An Astrobiological Lens on Planetary System Science

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Astrobiology's Lens

Four hundred years ago, Galileo put the final nail in the coffin of Aristotelian cosmology, advancing what became known as the Copernican revolution. Planetary science was born. The wandering orbs were shown to be worlds like our own, orbiting the Sun, harboring mountains and moons. The Sun was a star, and stars were Suns. The Earth was a planet, and some planets might be like Earth.

In the decades and centuries to come, the question of how Earth-like are nearby worlds would motivate much of the scientific investigation of our Solar System. We would come to understand that the laws of physics and the principles of chemistry and geology apply beyond our home planet. But the biological potential of other worlds remained largely a topic of uninformed speculation and science fiction until the early-to-mid twentieth century, when the seminal origin of life research of Alexander Oparin, J.B.S. Haldane, Juan Oro, and Stanley Miller, coupled to the pioneering astronomical observations of V.M. Slipher, Vasily Moroz, and Gerard Kuiper, began the scientific study of life's potential in a planetary context. Now, as our active exploration of space begins its sixth decade, we have, for the first time in the history of humanity, the tools and techniques to probe the profound questions of planetary habitability: Why does Earth have conditions that have allowed life to thrive for roughly 4 billion years? Where else in this planetary system or others might we find conditions that allowed life to originate and flourish? And the ultimate question: Can we detect life beyond Earth?

Astrobiology addresses these questions, providing a lens through which all of planetary science and solar system exploration, as well as life on Earth, can be viewed. Astrobiology is the study of the origins, evolution, and distribution of life in the universe. Its scope includes the past, present, and future of life on Earth. Like planetary science, it is a systems-level science. In planetary science, one must understand connections between geophysics, magnetophysics, geochemistry, atmospheric chemistry, hydrology, etc. From this emerges an understanding of how magnetospheres, atmospheres, hydrospheres, lithospheres, and cryospheres combine to yield the variety of worlds we observe in our solar system and beyond. In astrobiology, one must add to this array of fields geobiology, biogeochemistry, and evolutionary and environmental microbiology. Addressing the questions of astrobiology thus implicitly involves addressing many of the questions of planetary science, adding some of the most fundamental questions about biology and the origin of life, and then going beyond.

Astrobiology and Planetary Science

From Mercury to the Kuiper Belt, objects large and small provide a window on processes or phenomena relevant to the history of Earth's habitability, with implications for habitability elsewhere. The atmosphere of Venus warns of a runaway greenhouse effect; the cold surface of Mars indicates the importance of a magnetic field and plate tectonics; the putative subsurface oceans of Europa, Ganymede, Callisto, and Enceladus raise questions about the energetic limits of life; and Titan's organic chemical stew may serve as a testament to abiotic chemical complexity or the novelty of biological possibilities.

Planetary science thus both informs and is guided by astrobiology. Planetary scientists have long sought to map the elemental and chemical compositions of solar system bodies, providing perspective on where we might find the "stuff of life." At the same time, understanding the origin and evolution of habitable worlds has become a key theme in Solar System exploration. In recent decades the traditional paradigm for habitability has been largely overturned by the discovery of terrestrial microbes surviving under a variety of extreme conditions, and by the discovery of liquid water oceans in ice covered worlds. Microbial life on Earth is tenacious. It exists over an extraordinary range of pH, temperature, pressure, salinity, and radiation levels. This guides our assessment of the habitability of other worlds. For example, we now have good evidence for five liquid water oceans in existence today beneath the icy shells of moons orbiting Jupiter (Europa, Ganymede, and Callisto) and Saturn (Titan and Enceladus). These oceans may contain 30-100 times the volume of liquid water in Earth's oceans, and as such become prime targets in our search for life elsewhere.

