Project Report: Delivery of Organic Materials to Planets

University of Colorado, Boulder
Executive Summary
Principal Investigator: Bruce Jakosky

Astrobiological research encompasses an array of scientific disciplines that is commensurate with the vastness of the range of the subject matter it pursues−from the origin and evolution of genes and the amazing complexity of microbiological systems on Earth to the life−process pertinence of the climatic and environmental characteristics of Mars and Saturn's Titan to the far reaches of other solar systems in the Milky Way.

The University of Colorado Center for Astrobiology is a collaborative effort among faculty, researchers, and students from departments and programs that span the breadth of disciplines that are pertinent to the field. Our approach has been to bring together research activities in the entire range of disciplines in astrobiology in a way that will emphasize the manner in which the various disciplines are interconnected with each other and in which multiple approaches are necessary in order to understand the potential and actual distribution of life in the Universe. Faculty come from the physical sciences, the biological sciences, and the humanities, and interact together through the Center for Astrobiology. Our major efforts involve a tripartite approach to astrobiology, and include cutting−edge research in relevant areas, an interdisciplinary graduate program to train students broadly in astrobiology, and outreach to the broader community.

Research activities

Our activities span the entire range of astrobiology research. Specific tasks funded through our program include the following:

1. Understanding the environments in which stars form and the implications for planet formation, as a way of constraining the types of solar systems that might exist in our galaxy
2. Determining the geological environment on the early Earth and the earliest history of life on Earth as reflected in the geological record
3. Using RNA molecules in modern−day organisms to understand the nature of living organisms, the origin of the genetic code on Earth, and the possible nature of an “RNA world” that preceded the present “DNA world” and in which RNA was the primary molecule for containing and transferring genetic information and catalyzing reproduction

4. Using DNA and RNA molecules in modern organisms to determine the genetic relationships between organisms (i.e., constructing the “Tree of Life”), the nature of organisms that live in what we would consider to be extreme environments, and the diversity of environments on Earth that can support organisms
5. Exploring the nature of the origin and evolution of genes by examining the role of lateral gene transfer versus descent through mitochondria for the genes responsible for producing glutathione

1. Exploring the nature of symbiosis between fungi and green algae as a way of understanding the formation of multicellular plants and their transition onto land during the Ordovician
2. Examining the nature of the climate and climate evolution on Earth−like planets (including Mars and Titan, as examples), in order to constrain the possible locations for life in our Solar System and the potential habitability of planets in other solar systems
3. Determining the nature of the coupled volatile, geological, and geochemical systems on Mars and the implications for the potential for life on Mars, and using the results to define the range of planetary habitability and nonhabitability
4. Exploring astrobiology from a “philosophy of science” perspective, including the nature of astrobiology as predominantly a “historical” science and the validity of trying to “define” life
5. Examining the societal issues in astrobiology, including the implications of the tremendous public interest in life elsewhere and the exploration of our Solar System, galaxy, and the Universe

Each of these tasks has resulted in significant results that have been presented at the national and international astrobiology conferences and workshops and in papers in the refereed literature. Rather than describing each task in detail, which is the function of the accompanying individual project reports, here we summarize some of the most interesting and important findings from this past year of research.

Planet formation in star−forming regions. The physical environment in star−forming regions that are relatively nearby in our own galaxy was examined. Stars generally do not form in isolation, but do so instead in large clusters that formed from the collapse of interstellar clouds of gas and dust and the fragmentation into clouds that form individual stars. Of key significance, the intensity of ultraviolet (UV) light in these clusters of newly forming stars is very intense, owing both to the large number of stars there and to the high ultraviolet output of young, massive stars. The high intensities of UV light have the ability to break apart dust disks relatively rapidly owing to the intense pressure exerted on small dust grains by the light. Disks typically can be destroyed in less than 1 million years, much more quickly than the dust can accumulate into planetesimals that would be large enough to withstand the radiation. Estimates are that perhaps 90% of stars are born in environments in which the UV radiation would preclude planet formation. If this result is correct, and can be accurately generalized to stars throughout our galaxy and over time, then it would be unlikely that planet formation would be as widespread as is currently thought. In such a case, planetary systems similar in architecture to our own Solar System might be relatively rare.

