related proposal was submitted to the NSF. This proposal sought $500,000 toward initial research on the planned km−long Hamersley−Fortescue drill core, emphasizing characterization of biology and environment in the late Archean. Principal Investigators (PIs) on this proposal were Ariel Anbar, Roger Buick, Alan Jay Kaufman, Andrew Knoll, Timothy Lyons, and Roger Summons. This proposal was recommended for funding in August, 2004, shortly after drilling commenced.

These activities constitute an unusual and successful collaboration between NASA and NSF, and between different drilling teams.



Stratigraphy to be sampled by the 1 km drill core of the Deep Time Drilling Project. These pristine sediments sample the last ~ 250 million years before the rise of oxygen– the last days of the Archean biosphere.

Highlights

- Sampling of early biosphere begins

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

- ***Objective No. 5.2:*** Co−evolution of microbial communities
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 7.1:*** Biosignatures to be sought in Solar System materials

Field Expeditions

Field Trip Name: Deep Time Drilling Project	
Start Date: June, 2004	***End Date:*** August, 2004
Continent: Australia	***Country:*** Australia
State/Province: Western Australia	***Nearest City/Town:*** Marble Bar
Latitude:	***Longitude:***
Name of site(cave, mine, e.g.):	***Keywords:***
Description of Work: Drilling of three drill cores of the Deep Time Drilling Project	
Members Involved:	

Focus Groups: Europa

Chair:	***Ronald Greeley***

Project Progress

Overview

The Europa Focus group (EFG) was formed in 2001 in recognition that Europa, a moon of Jupiter, is a high priority object for astrobiological exploration. The goals of the EFG were to foster research dealing with Europa and to encourage the formation of collaborations among planetary scientists, sea–ice experts, chemists, and biologists familiar with ice–rich environments.

The general approach to meet the goals of the EFG was to hold a series of workshops, each of which was organized into two parts: Part 1, consisting of presentations in which participants would share the results of their research, and Part 2, consisting of topical discussions on issues (such as future missions) from which a consensus might be derived. The EFG was the first Astrobiology Focus Group that was open to the entire community; workshops were widely advertised for participation and registration fees were kept to a minimum; the only requirement was that participants had to submit an abstract outlining their relevant work. The formal presentations by each participant were short (5–10 minutes) and organized in alphabetical order by presenter, rather than by sub–topic. This helped to ensure that participants would remain to hear all of the presentations, and to encourage "off–line" interdisciplinary interactions.

Results

Three workshops and one field conference were held by the EFG. The first (kick–off) workshop was held at NASA–Ames Research Center 1–2 February 2001. In addition to participant presentations, the general goals and approach of the EFG were discussed and ideas solicited for future meetings. The second and third workshops were held at the U. S. Geological Survey field center in Flagstaff, Arizona in September 2001 and May 2002, respectively. Discussions included issues such as future missions to Europa and potential landing sites appropriate for astrobiological exploration. The fourth workshop was held as a field conference in Barrow, Alaska, to provide the participants with the opportunity to visit sea–ice first–hand under the guidance of terrestrial ice experts. The workshop was held at an Arctic research center to take advantage of local logistics, including the use of housing and snowmobiles for excursions

onto the sea ice.

Abstracts of work by each participant from the workshops are posted on the Astrobiology website at http://astrobiology.asu.edu/focus/europa/discuss/discuss.html.

In the latter stages of the EFG, participants played an increasing important role in NASA "programmatics," first by serving on the National Research Council (NRC) committee chartered with the responsibility of formulating the scientific goals for future solar system exploration and, second, by serving on the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO) project. The "flagship" mission recommended by the NRC group was a project to Europa. The JIMO project was NASA's response to the NRC recommendation, and consists of a substantially more capable mission than originally envisioned. In both the NRC and JIMO committee discussions, the results of the EFG played an important role. For example, one of the key recommendations of the JIMO SDT is the inclusion of a landed package on Europa. The rationale for such a landed package was derived directly from EFG discussions and recommendations.

The Future

With the current restructuring at NASA and the formation of the exploration theme focusing on the Moon and Mars, the future of outer solar system programs remains uncertain. The JIMO project remains, but the current separation of science from engineering may cloud the prospects for near–term science returns. This situation means that the planetary science community must remain resolute in ensuring that NASA's exploration program is "science–driven;" to be effective in this approach, the community must speak with a relatively uniform voice in which a consensus is put forward for scientific goals and priorities, including the spacecraft projects and related programs to meet those goals. It is likely that Astrobiology Focus Groups can continue to serve in the role of providing a venue for deriving such a consensus.

Focus Groups: Evogenomics

Chairs:	***S. Blair Hedges , James Lake***

Project Progress

EXECUTIVE SUMMARY

The purpose of the Evolutionary Genomics Focus Group (EvoGenomics) is to coordinate, combine, and enhance research efforts involving evolutionary genomics across the multiple disciplines and institutions represented in the astrobiology community. EvoGenomics is a unique collaboration of astrobiologists combining expertise in molecular evolutionary analysis, organic chemistry and biochemistry, Earth history, and paleontology. The focus group serves as a forum for discussions and collaboration among researchers with similar interests, through workshops, videoconferences, and breakout sessions at annual meetings. New research initiatives and database activities are fostered through focus group activities.

Genomes provide a record of the history of life. Therefore, evolutionary analysis of genomes is fundamental to understanding that history and how life affected the biosphere. This corresponds to Goal 4 of the NASA Astrobiology Roadmap (Earth's early biosphere and its environment). Other relevant goals are Goal 5 (Understand the evolutionary mechanisms and environmental limits of life), Goal 3 (Origins of life), and Goal 7 (Signatures of life).

The current participants of the Evolutionary Genomics Focus Group are Steven A. Benner (University of Florida), Jack D. Farmer (Arizona State University), James R. Garey (University of South Florida), Eric A. Gaucher (University of Florida), J. Peter Gogarten (University of Connecticut), S. Blair Hedges (Penn State University), Christopher H. House (Penn State University), David K. Jacobs (University of California, Los Angeles), Joseph L. Kirschvink (Caltech), Sudhir Kumar (Arizona State University), James A. Lake (University of California, Los Angeles), Charles R. Marshall (Harvard University), Monica Riley (Marine Biological Laboratory), Lynn J. Rothschild (Ames Research Center), Bruce N. Runnegar (University of California, Los Angeles), and Mitchell L. Sogin (Marine Biological Laboratory).

Three workshops and symposia were held during the first three years of the focus group. One workshop took place at the University of California, Los Angeles (9–11 March, 2001), hosted by co–chair Lake, and it focused on discussions of animal origins and the influence of Neoproterozoic snowball

Earth events and relationship with the Cambrian Explosion of animal phyla in the fossil record. A focus group symposium (Special Session) was held at the NAI General Meeting, 10–12 February 2003 at Arizona State University, chaired by Lake and Hedges. Speakers included Herve Philippe (University of Montreal), Beverly Green (Vancouver), Lake, Riley, Janet Siefert (Rice University), James Staley (University of Washington), Blair Hedges, and additional presentations were given by graduate students and postdoctoral fellows (Eric Gaucher, Davide Pisani, Jaime Blair, Maria Rivera, and Cody Nash).

