

# **Astrobiology Science Goals and Lunar Exploration: NASA Astrobiology Institute White Paper**

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## Executive Summary

The Moon preserves unique information about changes in the habitability of the Earth-Moon system. This record has been obscured on the Earth by billions of years of rain, wind, erosion, volcanic eruptions, mountain building, and plate tectonics. In contrast, much (most?) of the lunar surface still contains information that reflects events at the time of life's origin and subsequent evolution on Earth. Therefore, lunar research can address critical astrobiology science questions. In particular, the lunar record allows us to focus on two specific issues in the early solar system—the history of impacts and the history of exposure to radiation. The Moon, as Earth's closest neighbor, is probably the only body in the solar system where we can address these issues quantitatively.

Impacts probably played an important role in the earliest history of life on Earth. Large impacts would have temporarily altered the environment and creating hostile conditions in which life could not survive. Later impacts probably shaped life's evolution by forcing successive mass extinctions of large numbers of species. The terrestrial impact history is better recorded on the Moon than on the Earth. Central science goals are to determine the impact rate onto the Moon (and, by extension, the Earth) during the period when life was originating early in solar-system history, as well as in geologically recent times. We can use the beautifully preserved record on the Moon to help us to understand the habitability of the Earth at the time of life's origin and earliest evolution and determine the frequency of impact-driven mass extinctions and the subsequent course of evolution.

During Earth's earliest history, its surface also was bombarded by high-energy particles associated with solar activity (from a solar wind that was enhanced during early history and from solar flares) and galactic cosmic rays, and possibly from nearby supernovae and events associated with gamma-ray bursts. This bombardment must have had deleterious effects on life at the Earth's surface, and may have severely affected the formation and earliest evolution of life. These ancient events are recorded in the lunar regolith, formed throughout lunar history by the impact of micrometeorites and which were buried and preserved by subsequent lava flows. Sampling the effects of this radiation within these fossil regoliths, then, provides a window into the energetic-particle environment at the time that the regolith was buried, and sampling many different locations can provide detailed information over time. This will provide a better understanding of the environmental and evolutionary effects of changes in solar activity, of episodes of harsh radiation, and of energetic particle influx from outside the solar system.

Each of these problems can be addressed in a step-wise manner by a lunar science program that includes orbital imaging and remote sensing, in-situ analysis from landed spacecraft on the lunar surface, robotic sample-return missions, and human-exploration missions.

## **I. Introduction**

On January 14, 2004, President Bush gave a major policy speech in which he presented a new vision for NASA that emphasized exploration and the search for life. Within our solar system, the emphasis was to be on exploration of the Moon and Mars, first with robotic spacecraft and then with humans. Vigorous discussion ensued regarding the scientific questions that we can pose today about the formation and evolution of our solar system and about the conditions within it that relate to the occurrence, evolution, and distribution of life. These questions feed, as well, into an understanding of the potential for life beyond our solar system and the search for evidence of its existence.

In response to this vision, the NASA Astrobiology Institute (NAI) sought to develop a white paper to articulate the astrobiology science goals that would be addressable by doing lunar science using data returned from orbital, in situ robotic, sample return, and human exploration missions. This perspective on “astrobiology at the Moon” is one that had not been explored previously, although a number of papers in the literature had discussed the importance of the cratering record. To allow a rapid response that would provide useful input into the ongoing replanning at NASA, this effort focused on areas not being addressed elsewhere. Some astrobiology science goals can be met via lunar-based astronomical observations, lunar biosciences experiments, and lunar bioastronautics studies. The first of these has been addressed in numerous recent reports, and the latter two are objects of ongoing analysis within NASA’s Exploration Systems and Space Operations offices.

This white paper was prepared in response to a request by Dr. James Garvin, the Lead Scientist for the Moon and Mars at NASA Headquarters, and was informed by planning activities undertaken by the NAI at and subsequent to its Strategic Planning Retreat held in October, 2003. The results were provided as input into planning activities at NASA and to the Presidential Commission on Moon, Mars, and Beyond (the so-called Aldrich Commission) that recently has discussed the implementation of the new space vision for NASA.