Environment on the early Earth. The geological record of the environment on the early Earth, including sulfur isotope analysis as a constraint on oxygen content of the early atmosphere and the use of ancient zircons to determine the environment on the earliest Earth, has been investigated. Here, we will summarize the implications of the sulfur isotope analysis.

Sulfur isotope anomalies in a diverse suite of sedimentary rocks can be used to place constraints on the nature of ancient atmospheric chemistry and, in particular, the abundance of oxygen in the atmosphere. We used a secondary ion mass spectrometer (SIMS; ion microprobe) multicollector technique previously developed to measure sulfur (S) isotopic anomalies in Martian meteorites. Our data reveal large anomalies in the sulfur isotopes, in a manner that is termed “non−mass−dependent” and implies a variation that is different from that which arises solely from the mass differences in ^{32}S, ^{33}S, and ^{34}S. The non−mass−dependent isotopic anomalies result from processes that can occur in the atmosphere, due to photochemical processes, and have been well documented in today's atmosphere. We find large anomalies in sulfides from ancient

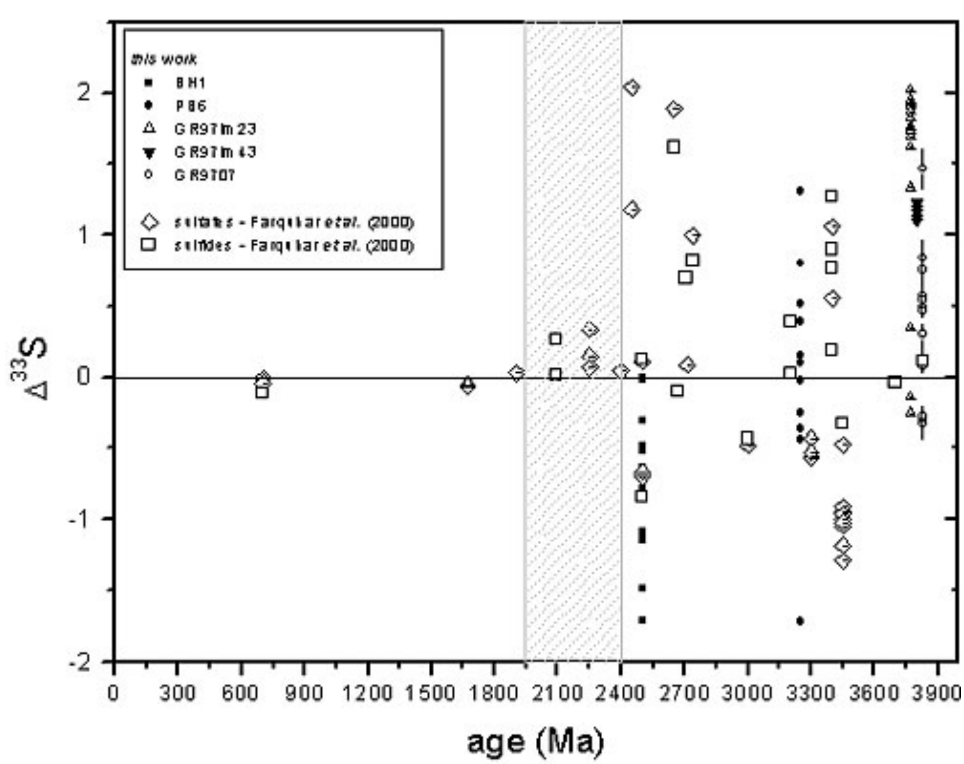

Figure 1. Mass−independentsulfur isoltope anomalies in ancient sedimentary

rocks.

Archaean sediments corroborate prior bulk measurements of Precambrian sulfides, and that most likely reflect atmospheric sulfur subsequently transferred to the oceans, implanted into marine sediments, and preserved within sedimentary sulfides. Our ion microprobe data provide additional support for a postulated anoxic and photochemically active atmosphere on the Earth prior to about 2.2 Ba (billion years ago), ago, and extend the record of atmosphere−hydrosphere interactions revealed by sulfur isotopes to ^{3} 3.8 Ba (see fig.1).