Another Evolutionary Genomics Focus Group "special session" was held at the Gordon Research Conference on the Origin of Life at Bates College, Maine (13–18 July, 2003), chaired by Hedges and Lake. In this case, the 19 speakers were split into two sessions on separate days: “Origin and Evolution of Eukaryotes” (Beverly Green, Peter Gogarten, Herve Philippe, Maria Rivera, Jim Lake, Blair Hedges, Leonid Moroz, Lynn Rothschild, Hyman Hartman) and “Tree of Life and Horizontal Gene Transfer” (Joe Kirschvink, Yuri Wolf, Peter Gogarten, Herve Philippe, Richard Greenblat, Jim Lake, Eugene Koonin, Joshua Rest, Blair Hedges, and Ford Doolittle).

Research by focus group participants, augmented with support from NAI, has led to several discoveries. For example, proteins that existed three billion years ago were "resurrected" in the lab and shown to support a model for the early Earth environment (Gaucher et al., 2003; ***Nature*** 425:285–288), major divergences within fungi were estimated to have occurred deep in the Precambrian (Heckman et al., 2001; ***Science*** 293:1129–1133), and a new mechanism for protein synthesis was proposed that suggests how the current RNA/Protein world may have started from an RNA world (Simonson and Lake, 2002; ***Nature*** 416: 281–285).

The Evolutionary Genomics Focus Group web site (www.evogenomics.org) describes the function of the focus group, participants and contact information, and research undertaken by the participants. Publications of the focus group participants since creation of NAI in 1998 are listed by year, and electronic copies of the papers are linked to the citations. One web page presents links to computational tools. Undergraduate, graduate, and postdoctoral research and educational opportunities are presented on separate pages. Finally, a calendar page lists links to upcoming meetings and events of interest to astrobiologists and participants of the focus group and evolutionary genomics community.

Future workshops will be organized and held over the next three years. The themes of each workshop will be timely and pertain to key issues in evolutionary genomics, with relevance to astrobiology. Examples of some possible themes are: (i) molecular phylogenies and the early history of life, (ii) prokaryote genomes and phylogeny, (iii) molecular evidence for the origin of eukaryotes, (iv) a timescale of Precambrian evolution, (v) evolutionary genomics and the Cambrian explosion, and (vi) horizontal gene transfers in early evolution. Workshop participants will include world leaders in each of the research areas (NAI members and persons not affiliated with NAI). In each case, arrangements will be made with an astrobiology or related journal to publish the proceedings of the workshop.

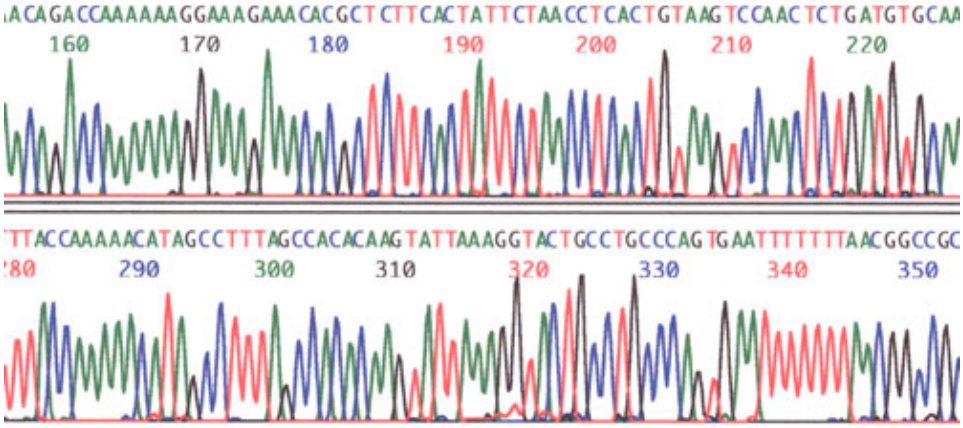
Several members of the focus group are involved with developing and/or curating internet databases of interest to the astrobiology community. The Marine Biological Laboratory (Mitch Sogin, Monica Riley) hosts several public databases, including GenProtEC (http://genprotec.mbl.edu/) which presents functional data for proteins of the eubacterium *E. coli* , and Microscope (http://microscope.mbl.edu/reflections/baypaul/microscope/general/page_01.htm), which contains images, classification schemes, and educational resources pertaining to microbes. The Paleobiology Database (http://www.paleodb.org/) is being developed by a consortium of paleontologists, including focus group member Charles Marshall (Harvard University) and includes collection–based occurrence and taxonomic data for marine and terrestrial animals and plants. Sudhir Kumar (Arizona State University) and Blair Hedges (Penn State University) are developing (with support from the National Science Foundation (NSF)) a database of molecular and fossil times of divergence, to be released later this year. Focus group members will continue development of databases of interest to the astrobiological community.

FOCUS GROUP DESCRIPTION & ACTIVITIES

The activities of the Evolutionary Genomics Focus Group during this past year began with a workshop ("special session") at the Gordon Research Conference on the Origin of Life at Bates College, Maine (13–18 July, 2003), chaired by Lake and Hedges. It was supported by workshop travel funds provided by NAI. In this workshop, 19 speakers were split into two sessions on separate days: "Origin and Evolution of Eukaryotes" (Beverly Green, Peter Gogarten, Herve Philippe, Maria Rivera, Jim Lake, Blair Hedges, Leonid Moroz, Lynn Rothschild, Hyman Hartman) and “Tree of Life and Horizontal Gene Transfer” (Joe Kirschvink, Yuri Wolf, Peter Gogarten, Herve Philippe, Richard Greenblat, Jim Lake, Eugene Koonin, Joshua Rest, Blair Hedges, and Ford Doolittle). The importance of horizontal gene transfer in the early history of prokaryotes and eukaryotes provided a focal point of debate for both sessions.

Early in 2004, the focus group co–chairs submitted a proposal to NAI for renewal of the focus group, for an additional three years. The proposal was circulated among the NAI Executive Council and a presentation was made in–person to that group during the Astrobiology Science Conference held at Ames Research Center in March, 2004. The NAI Executive Council approved the proposal later that day and the co–chairs received final approval from the director of NAI.

The co–chairs have since discussed plans for future workshops. One workshop on molecular clocks has tentatively been set for May, 2006, at Arizona State University. It will be held in conjunction with the annual meeting of the Society for Molecular Biology and Evolution, hosted by Evogenomics Focus Group member Sudhir Kumar.



DNA sequence from a portion of a gene, as detected by a genetic analyzer, where the four colors represent the four constituent bases: adenine, cytosine, guanine, and thymine.

Highlights

- Focus group workshop at Origin–of–Life meeting: The Evolutionary Genomics Focus Group held a workshop at the Gordon Research Conference on the Origin of Life in July, 2003. The importance of horizontal gene transfer in the early history of prokaryotes and eukaryotes provided a focal point for debate.

Roadmap Objectives

- ***Objective No. 4.1:*** Earth's early biosphere
- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

*Mission Class**	*Mission Name (for class 1 or 2) OR Concept (for class 3)*	*Type of Involvement***
2	TPF	Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa,

biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

The work in this focus group provides background information for all NASA missions searching for life elsewhere. A better understanding of the early history of life on Earth, and evolution of the atmosphere (tied in many ways to the origin and evolution of microbes and other organisms), provides general biosignatures for life, as will be needed in interpretation of data from TPF (for example).

Focus Groups: Impacts

Chairs:	***Frank Kyte , Peter Ward***

Project Progress

EXECUTIVE SUMMARY

The Impact Focus Group attempts to explore the relationship of large–body bolide impacts and the history of mass extinctions on Earth. We know that one of the largest mass extinctions of the past 500 million years (Ma) was caused by impact (the so–called Cretaceous/Tertriary, or K/T mass extinction at 65 Ma; e.g., Alvarez et al., 1980). What of the many other mass extinctions?