The results of this report are not intended to represent a community consensus, given the short timescale available in which to prepare it and have maximum utility. However, the report is grounded in science concepts that have been vetted by the lunar science community over many years, and that are discussed in numerous reports from groups such as the Lunar Exploration Science Working Group (LExSWG) (see references in Appendix I).

The preliminary concept of lunar astrobiology science goals was discussed at the NAI Strategic Planning Retreat held in Jackson, Wyoming, in October, 2003. The idea of a white paper on these issues was raised in discussions with Dr. Garvin in February, 2004, and led to a formal request to the NASA Astrobiology Institute. This resulted in a series of planning meetings to unite the ongoing efforts, and an agreement on Feb. 16 to carry out the activity under the aegis of the NAI. The major input for this report came from an evening workshop held at the Lunar and Planetary Science Conference in Houston on March 16, 2004. Scientists were invited to participate based on scientific discipline and institutional diversity, with the goal of having participants from the broad spectrum of science disciplines. (A complete list of participants is included in Appendix II.) Following that meeting, a draft viewgraph package was prepared and distributed to workshop participants for comments and suggestions. A revised viewgraph package was distributed to the NAI Executive Council prior to their meeting on 27-28 March, and was discussed at that meeting. In addition, the package was presented and discussed in open forum at the Astrobiology Science Conference held at NASA’s Ames Research Center, on

March 29. The final viewgraph package was distributed to the NAI Executive Council for approval on April 2, approved on April 9, and distributed on April 14. Subsequently, it was presented and discussed at NASA Headquarters (April 19), before the Aldrich Commission (May 3), and to the National Research Council's Committee on the Origin and Evolution of Life (COEL, May 11). The viewgraph package is available at the NAI web site (<http://nai.arc.nasa.gov>), and formed the basis for the present written report. This written report was distributed on June 4 to the attendees at the LPSC workshop for comments, and a revised version was distributed to the NAI Executive Council on June 24 for discussion and approval, and it was approved in final form on July 19.

## **II. Astrobiology Science Goals and Lunar Exploration**

Astrobiology seeks to understand the processes that shape planetary habitability, including those responsible for the current architecture of our solar system (i.e., “making habitable planets and making planets habitable”), as well as a specific search for life. In this context, exploring the life-related issues within our solar system includes understanding the origin and evolution of our solar system, the geological, geophysical, and geochemical processes that occur on planets and satellites, the occurrence and nature of potential habitable environments on the planets and satellites, the origin and evolution of volatiles, and the actual occurrence, distribution, and nature of life.

In our solar system, the Moon acts as a recorder or “witness plate”, containing an accessible, long-duration record of the near-Earth space environment going back to the early history of our solar system. The Moon has surfaces with ages that span almost the entire history of the solar system, with younger surfaces having been remelted and had their ages reset by impacts, and we can use it to better understand the dynamical processes that have taken place.

In particular, we anticipate that issues of particular importance to astrobiology that can be addressed with lunar measurements include:

The bombardment history in the inner solar system (and, by extrapolation, throughout the solar system), both in early times and in geologically more recent epochs; and

The “energetics” (radiation plus high-energy particles) over the last 4 Ga.

These issues are discussed in more detail below, along with other astrobiology issues that are of high priority to explore.

### **A. Bombardment history of the Moon**

We can divide the bombardment history into the earliest history and more-recent epochs.

One of the major issues in understanding the early history of the Moon is whether or not there was a “late heavy bombardment” or “terminal cataclysm”. Measurements of the ages of lunar impact-derived rocks show a clustering at 3.9 Ga age. One interpretation of this observations is that there was a dramatic increase in the impact rate at this time, termed the late-heavy bombardment. An alternative is that the impact rate was exceedingly high during planetary formation and decreased exponentially at the end of accretion. In this scenario, the clustering of ages represents either the final “resetting” of the radiometric clocks during the final

stages of accretion or the pervasiveness of products of the huge Imbrium impact in materials sampled to date.

A second issue is the role played by impacts in providing both volatiles and organics to the early Earth. Did the water, carbon dioxide, and other volatiles arrive at the Earth during and as a result of the general accretion process, contained within the planetesimals, or did they arrive in comets and other icy objects that accreted at the end of planetary formation? How, when, and in what abundance were organic molecules supplied to the Earth by impact? Meteorites today contain organics, and their supply to the early Earth may have played an important role in providing the raw materials out of which life could form.

