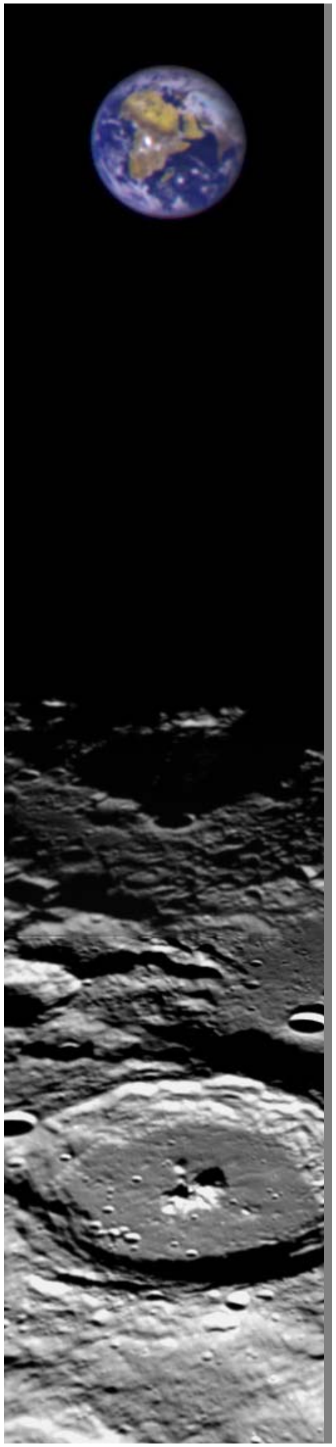

Astrobiology Science Goals and Lunar Exploration

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Summary: Focus on the Historical Record

The Moon preserves unique historical information about changes in the habitability of the Earth-Moon system, a record obscured on Earth. This record provides information that is key to understanding the environment surrounding the earliest life on Earth.

Impact history recorded in lunar crater record

- Goals: Determine the impact rate onto the Moon (and, by extension, the Earth) during the period when life was originating and in geologically recent times.
- Motivations: To better understand the habitability of Earth at the time of life's origin and earliest evolution and the frequency of impact-driven mass extinctions and evolutionary radiations.

Energetics and chemical history recorded in buried lunar regolith

- Goals: Determine the nature of solar activity (solar wind and flares) and galactic cosmic rays, and the frequency of nearby supernovae and Gamma Ray Bursts (GRB) events, over time.
- Motivations: To better understand 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.

Charter and Background

- Charter: Develop a white paper to articulate the astrobiology science goals addressable by doing lunar science, using data returned from orbital, *in situ* robotic, sample return, and human exploration missions.
- To allow rapid response, this effort focused on areas not being addressed elsewhere. Some astrobiology science goals can be met via lunar-based astronomical, lunar biosciences, and lunar bioastronautics activities. The first has been addressed in numerous recent reports, and the latter two are objects of ongoing analysis within Code U at NASA HQ.
- The present activity was in response to a request by Dr. James Garvin, Lead Scientist for the Moon and Mars at NASA HQ, and incorporates preliminary planning activities undertaken by the NAI at and subsequent to its Strategic Planning Retreat in Oct. 2003.
- Results are intended as input to ongoing planning activities at NASA Headquarters and to the Aldrich commission in response to the new presidential vision for NASA.
- Results are not intended to represent a community consensus, given the short timescale involved. However, report is grounded in science concepts vetted by the lunar science community over many years.

Sequence of Events

- Preliminary concept of lunar astrobiology science goals discussed at NAI Strategic Planning Retreat, Oct. 2003.
- Request for white paper received from Dr. James Garvin on Feb. 13.
- Planning meetings to unite ongoing efforts and to carry out activity under aegis of NASA Astrobiology Institute, Feb. 16.
- Evening workshop held at Lunar and Planetary Science Conf. on Mar. 16, with invited participants selected to include discipline and institutional diversity, breadth, expertise.
- Draft viewgraph package distributed to workshop participants for comments and suggestions.
- Viewgraph package distributed to NAI Executive Council prior to their meeting on Mar. 27-28, and discussed at that meeting.
- Viewgraph package presented and discussed in open forum at the Astrobiology Science Conference, Mar. 29.
- Viewgraph package distributed to NAI Executive Council for final approval, 2 Apr., and finalized on 9 Apr.