While the quest to understand the roots of habitability and to search for life and habitable environments serves as a key unifying theme for planetary science, it is also important to consider the role that biology, and our understanding of biological processes, can play in advancing our understanding of planetary processes. The issue of processes–essentially, how planetary systems work–is the "keystone of planetary science." Interestingly, as we continue to learn more about the planets in our solar system, we have discovered several cases of disequilibrium processes. Methane on Mars, the plumes of Enceladus, and the methane cycle on Titan all reveal worlds out of steady state. For the latter two examples, geophysical and geochemical processes likely provide the disequilibrium. For the case of methane on Mars, a geochemical disequilibrium must exist to maintain the observed abundance of methane. Though we are a long way from linking any of these processes to life, the simple fact that our continued exploration of the solar system has revealed such dynamic worlds opens the door to biological processes. Life as we know it requires an environment in energetic disequilibrium. Where chemical disequilibrium and other potential conditions for life exist, questions of biology naturally arise.

Biology as a planetary process is important not only for understanding current activity, but also for understanding the past. Much of Earth's geological record has been heavily influenced by biological processes. For example, Hazen et al. (2008) have argued that most of Earth's 4300 known mineral species are the result of biochemical processes. From ancient reef and stromatalite structures to our modern oxygen-rich atmosphere, the links between biology and geology are ubiquitous on Earth. Indeed, one of the key challenges of astrobiology has been to determine just how far back into the rock record we can still discern the influence of biology. This connection between the geological and the biological becomes an increasingly important consideration as we continue to map the rocky surfaces of planets like Mars with improved imagery and spectroscopy, revealing morphology and mineralogy that may testify to the past habitability of such worlds.

How do biological processes affect chemical and geological processes? What have we learned from life on Earth? How does biology influence the rock record? How are chemical processes affected by biological processes? These are just a few of the astrobiology questions that have become ever more timely for planetary science as a result of our rigorous program of *in situ* and orbital exploration.

Missions at all levels, from Discovery to Flagship, benefit by including investigations and measurements of astrobiological relevance. Although any discoveries of new and interesting chemistry or geology are clearly useful contributions to our knowledge of the Solar System, the significance and impact of such measurements can often be greatly expanded if the new information is put in the context of habitability and the history of life on Earth and the potential for life elsewhere. Simply put, since we are life, we feel a deeper connection to endeavors that provide a greater understanding of life in the context of the Universe. Astrobiology provides that context.

Measurements for astrobiology present an interesting challenge. On the one hand, assessing the habitability of a world like Mars or Europa can be well-served by traditional tools and techniques of planetary missions (e.g. cameras, spectrometers, magnetometers, radar, etc.) On the other hand, detecting signs of life may require tools and techniques specific to our understanding of life, generalized from the single example provided by Earth. Because a universal definition of life will be impossible without the discovery of extraterrestrial life and the advent of comparative planetary biology, the search for life must involve, in addition to the investigation of "known" biomarkers, a broad characterization of planetary environments and a broad search for anomalous planetary characteristics. Such a search is consonant with the overall goals of planetary exploration.

The Importance of R&A

The most important factor enabling this astrobiological perspective on Earth's life and Planetary Science has been support for basic research and data analysis provided by NASA through the Research & Analysis (R&A) program. Support from NASA's Exobiology R&A Program, the predecessor and now a component of the Astrobiology Program, dates back to NASA's earliest days. Seminal research supported by the Exobiology Program included Lynn Margulis' work on the endosymbiotic origins of eukaryotic cells; Carl Woese's discovery of the Archaea; the Alvarez theory of an asteroid as the cause of the K-T extinction; Raup and Sepkoski's work on periodic mass extinctions; the discovery of microfossils possibly as old as 3.45 billion years; and Lovelock's Gaia hypothesis, just to name a few (Strick 2004). More recent discoveries from the Astrobiology Program (supported by the NASA Astrobiology Institute and in some cases the Exobiology Program) include a subsurface ecosystem on Earth sustained by energy from radioactive decay; a "rare biosphere" that co-exists with more familiar life in the deep ocean; the importance of "Snowball" events to Earth's biological and geological evolution; evidence for a hydrosphere interacting with Earth's crust only 200 million years after the collision that formed the Moon; methane on Mars; and key prebiological compounds in meteorites and comets ("*Assessment of the NASA Astrobiology Institute,"* 2008).