Mass extinction events (MEEs) significantly affect the evolutionary history of Earth's biota in two competing ways. In each of the major events of the Phanerozoic, biotic diversity was substantially reduced for several–million–year intervals following the MEE. Yet these same extinctions and diversity depressions were followed by rapid periods of diversification that, in each case, resulted in a higher global biodiversity than was present prior to the mass extinction, composed of different assemblages of organisms. The mass extinctions seem linked to diversity enhancement as well as the formation of biotic novelty. This seems to occur through the elimination of incumbent taxa, and the opening of ecological niches. Mass extinctions are thus both instigators as well as foils to evolution and innovation (e.g., Sepkoski, 1993). Clearly, impacts and MMEs play an important role in the path of biotic evolution, and are thus relevant to astrobiology.

The Impact Focus Group has concentrated on researching the two greatest terrestrial MMEs that directly preceded the K/T event — the Triassic/Jurassic mass extinction at 200 Ma and the greatest of all MMEs, the Permain/Triassic mass extinction at 251 Ma. Our work has concentrated on the analysis of rock samples collected from outcrops that record these MMEs. Focus Group co–Chairs Peter Ward (University of Washington (UW)) and Frank Kyte (University of California, Los Angeles (UCLA)) have initiated studies of samples from a number of Triassic–Jurassic (T/J) and Permian–Triassic (P/T) localities to examine whether there is evidence of bolide impact coincident with these MMEs. This work has involved several members and affiliates of the UW and UCLA NAI teams who are analyzing the trace element, noble gas, and carbon–isotopic compositions of key rock sequences.

An important new initiative has been the organization of a group of researchers for a planned consortium study of the P/T boundary at Meishan, China . This has developed as result of an earlier workshop. In February 2002, NAI partially supported a small workshop at UCLA called the Rubey Colloquium (http://www.ess.ucla.edu/rubey/index.html). The title of this meeting was “Impacts and the Origin, Evolution, and Extinction of Life,” and the proceedings of this colloquium were published in the journal Astrobiology (Kyte, 2003). One of the most discussed topics at this workshop was the work of Becker et al. (2001; Science 291, p. 1530) who reported discovery of fullerenes and extraterrestrial noble gases in P/T boundary sediments from Meishan, China, and Sasayama, Japan. This paper was followed by technical comments by Farley and Mukhopadhyay (2001; Science 293, 2343a) and Isozaki (2001), with a reply by Becker and Poreda (2001). At our colloquium there was considerable discussion about this problem and the need to have these results replicated by other laboratories. There have been new developments in the P/T boundary debate since then (e.g., Basu et al., 2003; Science 302, 1388), but the presence or absence of an extraterrestrial signature in the P/T boundary in China remains an important problem. Meishan is the type section and possibly the best−preserved marine P/T boundary. It's fair to say that there are still many skeptics as to whether there is an extraterrestrial signature in Meishan rocks. This will probably remain the case until the results of Becker et al., (2001), can be reproduced by other labs. The main purpose of this consortium is to organize a group of interested scientists to make a good faith effort to try and collect the best set of samples possible from Meishan, and to try to reach a conclusion as to what are the chemical and mineralogical characteristics of the Meishan boundary section.

We are currently organizing a sample collection party, which will be supported by NAI and the Impact Focus Group to collect samples. Jin Yugan of the Nanjing Institute of Paleontology has headed an intensive effort to obtain large quantities of very fresh samples from the quarry at Meishan. This has been accomplished by obtaining a drill core across the boundary and by creating fresh quarry faces from which very fresh samples can be collected. These samples are being curated by Jin in Nanjing . Our main contacts with Professor Jin are Doug Erwin (Smithsonian) and Sam Bowring (Massachusetts Institute of Technology (MIT)). We currently plan a sample collection party in Fall 2004 including Kyte, Erwin, and Bowring to collect samples, with Ward and Becker (University of California, Santa Barbara) to act as observers and advisors to the sample collection. Rock samples will be prepared at the Smithsonian by Kyte, Erwin, and Bowring for distribution to several labs for analysis. To date, we have commitment from at least 12 research labs to examine various characteristics of the chemical, isotopic, paleontological, and mineralogical composition of these samples.

We hope that this consortium study will play an important role in determining whether a large−body impact, or other extraterrestrial event played an important role in the P/T boundary MEE. If this consortium effort is successful, it could set a standard for interlaboratory analysis of key samples of important events in the history of life.

References :

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Farley, K. A., Mukhopadhyay, S., Isozaki, Y., Becker, L., and Poreda, R. J. (2001). An Extraterrestrial Impact at the Permian–Triassic Boundary? Science 293: 2343a

Impacts and the Origin, Evolution, and Extinction of Life (2003). F.T. Kyte, guest editor, Proceedings of the 10th Rubey Colloquium, Astrobiology , 3(1): 215 pp.

Sepkoski, J.J. (1993). 10 Years in the Library – New Data Confirm Paleontological Patterns. Paleobiology 19(1):43–51.

FOCUS GROUP DESCRIPTION & ACTIVITIES

Analyses are in progress to examine the trace element, noble gas, and carbon–isotopic compositions of key rock sequences from selected P/T and T/J boundaries sections. We have also made significant progress in organizing a consortium group of at least 12 research labs to analyze P/T boundary rocks that will be collected from Meishan, China, in Fall 2004.

Roadmap Objectives

- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere

Focus Groups: The Astrobiological Exploration of Titan Focus Group

Chair:	***Jonathan Lunine***

Project Progress

Executive Summary

Since the discovery of a methane atmosphere around Titan by Gerard Kuiper in 1944, Titan has been a world that has attracted much exobiological interest. Titan provides us with a planet−sized laboratory for testing the synthesis of organic compounds in a nearly neutral redox environment, over large spatial scales, both with and without liquid water. These natural chemical experiments could be ongoing today, and the products of such experiments in localized regions of elevated temperatures would be well preserved under the ambient 95 K temperatures and high atmospheric densities that shield the surface from destructive radiation.

The Cassini−Huygens mission arrived at Saturn June 30, 2004 , and made a first set of distant observations of Titan (figure 1) before its planned inventory of the surface from a variety of remote sensing and in situ techniques, over the time period late 2004 through late 2008. The Huygens atmospheric probe will descend to the surface in January 2005. Before and after that the Orbiter will undertake some 45 close flybys of Titan. The result of the Cassini−Huygens mission will be a level of understanding of the geology, geodesy, atmospheric physics and surface−atmosphere interactions on Titan rivaling that for Mars after Mars Global Surveyor (MGS) (with the exception of a lack of a detailed global altimetric map of the body). Further, Cassini−Huygens will provide us with information regarding the distribution and nature of organics spread across the Titan surface. Should there be surface compositional variations in the organics, especially correlated with apparent geologic activity or crustal melting, the interest in returning to Titan to sample those interesting places directly, for signs of oxygen−bearing organics like amino or carboxylic acids for example, will be high.

Indeed, NASA has already expressed interest in initial planning for a post−Cassini mission to Titan, and it appears likely that such a mission will be high on the list of astrobiologically interesting programs in the planetary decadal strategy now being prepared. In March 2004 NASA selected two future Titan missions for study, one of which is led by the Titan Focus Group (TFG) Chair and is an organics analysis package for Titan's surface. A highlight of this effort will be a Jet Propulsion Laboratory (JPL) Team−X study of the mission, in

2005, in which the TFG will participate.

The Titan Focus Group is open to all interested parties, but all individuals who desire to participate are asked to identify themselves, their institution, and to commit to a certain amount of time and activity. Hence casual chat room browsers are discouraged. Most of the work of the group is by e–mail, but two or three meetings of the focus group are organized around convenient ancillary meetings (such as the NAI annual meeting).