Participants in the March 16 Lunar Astrobiology Workshop

Participants were selected to provide expertise that spanned the entire range of disciplines in lunar science, in the early Earth environment and history of life, and in the broad context of astrobiology.

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

* Participated by telecon

Intersection of Astrobiology and Lunar Science

- Astrobiology seeks to understand the processes that control 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.
- 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.
- Issues of particular importance to astrobiology that can be addressed with lunar measurements include:
  - The bombardment history throughout the solar system, both in early times and in geologically more recent epochs.
  - The “energetics” (radiation + high-energy particles) and chemical environment over the last 4 Ga.

Astrobiological Relevance of Bombardment History

Specific to Earth

— *Early Earth*

- Timing of impact events in early history and reality of “late-heavy bombardment”
- Supply of volatiles and organics to prebiotic Earth
- Habitability of Earth’s surface shortly after formation
  - What conditions were “typical” (episodicity of catastrophic impacts)?
  - How severe (for life) were catastrophes? (Potential for ocean-vaporizing or Earth-sterilizing impacts, “impact frustration” of life’s origin and a thermophilic “last common ancestor” to have survived the bottleneck of early impact heating.)
  - Potential role of impacts in *creating* suitable (hydrothermal) environments for life.
- Potential for finding impact-ejected ancient Earth (and Mars or Venus) rocks

— *More-Recent Epochs*

- Impacts as drivers of mass extinctions and evolutionary radiations
- The recent impact hazard to the Earth

Relevance to other planets…

- Extrapolation to impact environment in the inner solar system (Mars, Venus).
- Implications for evolution of life on Mars, Venus.
- Potential for early cross-fertilization between Earth, Mars, Venus.

The Lunar Surface and Bombardment History: *A Recorder for the Earth-Moon System*

The Potential

- 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 in the mass flux and in the size distribution of impactors

The Present Reality

- 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)
- There are fundamental controversies about this early record (e.g., was there a “terminal lunar cataclysm” or “late heavy bombardment”?) because:
    - Only a handful of sites were sampled by Apollo and Luna missions; while augmented by lunar meteorites, those are of uncertain provenance
    - Relating existing samples to particular basins is challenging due to the limited geographical distribution of samples (especially the lack of farside samples) and the uncertain field relationship of Apollo sites to lunar basins, Imbrium in particular.
- The Moon also preserves an exquisite record of bombardment since 3.5 Ga, including the last 0.5 Ga (the Phanerozoic), in the form of isotopically dateable crater ejecta impact glasses and melt rocks. This record is largely unexplored.

JnT1

Slide 8

JnT1 We can date craters by determining the cosmic ray exposure ages of ejecta. We dated five craters this way from Apollo samples. This method saturates at some age, maybe around 200 My (worked fine for 100 My Camelot crater at Apollo 17). Impact glasses are not very useful unless we can show they come from a given event. I'd omit the phrase "impact glasses" as there are lots of them in the regolith; although their ages might cluster, they cannot be assigned to a specific crater. Impact melts are essential for dating older craters.

Jeff and Twyla, 4/7/2004

Early Bombardment History and Lunar Exploration

Requirements:

- Unambiguous, precise dating of ancient ***large craters and basins*** to resolve ambiguities of present sample age database and broaden statistics by sampling new locations.
- Collect samples from at least one basin of known stratigraphic position, e.g., South Pole-Aitken basin. Landing sites within the basins must 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 locales will be needed to provide detailed field context and multiple, documented samples that can unravel the complex original stratigraphy of basin floor deposits.

Potential Contributions of Mission Architectures:

- **Orbital:** Site selection, using imaging and compositional data to refine lunar stratigraphy.
- ***In situ* robotics:** Seismic data for structural characterization.
- **Robotic sample return:** High-precision geochronology and trace element analysis.
- **Human exploration missions** – documented sampling, field study, traverse geophysics**.**

Post-3.5-Ga Bombardment History and Lunar Exploration

Requirements:

- Precise relative dating of a ***large population of small craters*** to constrain the rate of the bombardment flux, potentially resolving episodicity and periodicity, particularly in the last 0.5 Ga.
- Absolute dating of a relatively small number of craters may be adequate to calibrate relative chronology derived from remote-sensing data.
- Assessing basin/crater structural geology important for assessing impactor mass/velocity (provides indirect information on composition and origin of impactors).