Both of these issues relate directly to the habitability of the Earth's surface shortly after its formation. What environmental conditions were "typical", and how often did catastrophic impacts occur? How severe for life were the largest impacts? We believe that they held the potential for ocean-vaporizing or Earth-sterilizing impact events, and hence for the "impact frustration" of life's origin and early evolution. Such impacts may have created conditions that were severe enough that only a thermophilic "last common ancestor" of life could have survived the bottleneck of surface sterilization, finding shelter in the deep sea or deep within the crust. Conversely, it is possible that the heat from impacts *created* hydrothermal systems conducive to the origin of life.

An additional aspect of the early bombardment history is the potential for finding well-preserved ancient Earth rocks that were ejected during impact events and survived delivery to the lunar surface. Rocks more than 3.5 billion years old are exceedingly rare on Earth, and materials from the period of the postulated late heavy bombardment are almost absent. Almost all rocks of this antiquity have been heavily altered. If we could identify Earth rocks of this age on the surface of the Moon, they might contain information about the early Earth's environment or even the earliest history of life, both unavailable elsewhere. While the potential for discoveries are tremendous, there is large uncertainty as well. It is not yet clear whether rocks would be ejected from Earth and then land on the lunar surface without sustaining substantial alteration, and the challenge of finding and identifying Earth rocks on the lunar surface is daunting.

In more-recent epochs, impacts appear to have played a major role in mass extinctions over the last half-billion years and leading to opportunities for evolutionary radiations into newly available ecological niches. Impacts also represent a present-day hazard to the Earth; while telescopic observations provide the best way to understand today's impact rate, the recent impact rate onto the Moon can provide a better estimate of the average impact rate during geologically recent times.

Understanding these issues for the Earth and Moon allows us to look beyond the Earth and Moon. We can extrapolate the impact rate to elsewhere in order to understand the roles that impacts have played on Mars and Venus and the implications for life there. We can determine the potential for cross-fertilization of life between the planets in the inner solar system by exchange of rocks that might have contained living organisms. And, by better understanding the impact environment in the early solar system and the processes that are responsible for controlling it, we can understand how the same processes might have operated in other planetary systems and affect the potential for life beyond our own solar system.

*Early bombardment history and lunar exploration*

The Moon's surface provides the best and most accessible record of the bombardment history of the Earth and the inner solar system, including changes through time in the mass flux and in the size distribution of impacting objects. The existing data for radiometric ages of returned lunar rocks and for crater densities on the lunar surface are the primary basis for our present understanding of the early bombardment history of the inner solar system and the early Earth (>3.5 Ga). These data constitute one of the most profound scientific legacies of the Apollo program.

However, there are fundamental controversies about this early impact record that can only be resolved by further lunar sampling and geochronology. Only a handful of sites were sampled by Apollo and Luna missions. While these samples have been augmented by lunar meteorites collected on the Earth, the latter are of uncertain provenance. Even samples collected on the Moon are not easily related back to particular impact basins because of the limited geographical distribution of the samples (especially the lack of samples from the far side) and the uncertain field relationships of the Apollo landing sites to lunar basins.

These questions can be addressed in a substantive way by obtaining unambiguous, precise *absolute* dates of ancient large craters and basins. In the foreseeable future (e.g., 20-year horizon), such careful geochronology is most effectively done on Earth rather than on the Moon. Therefore, envisioned lunar activities focus on refined sample selection. We would want to collect samples from at least one basin of known stratigraphic position, such as the South Pole-Aitken Basin, which is the largest impact structure on the far side of the Moon and possibly the oldest. Landing sites within the basins would have to be carefully selected on the basis of basin structure and composition, as determined from remote-sensing data. Such sampling can be accomplished by robotic missions that collect a large number of small rock samples (>4 mm) and whose landing sites have been selected on the basis of high-quality remote-sensing data.

Ultimately, human missions to appropriate sites will be needed in order to provide detailed field context and multiple documented samples. These would allow us to unravel the complex original stratigraphy of basin floor deposits.