Focus Group Description & Activities

The TFG met at NASA Ames this year after the AbSciCon 2004. A summary of the meeting is appended. It was decided to attempt the construction of a website for laboratory photochemical data to be used in analyzing Cassini data beginning late this year. Dr. Robert Minard of Penn State has agreed to begin this process

Highlights

- Cassini reached Saturn orbit on June 30, 2004.
- NASA initiated two future Titan studies, one of which involves individuals from the Focus Group as PIs and collaborators.

Roadmap Objectives

- ***Objective No. 1.1:*** Models of formation and evolution of habitable planets
- ***Objective No. 2.2:*** Outer Solar System exploration
- ***Objective No. 3.1:*** Sources of prebiotic materials and catalysts
- ***Objective No. 3.2:*** Origins and evolution of functional biomolecules
- ***Objective No. 7.2:*** Biosignatures to be sought in nearby planetary systems

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
1	Cassini–Huygens	Science Team Member
3	Titam Organics Explorer	Project Investigator

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)

3. Long−lead future mission / societal issues (e.g., far−future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co−I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Cassini−Huygens will provide the data foundational to planning future missions to look for organic molecules on Titan's surface.

Titan Organics Explorer is a Visions mission proposal funded by NASA to study how to deliver advanced organics analysis packages to the surface of Titan

Focus Groups: Virus

Chairs:	***Kenneth Stedman , Baruch Blumberg***

Project Progress

I. ***Brief background and proposed future activities:***

1. ***Background*** : The purpose of the NAI Virus Focus Group, founded in September 2002, is to study the role of viruses in astrobiology. It addresses the question of how these infectious agents, that are extremely widely distributed and abundant on and in contemporary Earth, were involved in the origin and early periods of life on Earth and elsewhere.
2. A workshop/field trip is planned to take place from June 22 nd to 24 th at Mono Lake and the Long Valley Caldera in the Mammoth Lake region in eastern CA. A full report will be submitted in our next annual report. It will be a collaborative research project including Focus Group members (and others) who require material collected on the field trip for their research. We will also invite prominent virologists and microbiologists not currently directly involved in astrobiology to take part in the project in order to introduce them to the excitement of the program. Participants will have different observational and experimental methods and different hypotheses to test. Since many of the observations will be made on specimens collected in the same place, and on some of the same specimens it will be possible for those who wish to do so to combine their data for more complex meta–analyses. The collected samples will be archived for future use.
3. An informal meeting will be held at the American Society for Virology annual meeting in Montreal , Canada (August 2004).

II. Focus Group Activities

1. A Focus Group meeting and Workshop was held at Portland State University . In Portland , OR, October 16–17, 2003 (see below).
2. A second Focus Group Meeting was held at the Astrobiology Science Conference at NASA Ames Research Center (April 2004).
3. A highly successful symposium on viruses and astrobiology organized by members of the Virus Focus Group and others was on the program of the Third Astrobiology Science Conference (March 28 th – April 1 st , 2004). The program for this symposium is attached.

4. We propose publishing the proceedings of the Virus Focus Group Workshop held in Portland, OR, October 16–17, 2003 (see below), and the field trip/workshop at Mammoth Lakes in June, 2003, in the Journal "Astrobiology". The Editor, Dr. Cady, has welcomed the submission of these papers. We expect to submit these by September 1, 2004 , at the latest. Drafts of four reports have already been received.

III. ***Relevance to the Astrobiology Roadmap*** listed in the order given in the Astrobiology Roadmap brochure.

1. ***Objective 2.1 Mars exploration.*** If signatures of the presence of virus can be determined it would be appropriate to search for these on Mars, or in returned material from Mars. Virus fossils have not been reported, but if they can be identified they would also be the subject for searches. Members of the focus group are investigating virus mineralization in the laboratory as evidence for the potential existence of these fossils.
2. ***Objective 4.1 Earth's early biosphere.*** Investigations similar to those described for Mars would be appropriate.
3. ***Objective 4.2 Foundations of complex life.*** Viruses may have appeared on Earth soon after the development of cells, or conceivably before the event if earlier forms of viruses could exist independent of cells. Evidence was presented at the recent workshop for virus types that may have pre–dated the split of the Eukarya, Archaea, and Bacteria lineages.
4. ***Objective 4.3 Effects of extraterrestrial events upon the biosphere.*** The effect of impacts on microorganisms, including viruses, is a major theme for this objective. Virus persistence and stability are being tested by focus group members.
5. ***Objective 5.1 Environment–dependent, molecular evolution in microorganisms.*** Viruses would be included in the microorganisms studied, including bacteriophage, i.e., viruses of microorganisms. One research group in the focus group has this as the main focus of their research.
6. ***Objective 5.2 Coevolution of microbial communities.*** The role of viruses in microbial mats in different environments, particularly in lateral gene transfer.
7. ***Objective 5.3 Biochemical adaptation to extreme environments.*** The study of viruses from extreme environments under extreme conditions and, in particular, their ability to survive for very long periods of time, is the focus of two research groups in the virus focus group.
8. ***Objective 6.1 Environmental changes and the cycling of elements by the biota, communities, and ecosystems.*** Viruses will be included among the life forms to be studied under these conditions of change. (See Objective 5.1).
9. ***Objective 6.2 Adaptation and evolution of life beyond Earth.*** Viruses are important life and life–accompanying forms that should be studied beyond their planet of origin. The effect of the space environment on acute and chronic viral infection of humans and other animals and plants is an important part of the humans in space program.

IV. ***Relevance to space missions and astrobiology technology development.*** Decisions on future space missions will depend on future development of the field of viral astrobiology. This includes missions to Mars, Europa, and the other moons of Jupiter. The study of viruses in the International Space Station (ISS) and on free flyers and the exposure of viruses to the space environment are additional programs. Technology will be required for the robotic collection of viral specimens in extreme environments on Earth, under the sea, and on other planets and moons. Technology for the *in situ* detection and identification of viruses will be required. This will also have significant medical applications. The study of viruses of extremophiles in animal and plant pathology will require new technology.

V. ***Why continuation of the Virus Focus Group would be valuable.*** The field of viral astrobiology is in its infancy. Very little is known about the epidemiology of viruses in extreme environments, nor about their molecular biology, replication strategies, gene expression, and other characteristics. There have been few investigations of viruses in the space environment and their possible role in pathology in spacefarers. We have outlined above how virus studies fit within the Roadmap objectives; very few studies in this area have been accomplished. We envision the Virus Focus Group as a mechanism to focus attention on these issues and to conduct field trips and collaborative studies. In the future we intend to apply for research grants from the National Institutes of Health (NIH) and other agencies to fund virus research stimulated by the astrobiology endeavor.

VI. ***Final Report for the first year.*** The major activity for the first year has been a Virus Focus Group Workshop. The results are summarized below:

Report on the
NASA ASTROBIOLOGY INSTITUTE VIRUS FOCUS GROUP WORKSHOP
The Simon Benson House, Portland State University , Portland OR
October 16–17, 2003

Ken Stedman, and Baruch Blumberg convened the first meeting of the NASA Astrobiology Institute (NAI) Virus Focus Group at Portland State University , October 16–17, 2003 . An additional organizer of the meeting was David Smith, of the NAI Team at the University of Rhode Island , who was unable to attend.