Potential Contributions of Mission Architectures:

- **Orbital:** Constrain relative ages of large populations of craters, from changes in morphology, rock population and space weathering; refine lunar stratigraphy.
- ***In situ* robotics:** Refined stratigraphic and compositional information for site and sample selection; potential for moderate precision geochronology *in lieu* of or in advance of sample return.
- **Robotic sample return:** High-precision geochronology of properly selected samples.
- **Human presence:** All of the above, augmented by human adaptability and decision making. Potential for robotic platforms to explore large areas, controlled from crewed outpost(s) and utilizing a lunar laboratory to examine large numbers of samples.

Astrobiological Relevance of Energetic & Chemical Environment

Fossil regoliths that have been buried by subsequent lava flows will retain a record (from ~1-4 Ga) of the lunar energetic (i.e., radiation + high-energy particles) and chemical environment at the time of burial.

Specific to Earth

- History of the Sun's activity
  - Solar wind composition in early history
  - Solar flares (which would affect life at the Earth's surface)
- Nearby supernovae and Gamma Ray Burst (GRB) events
  - Consequences for atmospheric composition and surface radiation
  - Potential impact on life on Earth
- History of cosmic-ray exposure
  - Variation expected as the Sun passes through the interstellar medium

Relevance to other planets and solar systems…

- Implications for evolution of life on Mars?
- Implications for habitable/inhabited extrasolar planets in nearby planetary systems?

Energetic/Chemical Environment and Lunar Exploration

- Fossil regoliths (buried beneath lava flows) will retain geochemical, isotopic, and high-energy-particle record of activity at the time that the regolith was exposed.
- Present stratigraphic analysis suggests the existence of regoliths formed on top of one lava flow and buried by subsequent one. These can be accessed by trenching, by drilling, in the walls of rilles, or at sites where impacts have done the excavation for us.
- Ability to obtain a precise chronology of surface materials (i.e., dating lava flows) makes details available and accessible.
- Specific measurements would include radiometric dating of bounding lava flows, concentrations of 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 in the regolith, and measurement of the concentrations of radioactive and stable nuclides as a function of sample depth within rocks.

Potential Contributions of Various Platforms to the History of the Energetics Environment

Orbital:

- Imaging and compositional data to refine stratigraphic maps for future sample site selection

In situ robotics:

- Refined stratigraphic knowledge for future sample site selection
- Potential for moderate precision geochronology *in lieu* of or in advance of sample return
    - Cosmic ray exposure for younger materials (e.g., young ejecta blankets)
    - Long-lived radioactive isotopes for older materials (e.g., basalts, old ejecta/melts)
- Analyses of some nuclides and other tracers indicative of radiation or particle exposure

Robotic sample return:

- High-precision geochronology of properly selected samples
- Sophisticated analyses of compositions by petrography and electron microscopy and of nuclides and other tracers indicative of radiation or particle exposure

Human presence:

- All of the above, augmented by human adaptability and decision making
- Potential for active drilling to obtain samples
- Use of robotic platforms to explore large areas from crewed outpost(s)
- Use of a crewed lunar laboratory for screening large numbers of samples

Other Astrobiology Goals that can be Addressed (of very high priority)

- Potential for finding ancient Earth (and possibly Mars or Venus) rocks, ballistically transferred to the Moon following impact ejection into space; potential for finding unweathered carbonaceous chondrites
- Stochastic processes in inner solar system related to formation of Moon; chronology at time of origin of Moon
- Characteristics, formation, and evolution of primordial crust
- Geological and geophysical evolution of an end-member planetary-like object
- Organic chemistry recorded in polar regions as an analog of radiation-driven processing on interplanetary dust grains

Other Astrobiology Goals that can be Addressed (of high priority)

- Volatile inventory recorded in polar volatiles
- Evaluation of how water and other volatiles were added to the Earth
- Record of solar-wind-driven regolith processes involving production of methane or water
- Chemical characteristics of extra-lunar material
- Micrometeorite flux recorded in ancient regoliths

Conclusions and Findings

- Lunar exploration can address issues that are central to understanding the nature and occurrence 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 elsewhere 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.