Properties of the RNA world. A theory bearing on the likelihood of initiation of the RNA world has been completed and published. In particular, the first potentially realistic calculations of the amount of RNA (the number of molecules of arbitrary sequence) needed to evolve particular ribozymes have been made. Obviously, the more RNA that is required, the more difficult it would have been to evolve primitive RNA cells. These calculations suggest that the number of RNA molecules required in order to begin to evolve ribozymes is anti−intuitively small. Thus, an RNA cell (a ribocyte) is unexpectedly accessible. Zeptomoles of RNA molecules (1 zmol = 602 molecules), less than in a modern bacterium, might suffice (the "z*eptomole world"* hypothesis). In addition, selection itself strongly shaped the RNAs available to an ancient ribocyte. These effects can be summarized in three maxims: (1) the Maxim of Magnitude − newly selected RNA active sites will contain as few functional nucleotides as possible (1.6 specified nucleotides costs an order of magnitude more starting RNA); (2) the Maxim of Modularity − newly selected RNA active sites will be folded from as many separated contiguous sequences (modules) as possible?it is statistically easier to find small, separated sequences than one large contiguous sequence of the same total size; and (3) the Maxim of Minimization − the separate RNA modules folded together in three dimensions (3−D) to compose an active site will be as equal in size as is practical. Unequal pieces imply some larger, improbable ones, so real sites will tend to contain the smallest (most equal) modules.

An RNA enzyme (peptidyl transferase, PT) dating from the RNA world itself is built into the large ribosomal subunit to make peptide bonds and thus all cellular proteins. We have now synthesized and tested a second−generation transition state analogue (TSA) that binds to the PT site on the ribosome. Our first TSA (which can be abbreviated by the name CCdApPuro) was of unique importance in finding and elucidating the initial crystallographic structure of the ribosome's PT site. The new compound, called CCdApPuroC, was predicted from crystallography of the ribosome's large subunit to be even more complementary to the real PT site. As predicted, the new compound fits the ribosome even more accurately, binds more strongly, and will serve as an even better marker for this ancient ribozyme.

Microbial ecology of hypersaline environments. We have focused on a molecular analysis of the microbial constituents of hypersaline microbial mats, currently at Guerrero Negro, Baja California. Here, 10−cm−thick, tofu−like mats cover the bottom of about 70 square miles of evaporation ponds. The goals of our studies are to understand the organismal makeup of these communities and how the individual kinds of organisms contribute to the support of this remarkable concentration of biomass. This project is an essential interest of the EcoGenomics Team, the activities of which are directed toward a comprehensive understanding of this ecosystem. Brines are expected to occur in many planetary settings, so information about terrestrial organisms in such environments may illuminate properties useful in the search for life elsewhere. The results additionally contribute to our knowledge of the diversity of life in extreme environments. Although substantial effort has been invested in the study of chemical aspects of the Guerrero Negro system, relatively little is known about the organisms that compose these communities.

All previous studies of the microbial biology of the Guerrero Negro and other hypersaline microbial mats have relied on direct microscopy or on development of cultures of microbes for laboratory studies. However, microscopy detects only morphologically conspicuous organisms, and not many microbes are culturable with standard techniques. Consequently, we are using molecular survey methods in which ribosomal RNA (rRNA) genes are obtained directly from natural environmental DNA by Polymerase Chain Reaction (PCR) and molecular cloning techniques. The studies of Guerrero Negro mats have only just begun, but already are revolutionizing our view of the makeup of such communities. Specifically, previous conclusions based on microscopy and culture have focused on cyanobacterial photosynthesis as the main source of primary productivity (conversion of carbon dioxide into biomass). We find, however, that cyanobacteria are only one component, and generally a minor component, of the numerically dominant organisms. The generally more abundant organisms (rRNA genes) are representatives of the “Green Nonsulfur” phylogenetic division of bacteria. This was an unexpected result that changes fundamentally the way that the community needs to be modeled. The studies so far have discovered and molecularly described several hundred novel species of microorganisms. A phylogenetic breakdown of the microbial composition of the daytime surface of one Guerrero Negro mat analyzed is shown in figure 2.