Ken Stedman welcomed the participants. The program of the meeting, a list of the attendees, and a list of the members of the Focus Group is appended. ***Baruch Blumberg*** described the origin of the NAI Focus Groups; they were initiated at a meeting of the NAI Executive Council at NASA Ames Research Center on 12.18.99. The nature of the NAI Focus Groups were not defined at that time with the expectation that each Focus Group would determine its own character. The NAI Virus Focus Group was approved on 09.09.02 at the Executive Council meeting at Pennsylvania State University .

There are several interesting questions related to viruses and astrobiology. Were viruses an early form of life on Earth? Could they have preceded the origin of cells and survived, flourished and replicated cell–free in an earlier form? Did viruses exist on early Mars, or elsewhere away from Earth? If so,

how could their presence be detected? Is it possible to identify fossil viruses in the paleontological record on Earth or other places? Are there geological and/or geochemical signatures of viruses (that can exist in vast quantities in even the most hostile of environments) that could be detected with appropriate instruments? Viruses live in cells and many integrate into the genome of their hosts. These could be transmitted to subsequent generation in a manner similar to a mutation. Can viruses act as important agents of evolution? If so, is this an ongoing program? If an RNA world preceded the DNA world, were viruses involved in this development?

A particularly interesting question relates to the survivability of viruses in the space environment, a matter of interest to astrobiology and fundamental space biology. Can viruses and their host cells and organism survive in some form in the space environment and, in particular, in the interior of objects such as meteorites. What is the effect of the space environment on space farers chronically infected with a virus? Will viruses that are normally not pathogenic become so after long periods of time in space? These are issues of basic scientific interest that relate to the problems of human space flight.

There has been a major interest in astrobiology on the study of extremophiles, lifeforms that could have arisen and prevailed under the demanding conditions of early earth and other objects in the cosmos. The viruses of microorganisms – phages – often provide genes that are important to the life cycle of their bacterial hosts. For example, a phage is responsible for the toxins of the cholera vibrio. How common are phages in extremophiles and what are their distribution, diversity and other characteristics? Research on this topic was a major part of the Focus Group workshop.

Many of these questions were considered in the workshop, either directly or indirectly, and the details of the presented papers will be given in the final report. (***Sherry Cady*** the editor of the journal “Astrobiology,” who attended the workshop and is a member of the Virus Focus Group and the NASA–Ames NAI, has agreed to consider the final report for publication.) A brief summary of the presentations will be given here including information on field sites used by the investigators. (See attached program.)

Luis Ruedas discussed the ecology and medical virology of the Hantaan viruses and the effects on pathogenesis of the interaction of the host, the virus, and the environment. There are very different clinical manifestations depending on the local ecology. In some environments and geographic locations the disease can be severe and in others there are little or no clinical disadvantages. Host polymorphic susceptibility genes influence many chronic infections; beneficial effects to the host might be expected in some circumstances. Ruedas and his colleagues examined the possible beneficial effects of long–term infection with the virus on maximal aerobic capacity in infected experimental mice and longevity in their natural environment. They also determined that infection rates for Hanta viruses in humans were decreased in ecologies where there is greater diversity in the putative mammalian definitive hosts (i.e., mice and other rodentia). Fieldwork for this project included the Four Corners region of the southwest USA , the location for recent epidemic of Hantaan Virus infection, and other sites, including

Panama and greenspaces in Portland , OR .

Paul Turner studies the dynamics of evolution in bacteria, viruses and other microorganisms. He is now directing his attention to the role viruses and other gene transfer agents on the dynamics of evolution, particularly the role of genetic reassortment or “sex” in viral fitness. He and his colleagues are utilizing a field site on St. Lucia in the Windward Islands of the Caribbean Sea where there are several geothermal springs located near each other in a volcanic caldera. They provide an opportunity for field observations on differences in evolutionary directions in similar, but not identical, sites under different selective pressures.

Ken Stedman has done intensive studies on the viruses of the extremely thermophilic archaeon *Sulfolobus*. Many species have been isolated and sequenced, and their molecular biology, including means of replication, has been determined. They have unusual, one could even say bizarre, physical morphologies that have not been previously described. Stedman and his colleagues have published (Prangishvili *et al., Trends in Microbiology* , 9,39, 2001) a fascinating observation, echoed in other presentations in this Workshop: “… few ORFs in the genomes of these viruses show any similarity to ORFs encoding proteins in other viruses or organisms.” Stedman's research has produced a major body of data on life forms of particular interest to the Virus Focus Group. Collections of *Sulfolobus* species and their viruses have been made in thermal sites in Japan , Iceland , North America , Kamchatka , and elsewhere. Stedman showed images of the Kamchatka field site, a location with 43 active volcanoes and many extraordinary geothermal locations. He also discussed new results indicating that some virus morphotypes may have predated the Eukarya–Bacteria–Archaea divergance.

Ray Kepner has studied microbial mats in extreme locations with an emphasis on their “physiology” and ecological relations. He described mats that grow on the bottom of Antarctic ice covered lakes. Some rise in pinnacles, detach, float to the underside of the icy covering, migrate through the ice (a process that may take as much as 11 years), and rise to the surface where they dehydrate and blow off in the heavy winds of the region to become part of the surrounding landscape. This is an interesting example of the delivery of carbon–containing material from a marine location to land. There was a discussion of the role of the “quorum” sensing molecules that are important in the medical treatment of biofilms that form on implanted prosthesis such as artificial or exobiotic heart valves. Kepner suggested collaborations with others in the group interested in the identification and characterization of viruses in the material he is collecting.

Forest Rohwer presented a series of studies on the sequencing of viruses, mostly phages, from marine environments in San Diego and La Jolla , CA . He compared these to the sequences obtained from human feces. There is a remarkable diversity in the viral and phage types with striking differences between the two marine locations. He has made estimates of the prevalence of life forms in seawater. There are 10 X 10 6 viruses and phages per milliliter of seawater compared to 1 X 10 6 bacteria and lesser amounts of other forms (for example, algae). The oceans appear to be the biggest pool of biological material on earth with viruses being the most common form. His research

demonstrated that the genomic analysis of uncultured marine viral communities is feasible, pointing toward the possibility of similar studies elsewhere. Other collection sites included geothermal locations in Mammoth and Mono Lakes in eastern CA and the geothermal energy sites at El Centro and Imperial Spa, in southern CA. Twenty percent of the phage genomes did not have any close homologs in the sequence databases, a report similar to that of Stedman's (above).

This observation requires further support. It would be fascinating if phages, and particularly phages of extremophilic Bacteria and Archaea have unique genomic sequences. This could generate the hypothesis that they may have had a separate origin on Earth or that they originated elsewhere. These speculative hypotheses seem unlikely, but would certainly be interesting to test.

Alice Ortmann presented the paper from Curtis Suttle's group at the University of British Columbia , as Azeem Ahmed was unable to attend. Their laboratory has studied the viruses of the algae *Heterosigma akaskiwo* that affects farmed fish. The collections were accomplished from a Canadian Coast Guard vessel in the Straits of Georgia (east of Vancouver Island , BC). Collections were also made in the submarine hydrothermal vent field on Endeavour Ridge , BC . These collections add to the growing database on viruses of extremophiles. They also observe large amounts of diversity in their bacteriophage samples from all samples both spatially and temporally distributed. The group has been one of the leaders in the discovery and analysis of bacteriophage and viruses in marine environments.

Grieg Steward, the University of Hawaii , presented a paper that was not on the original program. He reported on an extensive series of studies of virally infected cells in widespread marine locations. These included, among others, sites in Long Island Sound (NY), in the eastern and western Caribbean , in the Gulf Stream and the Sargasso Sea , Mono Lake , CA , and under the arctic ice. The latter collections were made by Grieg on board a nuclear submarine during an extended undersea and under ice voyage from Groton , CN to Seattle , WA that included a single surfacing at the North Pole. This was part of the SCICEX 97 research program. Some of his studies were multiple collections over time, for example; HOTS, Hawaiian Ocean Time Series, and BAT, Bermuda Atlantic Time series. The extensive data set included information on virus infectivity, mortality, diversity, etc.

