Astrobiology Research Priorities for Mercury, Venus, and the Moon
A White Paper for the 2009 – 2011 Planetary Science Decadal Survey

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Introduction

Mercury, Venus, and the Moon provide unique and complementary information about the events and processes that shaped the early habitability of the terrestrial planets. Therefore, exploration of these bodies provides special insights into the conditions that influenced the origin and evolution of life in our Solar System. Such exploration also provides a baseline for understanding the formation and evolution of habitable planets in general – understanding that will be needed to assess the prospects for life in extrasolar planetary systems as observational data emerge in the coming decade.

These issues are discussed in more detail below, with specific reference to their relevance to the NASA Astrobiology Roadmap. The NASA Astrobiology Roadmap was last updated in 2007-08 (D. J. Des Marais *et al.*, *Astrobiology*, **8**: 715-730, 2008). The 2008 Astrobiology Roadmap was reviewed by the Executive Council of the NASA Astrobiology Institute and by the Committee on the Origins and Evolution of Life of the National Academy of Sciences Space Studies Board. The 2008 Astrobiology Roadmap is therefore the most recent authoritative benchmark against which to gauge the astrobiological relevance of the "inner planets" section of the 2009-2011 Planetary Science Decadal Survey.

This white paper is significantly informed by the 2004 document, *Astrobiology Science Goals and Lunar Exploration: NASA Astrobiology Institute White Paper* (Jakosky *et al.*; http://nai.nasa.gov/about/lunar_astrobiology.cfm). That document outlined the value for astrobiology of a robust lunar exploration program that would include orbital and in-situ robotic exploration, sample return, and human exploration of the Moon. The paper "Astrobiology and Venus exploration" is also an important foundation for this document (Grinspoon and Bullock, in *Exploring Venus as a Terrestrial Planet*, L. W. Esposito, E. R. Stofan, and T.E. Cravens, eds. AGU Geophysical Monograph Series, **176**: 191-206, 2007).

Relevant Goals and Objectives from the Astrobiology Roadmap

As stated in the Astrobiology Roadmap, "Astrobiology is the study of the origins, evolution, distribution, and future of life in the universe." Operationally, astrobiology is organized around three ancient but as yet unanswered questions: How does life begin and evolve? Does life exist elsewhere in the universe? What is the future of life on Earth and beyond? These questions are addressed by the NASA Astrobiology Program through a sustained research agenda that aligns with seven "Science Goals" that define critical areas of investigation. Each goal in turn consists of several "Science Objectives" that will guide research over the next ~ 5 years, until the next revision of the Astrobiology Roadmap. Here, we summarize the goals and objectives that have bearing on the study of Mercury, Venus, and the Moon. The nature of these connections is discussed in the next section.

Goal 1: Understand the nature and distribution of habitable environments in the universe. Determine the potential for habitable planets beyond the Solar System, and characterize those that are observable.

> *Objective 1.1: Formation and evolution of habitable planets.*
> Investigate how solid planets form, how they acquire liquid water and other volatile species and organic compounds, and how processes in planetary systems and galaxies affect their environments and their habitability. Use theoretical and observational studies of the formation and evolution of planetary systems and their habitable zones to predict where water-dependent life is likely to be found in such systems.

Goal 2: Explore for past or present habitable environments, prebiotic chemistry, and signs of life elsewhere in our Solar System. Determine any chemical precursors of life and any ancient habitable climates in the Solar System, and characterize any extinct life, potential habitats, and any extant life on Mars and in the outer Solar System.

> *The Objectives listed under Goal 2 in the current Roadmap focus on Mars and extrasolar planets. However, on a decadal time horizon Solar System objects other than Mars can be relevant.*

Goal 4: Understand how past life on Earth interacted with its changing planetary and Solar System environment. Investigate the historical relationship between Earth and its biota by integrating evidence from both the geologic and biomolecular records of ancient life and its environments.