We anticipate that significant contributions could be made from each of the different types of mission architectures that are being considered:

*Orbital missions* would provide information for site selection, using imaging and remotely sensed compositional data to refine the lunar stratigraphy and to select specific, key landing sites.

*In situ robotic missions* could provide seismic data for characterization of the structure of craters or basins, as well as observations of stratigraphic context, rock composition, and mineralogy.

*Robotic sample return missions* would return collected samples to the Earth, where high-precision geochronology and trace-element analyses could be carried out.

*Human exploration missions* would permit detailed documentation of collected samples, field study of their context, and traverse geophysics that can allow us to better understand the character of the craters or basins.

### *Post-3.5-Ga bombardment history and lunar exploration*

In addition to retaining a record of early bombardment, the Moon also preserves an exquisite record of the bombardment subsequent to 3.5 Ga. This includes the last 0.5 Ga, corresponding approximately to the Phanerozoic epoch on the Earth. This record, in the form of

isotopically dateable crater ejecta, impact glasses, and melt rocks, is largely unexplored. Questions relate to the impact flux during the recent epochs, the potential for variability of this record (episodicity or periodicity), and the composition and nature of the impactors themselves.

Many of these science issues can be addressed via precise *relative* dating of a large population of small impact craters in order to constrain the rate of the bombardment and its variability in the last 0.5 Ga. Relative dating can be done by examining changes in crater morphology and of surrounding ejecta and the extent of “space weathering” of materials exposed during crater excavation. Each of these characteristics evolves over time as a result of the continual flux of micrometeorites onto the surface. These parameters can be usefully constrained by observations from orbit. Absolute dating of a relatively small number of craters, either in situ or with samples returned to Earth, may be adequate to calibrate the relative chronology derived from remote-sensing data.

In addition, it is important to assess the structural geology of the basins and craters, as this will provide indirect information about the composition and origin of impactors. This will be valuable input into understanding the impactor mass and velocity, which may vary with time and between craters.

We anticipate that significant contributions could be made from each of the different types of mission architectures that are being considered:

*Orbital missions* can be used to constrain relative ages of large populations of craters from changes in morphology, rock population, and degree of space weathering, and to refine the lunar stratigraphy.

*In situ robotic missions* can be used to refine stratigraphic relationships and to obtain compositional information to calibrate remote sensing observations and to select sites and samples for geochronological dating on Earth. There also is the potential to develop the capability for moderate-precision *in situ* geochronology in lieu of or in advance of sample return.

*Robotic sample return missions* will allow high-precision geochronology of carefully selected samples from specific sites.

*Human exploration missions* can carry out all of the above tasks, augmented by human adaptability and decision making capabilities. In addition, there is the potential for robotic platforms to explore large areas, controlled from crewed outposts and utilizing a lunar laboratory for detailed study and analysis of large numbers of samples.

## **B. Energetic environment**

An important environmental condition related to the early potential for life on Earth is the radiation and energetic-particle environment in surface environments. High-energy particles that impinge onto the Earth’s surface have the potential to severely damage DNA, RNA, and other organic molecules, harming living organisms and making the origin and early evolution of life problematic. Such particles also can alter the composition of the Earth’s atmosphere in ways that are harmful for life.

The solar wind is thought to have been much stronger in the Sun’s earliest history than it is today. Solar-wind particles would have impinged onto the Earth’s atmosphere and been able to affect the chemistry and composition of the atmosphere. Solar flares might have occurred more often and might have been stronger; their high-energy particles could be severely damaging to surface life.

Additional factors that might have affected life on Earth include nearby supernovae that could have bombarded the Earth's surface with severely damaging radiation and particles. Gamma-Ray Burst events and periods of enhanced flux of galactic cosmic rays also could have been deleterious to life on Earth throughout its history.

Variations in the flux of radiation and energetic particles presumably affected the boundary conditions for life on other planets in our solar system as well. By telling us about the generic conditions in planetary environments, study of such variations provides us with information that can be used to understand the habitability of planets in nearby systems around other stars.