CONCLUSIONS AND PLANS FOR FUTURE MEETINGS AND ACTIVITIES.

The study of the viruses of extreme locations is currently, in large part, in a data collecting and inductive phase. That is, the data is being collected on which the hypotheses that will move the field forward will be based. The papers presented, which represent only a fraction of ongoing research, indicate how rich this field is and will become. It is already clear that there are many viruses and phages in extreme environments, that there is great diversity, and that the viruses are very unusual in their appearance and molecular biology. The phages and the microorganisms they infect produce a wide range of unusual proteins and enzymes that will have valuable, if unpredictable, applications in research, medicine, and industry.

The NAI Virus Focus Group has the potential of becoming an active and effective group of scientists who can help develop this important program directed towards understanding the origins, evolution, distribution and future of life on Earth and in the Universe.

NASA Astrobiology Institute Virus Focus Group Workshop: October 16–17, 2003

PROGRAM

The Simon Benson House, Portland State University , Portland Oregon .

Thursday, October 16 th , 2003

Session I. The Origin and Evolution of Viruses

9:00 – 9:15 Welcome and Introductions *Ken Stedman, Portland State University*

Baruch Blumberg, NAI/Fox Chase Cancer Center

9:15 – 9:45 The indissoluble bond: Virus–host interactions in an ecological context:

Luis Ruedas, Portland State University

9:45 – 10:45 Experimental evolution in viruses: *Paul Turner, Yale University*

10:45 –11:15 Break (Visit to PSU Electron Microscopy Facility)

11:15 –12:00 Discussion – *Participants*

12:00–13:30 Lunch

Session II. Viruses in Extreme Terrestrial Environments

13:30 – 14:30 Hot Viruses *Ken Stedman, Portland State University*

14:30 – 15:00 Break (Visit Stedman Lab, Center for Life in Extreme Environments, PSU)

15:00 – 15:30 Lysogenic cyanophage from polar microbial mats: Neglected, selected, injected, infected, inspected and... detected? *Ray Kepner, Marist College*

15:30 –17:00 Discussion – *Participants*

Friday, October 17 th , 2003

Session III. On the Ubiquity of Viruses

9:00 – 10:00 Viral Biodiversity *Forest Rohwer, San Diego State University*

10:00 – 10:30 Break

10:30 – 11:00 Virus Diversity in Marine Environments *Alice Ortmann, U. British Columbia*

11:00 – 11:30 Marine Viral Ecology *Grieg Steward, U. Hawaii*

11:00 – 12:00 Discussion – Participants

12:00 – 13:30 Lunch

Session IV. Future Directions of the NAI Virus Focus Group

13:30 – 15:00 Discussion Leader *Baruch Blumberg* . Potential Agenda Items: Next Meeting? Election/Nomination of Chair(s).

Workshop Participants (with e–mail addresses)

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Astrovirology Session, Abscicon, 2004. March 31 st 2004 .

	Astrovirology – Ken Stedman and Baruch Blumberg, Chairs		
2:00	Roger Hendrix	University of Pittsburgh	Bacteriophage genomics: evolution of the majority

2:30	Stephen S. Morse	Columbia University	The Origins and Evolution of Eukaryotic Viruses: Are Viruses Inevitable?
3:00	Mark J. Young, Kenneth Stedman, Blake Wiedenheft, Jamie Snyder, George Rice, Josh Spuhler, Francisco Roberto, Liang Tang, Trevor Douglas and J. E. Johnson	Montana State University	Viruses from Yellowstone's high temperature acidic environments.
3:15	Kenneth Stedman, Yannick Combet−Blanc, Blake Wiedenheft, Adam Clore, George Rice, Jamie Snyder, Josh Spuhler, Luisa Zoeller, Francisco Roberto, Mark J. Young, Wolfram Zillig	Portland State University	Genetics and Genomics of Fuselloviruses of hyperthermophilic Archaea
3:30	Paul Turner	Yale University	Why is experimental evolution important for astrobiology?
3:45	Baruch Blumberg	Fox Chase Cancer Center	Astrovirology. The NAI Focus Group.

Current members of NAI−Virus Focus Group (e−mail list): NAI members in ***bold*** :

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Roadmap Objectives

- ***Objective No. 2.1:*** Mars exploration
- ***Objective No. 4.1:*** Earth's early biosphere

- ***Objective No. 4.2:*** Foundations of complex life
- ***Objective No. 4.3:*** Effects of extraterrestrial events upon the biosphere
- ***Objective No. 5.1:*** Environment–dependent, molecular evolution in microorganisms
- ***Objective No. 5.2:*** Co–evolution of microbial communities
- ***Objective No. 5.3:*** Biochemical adaptation to extreme environments
- ***Objective No. 6.1:*** Environmental changes and the cycling of elements by the biota, communities, and ecosystems
- ***Objective No. 6.2:*** Adaptation and evolution of live beyond Earth

Mission Involvement

Mission Class*	***Mission Name (for class 1 or 2) OR Concept (for class 3)***	***Type of Involvement*****
3		Background Research

* Mission Class: Select 1 of 3 Mission Class types below to classify your project:
1. Now flying OR Funded & in development (e.g., Mars Odyssey, MER 2003, Kepler)
2. Named mission under study / in development, but not yet funded (e.g., TPF, Mars Lander 2009)
3. Long–lead future mission / societal issues (e.g., far–future Mars or Europa, biomarkers, life definition)

** Type of Involvement = Role / Relationship with Mission
Specify one (or more) of the following: PI, Co–I, Science Team member, planning support, data analysis, background research, instrument/payload development, research or analysis techniques, other (specify).

Decisions on future space missions will depend on future development of the field of viral astrobiology. This includes missions to Mars, Europa, and the other moons of Jupiter. The study of viruses in the ISS and on free flyers and the exposure of viruses to the space environment are additional programs. Technology will be required for the robotic collection of viral specimens in extreme environments on Earth, under the sea, and on other planets and moons. Technology for the in situ detection and identification of viruses will be required. This will also have significant medical applications. The study of viruses of extremophiles in animal and plant pathology will require new technology.

Field Expeditions

Field Trip Name: Mono/Mammoth Workshop	
Start Date: 22 June 2004	***End Date:*** 24 June 2004
Continent: North America	***Country:*** USA
State/Province: California	***Nearest City/Town:*** Mammoth Lakes
Latitude: Multiple	***Longitude:*** Multiple
Name of site(cave, mine, e.g.): Hot Springs	***Keywords:*** Viruses
Description of Work: Water samples were collected for virus and host analysis at high temperature (>70C) locations on Paoha island in Mono lake and hot springs at Hot Creek and Little Hot Creek in the Long valley caldera near Mammoth Lakes.	
Members Involved:	

Intl. Partners: International Partners Introduction

NAI has a partnership program with international astrobiology organizations to provide collaborative opportunities between NAI's researchers and the global science community. Foreign astrobiology organizations can propose to become either Associate (formal agreement between NASA and the foreign government) or Affiliate members (no formal government agreements) of the NAI. During Year 6, there were five international Associate or Affiliates:

- Astrobiology Society of Britain
- Australian Centre for Astrobiology
- Centro de Astrobiologia (CAB)
- European Exo/Astrobiology Network Association, EANA
- Groupement de Recherche en Exobiologie