> *The Objectives listed under Goal 4 are Earth-focused. However, improved understanding of the historical Solar System environment from studies of the Moon and other planets fall under Goal 4. An example would be studies of bombardment history from studies of lunar materials and craters.*

Goal 6: Understand the principles that will shape the future of life, both on Earth and beyond. Elucidate the drivers and effects of ecosystem change as a basis for projecting likely future changes on time scales ranging from decades to millions of years, and explore the potential for microbial life to adapt and evolve in environments beyond Earth, especially regarding aspects relevant to U.S. Space Policy.

> *Objective 6.2: Adaptation and evolution of life beyond Earth.*
> Explore the adaptation, survival, and evolution of microbial life under environmental conditions that simulate conditions in space or on other potentially habitable planets. Insights into survival strategies will provide a basis for evaluating the potential for interplanetary transfer of viable microbes and also the requirements for effective planetary protection.

Elucidating Early Events
Roadmap Goals: 1, 4

Bombardment History. The Moon plays a singular role in efforts to understand the history of the Solar System during its first billion years. The very existence of the Moon constitutes an important constraint on models of planetary formation. Its surface provides a uniquely accessible and exquisitely preserved record of the near-Earth space environment, spanning almost the entire history of the Solar System. In particular, our understanding of the bombardment history of the inner Solar System was profoundly altered by analyses of lunar materials returned by the Apollo missions. In addition to providing a chronology that has been extrapolated to determine the ages of surfaces of other Solar System bodies, radiometric age dating of lunar samples suggested that a "late heavy bombardment" occurred between ~ 3.9 and 3.8 billion years ago; all the large impact basins appear to date from this era. Once greeted with skepticism by planetary dynamicists, it is now thought that a late bombardment may be an understandable consequence of the early dynamical evolution of the outer planets (as described by the so-called "Nice model").

The bombardment history is of profound importance to astrobiology because the timing of the end of the hypothesized late bombardment coincides with the earliest evidence of life on Earth. It is logically presumed that the Earth experienced a similar "cataclysm"; the paucity of crustal rocks from before this time may be a consequence of such bombardment. The consequences for the origin and early evolution of life are uncertain but unavoidably profound. Massive impacts may have "frustrated" the origin of life. Alternatively, life may have originated and been extinguished repeatedly by massive impact events. Finally, we may be descended from those microbes that were able to survive such events, living in the deep, hot subsurface; this scenario is consistent with the position of hyperthermopillic organisms at the root of the ribosomal phylogenetic tree.

Further studies of the lunar cratering record can help address key questions about the bombardment era. In particular, a key test of the "late heavy bombardment" is to obtain precise radiometric ages of samples from the Moon's South Pole–Aitkin Basin. This is the largest and possibly the oldest impact structure on the Moon. If it is substantially older than the other basins, the Nice model may be falsified or require modification.

The surface of Mercury appears to be as ancient as that of the Moon (by contrast there appear to be no surfaces on Venus that date back to the early bombardment). Hence, future studies of surface features on Mercury may provide additional constraints on the timing and nature of the early bombardment, and in particular whether it extended throughout the inner solar system and whether the timing, size distribution, and composition of impacting objects varied significantly throughout this region. Although there are no samples of Mercury in our meteorite collection, the acquisition of high-resolution images, reflectance spectra and geochemical remote sensing observations of large impact structures on Mercury by current and planned spacecraft missions will permit an assessment of whether basins cluster in age (i.e., have similar size-frequency

distributions of superposed impact craters) or display of range of ages and whether there are signatures in the basin materials of the compositions, energies, and directions of approach of the impacting objects.

Volatile Delivery and Fate. The origin and evolution of life as we know it – based on the reaction of C-H-N-O-P-based compounds in H_2O solutions – depends on the abundances of volatile compounds at or near planetary surfaces. However, we do not have a good understanding of the processes by which terrestrial planets incorporate, retain, and lose volatiles. This understanding is needed if we are to develop informed hypotheses about the possible volatile inventories on extrasolar terrestrial planets when they are discovered. Yet, even the Earth's total inventory of water (including the amount of water in the Earth's interior) remains uncertain by an order of magnitude! The variability of the initial volatile inventories and compositions among terrestrial planets – and the causes of such variations – also remain poorly constrained. Volatile delivery could be a highly stochastic process.