These issues can be explored by sampling fossil (buried) regoliths that may preserve a historical record of the radiation and energetic particle flux. Regolith forms continually at the lunar surface as a result of the bombardment by micrometeorites, which break up surface rocks. At present formation rates, a layer up to 2 m thick can be created in a billion years that consists of fine, powdered rock. Particles and radiation that impinge upon this regolith leave behind decipherable "fingerprints". For example, gases from the solar wind can be retained by adsorption or chemisorption onto fine-grained surface, and energetic particles can create tracks that can be observed within individual mineral grains. "Fossil" regoliths formed when such material was buried by lava flows or impact ejecta, thus protecting the previously exposed regolith from subsequent alteration. The traces of radiation and energetic particles in fossil regoliths constitute an integrated record of particle implantation up to the time of burial.

The history of the energetic environment of the inner solar system could be reconstructed by sampling many such fossil regoliths buried at different times. There are many examples of such overlapping lava flows that date from the first billion years of lunar history. Many of these flows presumably buried ancient regolith, and some specific examples are known, such as Hadley Rille at the Apollo 15 landing site. These can be accessed by trenching, by drilling, in the walls of rilles, or at sites where impacts have done the excavation for us. Specific measurements required to study this historical record include radiometric dating of the bounding lava flows, concentrations and the isotopic composition of evolved-gas solar-wind components (C, N, noble gases, etc.) in bulk samples and grain-size separates, examination of energetic particle tracks in individual mineral grains, and measurement of the concentrations of radioactive and stable nuclides as a function of sample depth within rocks.

We anticipate that significant contributions could be made from each of the different types of mission architectures that are being considered:

*Orbital missions* would provide imaging and remote-sensing compositional data that would help us to refine stratigraphic analysis and aid us in identifying sites for sample collection.

*In situ robotic missions* would provide refined stratigraphic and compositional information for future sample site selection. In addition, the potential exists to develop techniques for moderate-precision geochronology in lieu of or in advance of sample return. This could be used to derive cosmic-ray exposure ages for younger materials (e.g., young ejecta blankets), and ages based on long-lived radioactive isotopes for older materials (e.g., lava flows, ejecta or impact melts). Analyses of some nuclides and other tracers indicative of radiation or particle exposure could be carried out *in situ* as well.

*Robotic sample return missions* would allow high-precision geochronology of properly selected samples to be carried out, along with sophisticated analyses of compositions by petrography and electron microscopy and of nuclides and other tracers indicative of radiation or particle exposure.

*Human exploration missions* would allow all of the above to be carried out more effectively, augmented by human adaptability and decision making capabilities. These missions also have the potential to allow active drilling to obtain samples, and the use of robotic platforms to explore large areas from crewed outposts with a lunar laboratory being utilized to screen and analyze large numbers of samples.

### **C. Other astrobiology science goals that can be addressed that are of high priority**

While the concepts summarized above are a central contribution to understanding the astrobiology of the Earth and solar system, other important astrobiology science goals also can be addressed on the Moon. The highest-priority matters would include the following:

*Potential for finding ancient Earth rocks on the Moon.* The importance of finding ancient Earth materials on the Moon was mentioned previously. If such materials could be identified and were not severely altered by the ejection and impact processes, they would provide a unique and truly exciting window into the early Earth. Similarly, there exists the potential for finding ancient samples from Mars or even Venus, as well as unweathered carbonaceous chondrites.

*Processes related to the origin of the Moon.* We can use the impact rate onto the early Moon to understand stochastic collisional processes that occurred within the inner solar system and that were related to lunar formation. In addition, samples from additional locations beyond those already obtained during the Apollo era can help us to understand the bulk chemical composition of the Moon for comparison with Earth and other terrestrial planets and the chronology of events at the time of lunar origin.

*Characteristics, formation, and evolution of primordial crust.* The lunar highlands represent the first crust formed after global melting on the Moon, and other terrestrial planets presumably would have had a similar early crust. If we are to understand the evolution of planetary surfaces, we must understand these initial crusts as well. The primordial lunar crust is the best-preserved, and possibly the only, example we have.