For advances like these to continue, sustained support from the R&A Program is vital. For example, continued Astrobiology Program support to study the diversity of microbial ecosystems is essential to further our understanding of the limits and extremes of life on Earth and to advance our capability to assess the habitability of other worlds. Work in this area should include interdisciplinary research in Mars-analog environments to inform the selection of landing sites offering the greatest potential for preserving biosignatures and evidence of habitability. Analog field studies are also needed to test instrumentation and verify spacecraft technology. These studies also serve to train and nurture the next generation of space scientists, engineers, and program managers.

Corresponding analog studies should continue for Europa. The study of chemosynthetic deep sea ecosystems and salt-loving (halophillic) microbial communities has expanded our understanding of what might be possible in the dark and salty depths of Europa's ocean.

In addition to continued Astrobiology Program support, several other investments are particularly important to astrobiology missions and goals. To explore Venus for clues to early environmental conditions, and the timing and nature of divergence from a more Earth-like environment, NASA must invest in the development of high temperature electronics, instrumentation and surface sampling mechanisms. Laboratory investigations into the kinetics of high-temperature mineral-atmosphere chemical interactions and mineral spectra at Venus temperatures will also be necessary for successful interpretation of these anticipated results.

Missions to the outer solar system, particularly to Europa, Titan, and Enceladus, require high resolution, high sensitivity instruments with low mass and low power consumption, and in the case of Europa, high radiation resistance. The *in situ* instruments required for these missions will also have to contend with low temperatures, for example, operating in the harsh environments of Titan's polar lakes and in its atmosphere at the base of the methane condensation layer. R&A support is needed now for the development of both the remote and *in situ* instruments, with particular emphasis on those required for exploring Titan and Enceladus, and radiation resistant systems for surface exploration of Europa.

Advancing the remote study of small bodies requires promoting several new technological capabilities. Since the end of the FUSE mission there has been no far-UV astronomical spectral capability in space; this is the only wavelength region in which some key parent molecules can be observed, and the only region where noble gases have transitions (Postman, 2009). Owing to the small size and large distances of these primitive bodies, ground-based observations face severe limitations on the types of measurements that can be made and on the number of objects that can be measured. A new generation of large aperture telescopes such as the TMT (Thirty Meter Telescope) or the ELT (Extremely Large Telescope) can, and will, lead to breakthroughs in our understanding of the chemical and isotopic properties of small body classes. NASA R&A support to access and use these new facilities will be crucial to continued progress.

Another area in need of support is astrodynamics research. Work in this area greatly enhanced the science return from the Galileo and Cassini-Huygens missions. However, research funding has been largely limited to the development and operations phases of flagship missions. NASA funding for general research in astrodynamics could uncover new techniques that would inform the formulation of new mission concepts, potentially even enabling new types of missions.

Moving beyond the Solar System, the discovery and study of exoplanets requires strong connections between models of planet formation and models for the geophysical and atmospheric conditions of such worlds. A key dimension of forging these connections is relating planet formation models to the observed characteristics and properties of our own solar system. These investments in modeling and theory are critical for interpreting transit and direct-imaging observations of extrasolar planets. Further research and development of coronographs and spectroscopic techniques for both ground and space-based observations of exoplanets is also essential. Given the wide range and rapid pace of discoveries in this field, a coherent and robust R&A effort is vital to producing and interpreting results.

Concluding Remarks

We argue that it is possible to view all aspects of solar system exploration and planetary science through astrobiology's lens. In a companion white paper, we apply this lens to the Planetary Science flight mission program. There is no more compelling approach to these remarkable human endeavors. As humans, we seek to understand the context for our existence, locally and universally. As we seek to learn how common life is in the universe, we come to understand ourselves and our home planet. Many things begin at home. Our home is in the solar system, and it is here that we have the greatest capacity to address astrobiology's profound questions in detail. At the same time, we have begun to develop capabilities needed to extend our quest to other planetary systems in our galactic neighborhood. This merging of the astro-, geo-, and biosciences is as fundamental a development in the history of science as was the original establishment of the scientific foundation for any of the three. Modern planetary science has always been an interdisciplinary undertaking, merging the geological, atmospheric, physical, and chemical. We now add the biological, transforming planetary science into a truly universal field. There is no challenge before us that is more exciting and important for understanding the nature of what is…and what could be.

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