Much of our information about these topics comes from studies of meteorites and, increasingly, other planets. The value of planetary studies is likely to increase in the next decade. For example, a key question is whether the processes by which the inner planets incorporated volatiles during accretion extended throughout the inner Solar System. The MESSENGER mission to Mercury is adding to the extensive evidence for surface volatiles – alkali metals in the exosphere, polar deposits that may consist of water ice, plasma ions in the magnetosphere that apparently include water and sulfur groups – through the discovery of geological evidence for explosive volcanic eruptions that carried pyroclastic material to considerable ranges. The latter result points to one or more volatiles in the subsurface, but it is not clear what volatiles were most important in driving eruptions. Possible candidates include CO, SO_2 and other sulfur species and H_2O, all of which have different implications for the source of volatiles on Mercury. Further investigation of the evidence for explosive volcanism on Mercury is needed to derive improved quantitative constraints on the identity, abundance, and history of volatiles on Mercury.

Venus offers additional insights into volatile delivery. It is widely accepted that the current dryness of the Venus atmosphere is the result of extensive evolutionary processes. The amount of carbon in the form of CO_2 in the Venusian atmosphere is comparable to the best estimates of the Earth's carbon inventory, which is largely locked up in carbonate rocks. This finding suggests that a "runaway" greenhouse scenario led to the lack of plate tectonics and biogeochemical cycling on Venus. According to this hypothesis, the primordial inventories of volatile elements on Venus and the Earth were similar (on a mass-adjusted basis); the present differences in distribution between atmosphere and lithosphere are evolved. If these planets had similar initial inventories, the extreme scarcity of H_2O in Venus' atmosphere could be a consequence of photolysis of primordial H_2O followed by loss of H to space, possibly within the first billion years. The high D/H ratio of the Venus atmosphere supports this hypothesis, but this interpretation is complicated by (a) the fact that volatiles can be accreted long after formation – even in the geologically recent past – in the form of

cometary impacts, and by (b) uncertainties in the D and H escape fluxes. Hence, the D/H observations could alternatively be a result of H_2O escape and resupply in the last billion years. Therefore, there is a pressing need for better observations and analysis of data on stable isotopes, escape fluxes and their responses to solar wind, and other variables in Venus' atmosphere. The ongoing ESA Venus Express mission has clarified aspects of the current escape flux, but the total time-averaged flux, including solar cycle variations and escape of neutral species that are not well observed with the Venus Express instruments, make it clear that further missions will be required to understand the current escape flux. *In situ* measurements of noble gas isotope abundances are required to distinguish among competing evolutionary histories. Measurements of surface mineralogy, and in particular the search for metastable hydrated minerals and possible fossil zircons, will ultimately be necessary to achieve more definitive understanding of the history of water on Venus.

Unraveling the starkly different, and apparently divergent, histories of water on Venus and Earth promises to greatly clarify the inner limits of terrestrial planet habitable zones around solar-type stars, as we prepare for the expected harvest of new information about extrasolar terrestrial planets over the next decade.

Although the Moon is an incredibly dry object, recent studies have shown that it contains small amounts of water in the interior. Future lunar studies could help to constrain the volatile content of early impactors and the post-bombardment accretion flux of organics and other volatile compounds.

Life in the Solar System: Past and Prospects

Roadmap Goals: 2, 4 and 6

Life's History on Earth. The realization that a meteorite impact event led to the extinction of the dinosaurs, and hence the rise of mammals, forever changed our perspective on the connections between the history of life and the Earth's celestial surroundings. Unfortunately, these connections remain largely hypothetical. Clarity may come from future exploration of the Moon.

In addition to recording the bombardment history of the first billion years of Solar System history, the lunar regolith is an unmatched repository of information about the impact flux after 3.5 billion years ago. For example, emerging radiogenic isotope studies of lunar impact glasses provide evidence for discrete impact episodes in the last billion years, in at least one case correlated with a major extinction event. If some of these episodes represent bombardment by multiple objects, then contemporaneous impacts on the Earth may be extrapolated and biotic effects inferred.