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Intl. Partners: Astrobiology Society of Britain

Astrobiology Society of Britain
Executive Summary
Director/Leader: Sir Martin Rees

For information about the Astrobiology Society of Britain visit
http://www.astrobiologysociety.org/

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Intl. Partners: Australian Centre for Astrobiology

Australian Centre for Astrobiology
Executive Summary
Director/Leader: Malcolm Walter

For information about the astrobiology research and activities going on at the Australian Centre for Astrobiology visit http://aca.mq.edu.au/

NASA ASTROBIOLOGY INSTITUTE
ANNUAL REPORT YEAR 6
[July 2003 - June 2004]

Intl. Partners: Centro de Astrobiologia (CAB)

Centro de Astrobiologia (CAB)
Executive Summary
Director/Leader: Juan Perez Mercader

For information about the astrobiology research and activities going on at the Centro de Astrobiologia visit http://www.cab.inta.es/index.php

Intl. Partners: European Exo/Astrobiology Network Association, EANA

European Exo/Astrobiology Network Association, EANA
Executive Summary
Director/Leader: André Brack

Introduction

The European Exo/Astrobiology Network Association, EANA, co–ordinates the activities in the field of exo/astrobiology of 17 European nations: Austria, Belgium, Denmark, Finland, France, Germany, Hungary, Italy, Poland, Portugal, Romania, Russia, Spain, Sweden, Switzerland, The Netherlands, the United Kingdom. T he specific objectives of EANA are to b ring together European researchers interested in exo/astrobiology programmes and to foster their cooperation, to attract young scientists to this quickly evolving interdisciplinary field of research, to interface the Network with European bodies such as ESA, ESF, the European Commission and with non European institutions active in the field and to popularise exo/astrobiology to the public and to students.

Recent activities (activities of CAB, GDR Exobio and ASB will be reported separately)

New EANA country members
Early in 2004, EANA welcomed 5 new member countries, i.e. Finland, Hungary, Poland, Romania and Russia, thus raising the number of member countries to 17.

Third European Workshop on Exo/Astrobiology
The Third European Workshop on Exo/Astrobiology was held in Madrid, Spain, 18–20 November 2003, co–organized by EANA and the Centro de Astrobiologia . Attended by 260 participants, the workshop was oriented towards the search for life on Mars. The following themes were covered by 58 oral communications and 129 posters:

- Martian atmosphere and hydrosphere
- Radiation state
- Terrestrial analogues
- Extremophiles as references
- Martian meteorites
- Planetary protection
- The Martian missions

Swedish Astrobiology Network, SWAN
SWAN held two national meetings, in Uppsala on 25 November 2003 and in Lund on 6 May 2004.

Federation of Astrobiology Organizations, FAO
EANA is a member of the Federation of Astrobiology Organizations, FAO, including the Australian Centre for Astrobiology (ACA), the Astrobiology Society of Britain (ASB), the Spanish Centro de Astrobiologia (CAB), the French Groupement de Recherche en Exobiologie (GDR Exobio), the American NASA Astrobiology Institute (NAI), the Red Mexicana de Astrobiología (RMA) and the Swedish Astrobiology Center (SWAN). EANA actively participated in defining the present status of the FAO, i.e. a federation of astrobiology networks, associations, institutes, research groups, and societies broadening the opportunities available to talented students from all countries, supporting activities that develop their academic and research potentials and harmonising the numerous astrobiology meetings.

EU−funded activities collaborating with EANA
COST Action
Within the framework of the European Commission COST Actions to foster cooperation in a specific research area, COST D27 *"Origin of life and early evolution"* was approved in 2001 for a period of 5 years. The main objective of the Action is to develop the chemistry connected with the origin of life and early evolution of life on Earth, with special emphasis on self−replicating systems, prebiotic synthesis of nucleic acids and polypeptides, as well as simple protocells as early models of biological cells. The Proceedings of t he First COST D27 Workshop "Origin of life and early evolution" held in Ravello, Italy, 17−20 October 2002 have been published: Guest Editor Luigi Luisi, Origins Life Evol. Biosphere (2004) Vol. 34, pp.1−275. The next COST D27 meeting will be held in Crete, from September 30 to October 2, 2004.
EU FP6 PACE
The scope of the EU FP6 integrated project "PACE" (Programmable Artificial Cell Evolution) is to create technologies necessary for the implementation of a minimal cell, i.e. a metabolic subsystem, a genetic subsystem and a membrane−forming subsystem. PACE includes a total of 10 partner organisations from all over Europe and three associated partnerships of members from US−organisations. PACE−initiating research activities were recently reported on two international symposia (Cf. S. Rasmussen et al., Science 303, 963−965, 2004).

Future activities and objectives

The Fourth European Exo/Astrobiology Workshop will be hosted by the Open University in Milton Keynes, November 23−25, 2004. The Workshop will be dedicated to ***l*** i fe in extreme environments .

The following objectives will be pursued:

- to interface the Network with European bodies such as ESA, ESF, the European Commission and with non European institutions active in the field

- to promote the Federation of Astrobiology Organizations, FAO
- to popularise Exo/Astrobiology to the public and to students

General publications

- III Euro pean Workshop on Exo/Astrobiology, *Mars: The Search for Life* , Madrid 18–20 november 2003, Eds. R.A. Harris and L. Ouwehand, ESA Special Publication ESA SP–545 (2004).
- Astrobiology: future perspectives (ISSI Workshop April 1–4, 2003, Bern), Eds. P. Ehrenfreund et al., Kluwer Academic Publisher (to appear in July 2004)

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Intl. Partners: Groupement de Recherche en Exobiologie

Groupement de Recherche en Exobiologie
Executive Summary
Director/Leader: Francois Raulin

GDR CNRS 1877, or Groupement de Recherche en Exobiologie, is a national federation of research laboratories in Exo/Astrobiology, created by the National Centre of Scientific Research (CNRS) in 1999 and renewed in 2003. Its main goal is to promote, induce and coordinate the development of Exo/Astrobiology scientific programs in France . It includes about 50 laboratories, and is supported by the CNRS and CNES (the French Space Agency).

4 main research topics are addressed:

- The ingredients of primitive life in their geological, planetological, and interstellar context
- From the chemistry of the origins of life to the emergence of life: structures and functions of biological molecules
- Terrestrial life as a reference: fossils, biomarkers, extreme environments
- Habitats and signatures of extraterrestrial life

• GDR Exobio has a scientific council consisting of 19 scientists from different fields, including astrophysics, planetology, physics, chemistry, earth sciences, life sciences, as well as philosophy and epistemology. The GDR has been affiliated with the NAI since November 2001.

Main recent activities

During the period July 2003–June 2004, the GDR Exobio, within the framework of its main 4 topics, has been active in several directions directly connected to NAI activities. Below are just a few examples of these activities, with the corresponding references given in the Reference List.

Several important results on Titan's organic chemistry have been obtained on the potential presence of oxirane and ammonia on Titan (Bernard et al., 2003; Coll et al., 2003). GDR members have participated in the CIRS–Cassini observation of Jupiter (Flasar et al., 2004). New evidences that POM may be a precursor of formaldehyde in comets has been obtained through laboratory experimental data and modeling (Cottin et al., 2004; Fray et al., 2004). Dual column gas chromatograph system has been developed for in situ analysis of a cometary nucleus (Szopa et al., 2004).