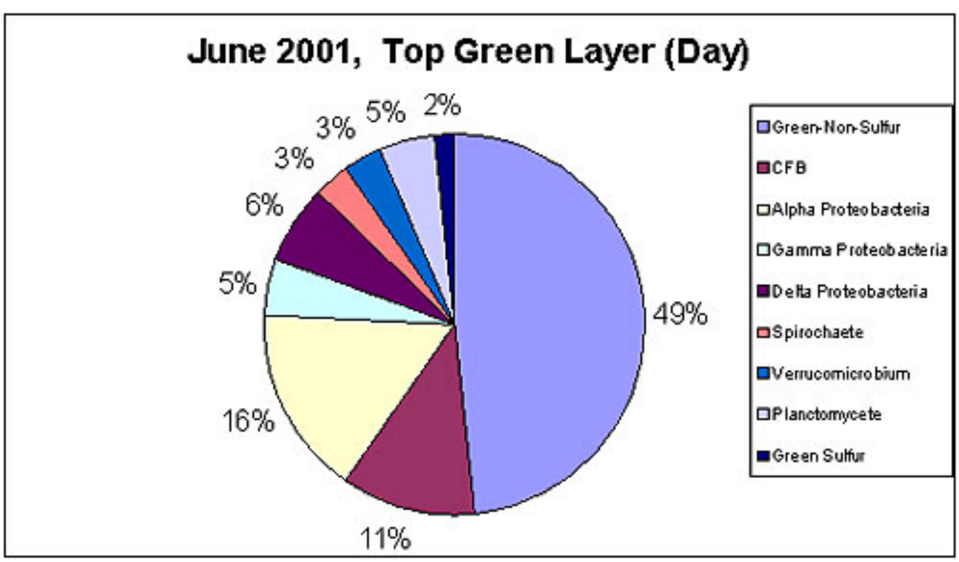

Figure 2. Phylogenetic breakdown of the microbial composition of the daytime

surface of one microbial mat analyzed at Guerrero Negro, Baja California, as part of the EcoGenomics Team efforts.

Habitability of Mars. We report on two different aspects of understanding the environment and potential habitability of Mars, one pertinent to ancient Mars and one pertinent to geological environments throughout time.

On ancient Mars, valley networks have been interpreted as requiring a thicker atmosphere and greenhouse warming; a possible alternative is suggested. On early Mars, collisions of asteroids and comets would have produced meters−thick global debris layers, which would have the effect of melting subsurface water and releasing water in the polar caps, and thereby contributing to global−scale rainfall. Water produced by this mechanism could be meters in depth, and may be responsible for producing the observed valley networks.

Volcanic activity has occurred throughout time on Mars and, along with the abundant groundwater inferred to have been present from morphological observations, would have created extensive hydrothermal systems. As with hydrothermal systems on Earth, the circulation of groundwater and the mixing of hot water that has equilibrated with the deep crust with cooler near−surface water would produce a chemical that was not in equilibrium with its environment. Reactions that move toward equilibrium would give off energy that could be utilized by organisms to support metabolism. Examination of the energy available in such systems and the potential biosphere that could be supported by it indicate that such environments could be very energy rich and could support amounts of biota similar to those in terrestrial hydrothermal systems (see fig. 3).