The lunar surface may also provide a record of the radiation and energetic-particle environment, including the effects of a more intense solar wind early in Solar System history, subsequent variations in solar activity, and evidence of more exotic events such

as supernova explosions and gamma-ray bursts, all of which could have affected Earth's environmental and biological history.

The Moon may also eventually provide direct information about past environmental conditions on the Earth itself. For example, there is the tantalizing prospect that intensive examination of lunar regolith would yield ancient material from the Earth (or Venus, or Mars), launched as ejecta from ancient large impact events. It is all but certain that such materials await discovery, although they may be very difficult to find. Such materials could provide information about ancient environments on these bodies, such as in the form of isotopic signatures in zircons or other stable minerals. It is also possible that the Moon may record information about the evolution of Earth's atmospheric composition in the form of fractionated O isotopes embedded in soils on the near-side of the Moon. Since high concentrations of oxygen in the Earth's atmosphere are a consequence of photosynthesis, it is conceivable that we will one day learn about the history of this metabolism on Earth by studying the composition of materials returned from the Moon.

Venusian Life? There are few more vexing topics in astrobiology than the possibility that Venus once hosted life. The gross physical similarities between the Earth and Venus, and the likelihood that, under the faint young Sun and before apparent loss of massive amounts of water, Venus and Earth enjoyed similar surface environments during the period in which life first appeared on Earth make this an appealing hypothesis. Unfortunately, it is maddingly difficult to test because of the geologically recent resurfacing on Venus and the harsh state of the surface today. Early in Solar System history, the terrestrial planets were not isolated bodies. Rather, because of frequent impact transport, they constituted an interconnected potential environment for early microbial life. If life did begin and evolve on Venus, it might plausibly have migrated to the clouds, which today on Venus may represent a habitable niche. Though highly acidic, this aqueous environment enjoys moderate temperatures, surroundings far from chemical equilibrium, and potentially useful radiation fluxes. Observations of unusual chemistry in the clouds, and particle populations that are not well characterized, suggest that this environment must be explored much more fully to test the idea that it may currently be a habitable environment, especially given the discovery of terrestrial extremophile organisms that thrive in extremely acidic conditions.

Life's Future Beyond Earth. The third major question asked by astrobiology is "What is the future of life on Earth and beyond?" In view of the centrality of microbes to all ecosystems, life's ability to spread to other planets depends critically on the adaptability of microbes to extraterrestrial environments. This is true of sustained human exploration as well as accidental transport, since microbially mediated chemistry will surely play a supporting role in even a partially self-sufficient architecture for long-duration exploration or colonization. Renewed human exploration of the Moon therefore offers the opportunity to study the effects of the space environment on microbial communities; to examine the adaptability and survivability of microbes to the space environment, with ramifications for both planetary protection and natural transport of microbes between

planets; and to develop and test methods to assay for microbial activity in the space environment.

Recommendations

Sample return from the South Pole–Aitken (SPA) basin on the Moon: SPA is probably the oldest basin on the Moon and hence would provide an important data point in testing the idea of a spike in the bombardment rate around 3.9 Ga (i.e., the cataclysm). This basin also samples the lower crust and possibly the mantle at a location far removed from the nearside sites sampled by Apollo and would therefore provide a new window into the lunar interior and bulk composition. Thus, high priority should be given to a sample-return mission to the SPA basin.

R&A investments for study of MESSENGER, Venus Express, and Venus Climate Orbiter data, and studies of lunar materials: Making the most of the data returned by the MESSENGER and Venus Express missions will require a commitment to sustaining a robust Research and Analysis (R&A) program. Many studies will continue for years after these missions end. Additionally, research on lunar samples will help to interpret remote sensing data from LRO and future missions and to prepare the community for SPA sample return. Thus, it is essential that R&A programs be adequately funded during the coming decade.

Venus surface science: The next big step in understanding Venus is to make quantitative analyses of the lower atmosphere (gas phases, isotopic compositions) and surface of Venus (mineralogy and chemical composition). *In situ* exploration to achieve these objectives should be a high priority for Venus exploration in the coming decade.