Our efforts were also devoted to investigate one of the most important biological aspects of the origins of life, the RNA world hypothesis. We discovered two co−ribozymes that are new hairpin ribozymes dependent on a prebiotic compound: adenine (Meli et al., 2003). On the other hand, we were able to show by Surface Enhanced Raman Spectroscopy (SERS) the detection of subpicomolar amount of nucleic acid components trapped on mineral surfaces (Elamri et al., 2003). We also studied the adsorption of adenine in meteorite specimens (Elamri et al., 2004a) and the micro−distribution of carbonaceous matter in Murchison meteorite by Raman imaging (Elamri et al., 2004b).

New data have been obtained in the field of biomakers and the search for fossil biofilms (Westall et al., 2003). The same team has organized two scientific meetings in 2004 related to these topics: a workshop in Les Treilles , France , and an EGU session in Nice. In addition, Philippe Labrot, a graduate student of the team, has created a website dealing with Mars and the origin of life at http://www.nirgal.net/.

New effects of the accretion of juvenile micrometeorites on the birth of life on the early Earth have been recently discovered. They focus on very high input rates of micrometeoritic SO_2 and smoke particles in the thermosphere, after the formation of the Moon. SO_2 ended up being temporarily stored as sulfates, which were recycled by hydrothermal sources, thus assisting the functioning of the sulfides and thioesters "worlds" of exobiology. Altogether with CO_2 and H_2O, also injected in the thermosphere by micrometeorites, SO_2 and smoke particles probably played a dominant role in the early greenhouse effect, at a time when the optical thickness of the cloud of smoke particles (about 10) made the early Sun looking like the full Moon (Maurette et al., 2003, 2004 a, b).

Our studies on extremophiles focus on the mechanism of DNA repair, recombination and replication in extreme conditions (high temperature and exposure to high doses of gamma rays). We have isolate new radioresistant hyperthermophiles of the domain Archaea (Jolivet et al., 2003b, 2004), including the most radioresistant hyperthermophiles known, *Thermococcus gammatolerans*. This archaeon is nearly as resistant than *Deinococcus radiodurans*. We have recently completed the sequencing of its whome genome. We also have isolate new enzymes from hyperthermophiles, including the first bipolar helicase (Constantinesco et al., 2004). We are currently searching for viruses from hyperthermophilic environments from different collections of hyperthermophiles, including a new one recently characterized at the molecular level (Lepage et al., 2004). A first virus of anaerobic hyperthermophiles has been isolated (Geslin et al., 2003). Our phylogenetic analyses point to a hyperthermophilic ancestr of archaea and have possibly revealed a novel mechanism that controls the rate of genome evolution (Brochier et al., 2004). They also suggest a very important role of viruses in early cellular evolution (Filée et al., 2003) and probably in the transition between the RNA and the DNA world (Forterre et al., 2004). We have previously shown that DNA was probably invented twice independently in the course of evolution (Myllykallio et al., 2002).

We have analyzed how rings of extrasolar planets may lead to a wrong determination in the planet radius from its thermal emission, and we have shown that the analysis of the planet light curve in reflected light circumvents this source of error.

Exobio'03, the 3rd bi−annual National exo/astrobiology summer school took place in Corsica in September, 2003. As for the 2 previous schools, it was attended by about 80 participants coming from astronomy and geophysics, chemistry and biology. The program of this 7−day school included four main topics: (i) evolution of complex systems, and auto−organization; (ii) time scales in astronomy, geology, chemistry and biology; (iii) impacts and volcanism; and (iv) interstellar chemistry. The second item was also the main topic of a dedicated 3−day workshop organized by M. Gargaud in St−Emilion (a well known vineyard) attended by 15 participants, which should induce a larger reflection on this problem and a joint publication.

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Future Hopes

The GDR wishes to participate in cooperative programs of research, on clearly identified topics, in the framework of its affiliation to NAI. The NAI connection should be a great opportunity to share and exchange researchers, in particular Ph.D. students, to promote joint participation in research programs on Exo/astrobiology, and to use the synergy induced by the different ways of thinking and working of researchers from different origins to promote the wide field of Exo/astrobiology. Targets such as Titan, in relation to Cassini–Huygens, Mars and its international program of exploration, and Europa and Extrasolar planets are already among the topics of high interest likely to be part of such joint research projects. In addition, the need for networking, with new and efficient tools for teleconferencing (including asynchronous communication) remains a technical priority.

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Appendix: Roadmap Objectives

Astrobiology and the roadmap

Astrobiology is the study of the origins, evolution, distribution, and future of life in the universe. It requires fundamental concepts of life and habitable environments that will help us to recognize biospheres that might be quite different from our own. Astrobiology embraces the search for potentially inhabited planets beyond our Solar System, the exploration of Mars and the outer planets, laboratory and field investigations of the origins and early evolution of life, and studies of the potential of life to adapt to future challenges, both on Earth and in space. Interdisciplinary research is needed that combines molecular biology, ecology, planetary science, astronomy, information science, space exploration technologies, and related disciplines. The broad interdisciplinary character of astrobiology compels us to strive for the most comprehensive and inclusive understanding of biological, planetary and cosmic phenomena.

This NASA Astrobiology Roadmap outlines these multiple pathways for research and exploration and indicates how they might be prioritized and coordinated. The roadmap embodies the efforts of more than 200 scientists and technologists, including NASA employees, academic scientists whose research is partially funded by NASA grants, and many members of the broader community who have no formal association with NASA.

Fundamental Questions

Astrobiology addresses three basic questions, which have been asked in some form for generations. Astrobiology is exciting today because we have the technology to begin to answer them.

- How does life begin and evolve?
- Does life exist elsewhere in the universe?
- What is the future of life on Earth and beyond?

Principles

This roadmap emphasizes the following four principles that are fundamental to the operation of the Astrobiology Program:

- Astrobiology is multidisciplinary in its content and interdisciplinary in its execution. Its success depends critically upon the close coordination of

diverse scientific disciplines and programs, including space missions.

- Astrobiology encourages planetary stewardship through an emphasis on protection against forward and back biological contamination and recognition of ethical issues associated with exploration.
- Astrobiology recognizes a broad societal interest in its endeavors, especially in areas such as achieving a deeper understanding of life, searching for extraterrestrial biospheres, assessing the societal implications of discovering other examples of life, and envisioning the future of life on Earth and in space.
- The intrinsic public interest in astrobiology offers a crucial opportunity to educate and inspire the next generation of scientists, technologists and informed citizens; thus a strong emphasis upon education and public outreach is essential.

Roadmap Objectives

Objective No. 1.1:	Models of formation and evolution of habitable planets
Objective No. 1.2:	Indirect and direct astronomical observations of extrasolar habitable planets
Objective No. 2.1:	Mars exploration
Objective No. 2.2:	Outer Solar System exploration
Objective No. 3.1:	Sources of prebiotic materials and catalysts
Objective No. 3.2:	Origins and evolution of functional biomolecules
Objective No. 3.3:	Origins of energy transduction
Objective No. 3.4:	Origins of cellularity and protobiological systems
Objective No. 4.1:	Earth's early biosphere
Objective No. 4.2:	Foundations of complex life
Objective No. 4.3:	Effects of extraterrestrial events upon the biosphere
Objective No. 5.1:	Environment–dependent, molecular evolution in microorganisms
Objective No. 5.2:	Co–evolution of microbial communities
Objective No. 5.3:	Biochemical adaptation to extreme environments
Objective No. 6.1:	Environmental changes and the cycling of elements by the biota, communities, and ecosystems
Objective No. 6.2:	Adaptation and evolution of live beyond Earth
Objective No. 7.1:	Biosignatures to be sought in Solar System materials
Objective No. 7.2:	Biosignatures to be sought in nearby planetary systems