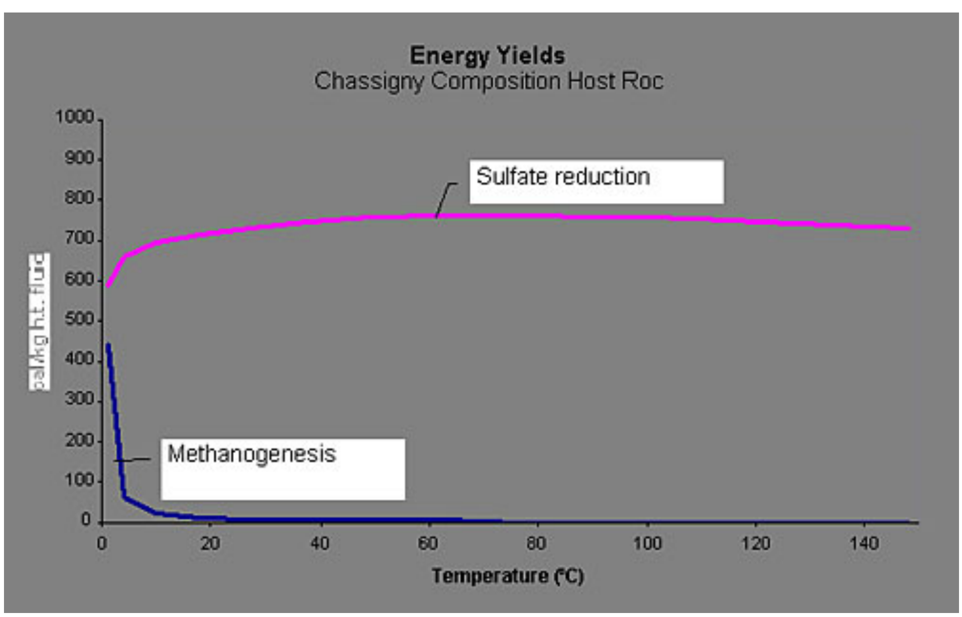

Figure 3. Energy yields as a function of temperature for reactions involving sulfate reduction and methanogenesis, calculated based on the reaction of Martian water with Chassigny, one of the Martian meteorites.

Philosophy of science in astrobiology. Good progress has been made on the issue of whether “life” can be defined, and the answer is “no”. The idea that a definition of life can be used to answer the question of “What is life?” rests upon confusions about the nature of definition and its capacity to answer fundamental questions about natural categories. What is required to answer this question is a general theory of the nature of living systems. In the absence of such a theory, we are in a position analogous to that of trying to define water prior to the advent of molecular theory. The best that could have been done would have been to define it in terms of sensible properties such as being wet, transparent, odorless, tasteless, thirst quenching, and a good solvent; but no amount of observational or conceptual analysis of these features of water can reveal that it is H_2O, although this is the scientifically most informative answer as to what it is. Similarly, in the absence of a general theory of the nature of living systems, analysis of the features that we currently associate with life is unlikely to provide a particularly informative answer as to what it is. These results have implications for the search for life elsewhere. Some of the most useful tentative criteria for use in the search for extraterrestrial life may not even be universal to terrestrial life. Features that are common only to life in certain kinds of terrestrial environments may prove more useful for searching for life in equivalent systems than features that might be universal to terrestrial life. Similarly, features that are extremely uncommon or nonexistent among nonliving terrestrial systems may make good criteria for present or past life, even if they are not universal to living systems, because they stand out against a background of non−living processes.

Educational activities

In addition to its research, the CU Center for Astrobiology has a strong commitment to education at all levels.

We have created a “Graduate Certificate in Astrobiology” in order to provide understanding of the breadth of disciplines in astrobiology for graduate students who still must focus on one particular area for their research. Our goal here was to provide broad−based training that would add to what students learned in their home departments and disciplines, rather than taking students out of their natural environment and weakening their discipline−based education. We graduated our first student with a Graduate Certificate this year.

We also initiated two courses intended for graduate students, one in astrobiology, providing exposure to the entire breadth of disciplines that make up the field and how they integrate together, and the second in the history and philosophy of astrobiology, intended to provide exposure to issues in the philosophy of science, religion, societal issues, and the practice of science and of astrobiology in particular.

We also support education of postdoctoral research associates. Currently, there are three NAI postdoctoral students in our program at CU, working on very different aspects of astrobiology.

In addition, a substantial number of graduate students and post−docs are supported through our research funding, and we are able to leverage our NAI funding through other sources to create an even larger program

As part of our educational program, we run an astrobiology seminar series, jointly with a different program each semester. This past year, our fall program was disrupted by the post−September 11 issues, but we still had presentations and interactions with other NAI team members during the year.

Outreach activities

Outreach is an integral part of our program, and we engage in outreach at all levels including to the university community, to K−12, and to the public. Most of our activities are highlighted in the outreach summary that is reported separately.

Here, we would like to summarize our major outreach activity. Each year, we sponsor a public symposium on an aspect of astrobiology. This involves an evening symposium, with nationally and internationally known speakers, presented to a public audience. Past symposia have been on exploration of Mars, the potential for intelligent life elsewhere, and the question of what life is, and have drawn as many as 500 attendees from the university, the local community, and even from as far away as Wyoming. Our most recent symposium on “What is life?” included participation and presentations from Dr. Stephen Mojzsis (Univ. of Colorado), Dr. Gerald Joyce (Scripps Inst.), Dr. Noreen Herzfeld (St. Johns), and well−known sci−fi author and futurist Ben Bova.

This year, we are planning a “capstone” symposium on the nature of astrobiology, and will explore the evolution of life on Earth and the potential for life elsewhere.