*Evolution of an end-member planetary object.* A key issue in astrobiology is to understand the processes responsible for the geological and geophysical evolution of terrestrial planets. In our solar system, the Moon is the smallest of these objects, and determining how interior processes and their coupling to the surface geology occurred over time should constrain how similar processes might play out (or have played out) elsewhere.

*Organic chemistry recorded in the polar regions.* Studies of the organic chemistry of ices and soils from the lunar polar regions may serve as an accessible analog of radiation-driven processing that occurs on interplanetary dust grains. As the organic molecules resulting from such processes may have played a significant role in the origin of life on Earth, it is important to understand the processes in more detail.

*Evaluation of how water and other volatiles were added to the Earth.* By examining the volatile content of meteoritic contaminants in the lunar regolith and of volatiles cold-trapped at the lunar poles, we can determine their chemical and isotopic composition and possible source regions. This will help us to determine how volatiles might have been added to the early Earth, and to understand why the Earth has the volatile inventory that it does. This study is complicated, however, by the possibility that polar volatiles and meteoritic debris are relatively recent arrivals on the Moon and, therefore, do not reflect conditions while the Earth and Moon were forming.

### III. Conclusions and Findings

Based on the discussion summarized in this report, we reach the following conclusions and findings regarding the value and role of lunar astrobiology:

Lunar exploration can address issues that are central to understanding the nature, occurrence, and history of life on Earth and elsewhere. These issues are compelling, rather than minor or secondary.

These issues can be addressed best at the Moon, because the record of these processes on Earth and other inner-solar-system bodies has been destroyed or highly altered. The Moon is unique in retaining a well-preserved record of the material and energy flux in the vicinity of the Earth spanning the last 4 Ga that allows us to address these questions.

Important components of the science goals can be addressed at each phase of a measured, incremental lunar science program — utilizing orbital remote sensing, *in situ* analysis from robotic spacecraft, robotic sample-return missions, and human exploration missions.

Infrastructures and approaches required for this lunar exploration program, centered on geological investigations of a harsh remote environment, may translate well to future human exploration of Mars in pursuit of astrobiology science goals.

A lunar science or lunar astrobiology working group should develop these concepts in detail as a follow-on to the present report.

## **Appendix I. Key reports with lunar science recommendations.**

A thorough compilation of key strategic planning documents is available on line at the Lunar and Planetary Institute “Return to the Moon” website, located at [http://www.lpi.usra.edu/lunar\\_return/documents.shtml](http://www.lpi.usra.edu/lunar_return/documents.shtml). The list includes:

*Lunar Surface Exploration Strategy*, Lunar Exploration Science Working Group (LExSWG), February, 1995.

*A Planetary Science Strategy for the Moon*, Lunar Exploration Science Working Group (LExSWG), 1992.

*America at the Threshold*, Report of the Synthesis Group on America’s Space Exploration Initiative, 1991.

**Appendix II. Participants in the March 16, 2004, workshop on lunar astrobiology held at the Lunar and Planetary Science Conference in Houston, TX.**

Ariel Anbar, University of Rochester and Arizona State University  
John Armstrong, Weber State University  
David Beaty, Jet Propulsion Laboratory  
Donald Bogard, NASA/Johnson Space Center  
Dana Crider, The Catholic University  
John Delano, SUNY Albany  
David Des Marais, NASA/Ames Research Center\*  
Michael Drake, University of Arizona  
Herbert Frey, NASA/Goddard Space Flight Center  
B. Ray Hawke, University of Hawaii  
Bruce Jakosky, University of Colorado  
Brad Joliff, Washington University at St. Louis  
David Kring, University of Arizona  
Laurie Leshin, Arizona State University  
Paul Lucey, University of Hawaii  
Kevin McKeegan, University of California at Los Angeles  
Michael Meyer, NASA Headquarters  
David Morrison, NASA/Ames Research Center\*  
Michael New, NASA Headquarters  
Roger Phillips, Washington University St. Louis  
Bruce Runnegar, NASA Astrobiology Institute\*  
Jeffrey Taylor, University of Hawaii  
Larry Taylor, University of Tennessee  
Richard Walker, University of Maryland  
Peter Ward, University of Washington  
Kevin Zahnle, NASA/Ames Research Center

\* Participated by telecon