Astrobiology Research and Technology Priorities for Mars

Authors:
Jack Farmer
School of Earth and Space Exploration, Arizona State University
480-965-6748
jfarmer@asu.edu

Mark Allen
NASA Jet Propulsion Lab

Tori Hoehler
NASA Ames Research Center

Michael Mischna
NASA Jet Propulsion Lab

Endorsed by:
Prof. Ariel Anbar (Arizona State University, Tempe, AZ)
Dr. Carl Allen (Johnson Space Center, Houston, TX)
Dr. Juan Gabriel Bueno, MD (Instituto Nacional de Salud, Bogotá, D.C., Colombia)
Dr. Nathalie Cabrol (SETI Institute, Mountain View, CA)
Dr. Susanne Douglas (Jet Propulsion Lab, Pasadena, CA)
Prof. M. Darby Dyar (Mount Holyoke College, South Hadley, MA)
Dr. Jennifer Eigenbrode (NASA Goddard Space Flight Center, Greenbelt, MD)
Dr. Stephen Grasby (Geological Survey of Canada, Calgary)
Dr. Nader Haghighipour (University of Hawaii)
Mr. Jacob Haqq-Misra (Pennsylvania State University, College Park, PA)
Prof. Kip Hodges (Arizona State University, Tempe AZ)
Dr. Richard Léveillé (Canadian Space Agency, Saint-Hubert, Québec)
Dr. Steven Mielke (NASA Goddard Institute for Space Studies, Greenbelt, MD)
Prof. Holger S. P. Müller (Physikalisches Insititut, Cologne, Germany)
Dr. Dominic Papineau (Carnegie Institution, Washington D.C.)
Dr. Victor Parro (Centro de Astrobiología, Madrid, Spain)
Dr. Thomas Pierson (SETI Institute, Mountain View, CA)
Dr. Michal Rozyczka (N. Copernicus Astron. Cntr., Warsaw, Poland)
Prof. Everett Shock (Arizona State University, Tempe, AZ)
Dr. John R. Spear (Colorado School of Mines, Golden, CO)
Dr. David P. Summers (SETI Institute, Mountain View, CA)
Dr. Inge Loes ten Kate, (NASA Goddard Spaceflight Center, Greenbelt, MD)
Dr. Steve Vance (Jet Propulsion Laboratory, Pasadena, CA)
Dr. Alian Wang (Washington University, Saint Louis, MO)
Dr. Kosei E. Yamaguchi (Toho University, Chiba, Japan)

Reviewed: Nat. Res. Council Committee on the Origin and Evolution of Life (COEL)

Goals, Objectives and Investigations

I. Determine if habitable environments have ever existed on Mars.

In a planetary context, the term “habitability” refers to the potential for an environment to support life. At the heart of the current Mars Exploration Program (MEP) are the questions: Have habitable environments have ever existed on Mars? If so, did life ever arise there and does it still persist today?

An important objective for the next decade of exploration will be to refine our understanding of what actually constitutes a habitable environment on Mars. For simplicity, the present discussion of habitability is organized around what are perceived to be the fundamental requirements for terrestrial life: 1) liquid water, the solvent for all known biological processes, 2) sources of biological elements and compounds, which comprise the basic building blocks of organisms and 3) sources of energy needed to sustain metabolism, growth and the replication of living systems. During the coming decade of exploration, we must discover places on Mars where liquid water has co-existed, both in time and space, with the critical elements and potential energy sources required for life.

For each of the lettered objectives below, Investigations (italics) have been ordered according to their perceived importance for advancing Mars Astrobiology in the coming decade.

A) Follow the Water - Water is essential for life as we know it, and has been recognized by the MEPAG as an important cross-linking theme in the overall conceptual framework for Mars exploration (MEPAG 2008). For example, the Martian water cycle is key for understanding the climate system of Mars and how atmosphere-crust interactions have evolved over time. Water also plays a fundamental role in the geologic processes that have shaped the Martian surface and crust, including the history of volcanism, glaciation, weathering, erosion, and sedimentation processes that have left a visible record in the geomorphology of the Martian surface. Finally, water is considered a crucial resource for the eventual human exploration and colonization of Mars.

A fundamental astrobiological goal of Mars exploration is to understand the past and present distribution of water in all its forms. Based on recommendations first articulated in “A Strategy for the Exobiological Exploration of Mars” (NASA 1995), the MEP has systematically pursued a phased program of exploration designed to “follow the water”, alternating orbital reconnaissance missions, with landed missions targeted to specific sites of high interest for astrobiology. This strategy has been remarkably successful. But there is still much to understand about the past and present distribution of Martian water, as a context for targeting the best places for life detection missions in the coming decade.

Priority 1) Subsurface Water: While there is abundant evidence for liquid water at the surface of Mars earlier in the planet’s history, a key question for assessing habitability on Mars today is the potential for zones of liquid water to exist in the subsurface. While the surface habitability of Mars has varied over the geological history of the planet, it is possible that the subsurface has provided continuously habitable conditions over the whole history of the planet. Orbital mapping by the ODY NS GRS experiment has shown water (as both ice and hydrated mineral phases) to be a widespread component of the upper half-meter of the Martian regolith. In addition, MER Spirit has excavated shallow soils with spectral features suggesting the dehydration of ferric sulfates. However, while there is geomorphic evidence for past reservoirs of subsurface liquid water, both as large (seemingly deeply sourced) outflow channels, formed during earlier epochs of Martian history and as small (geologically young) spring-and seep-carved channels, from locally sourced aquifers, or snow melt, direct evidence for a subsurface hydrosphere has remained elusive. In the next decade, we must continue to explore for subsurface water on Mars to more fully assess the potential for habitable subsurface environments that might support an extant Martian biosphere.

Priority 2) Ancient Surface Water: The Mars Odyssey (ODY) THEMIS, and MRO's HiRISE and CRISM experiments have revealed a wide variety of water-formed geomorphic features at the surface of Mars, covering terrains of all ages, and in many cases associated with spectral signatures of water-deposited minerals (e.g. sulfates, halides, phyllosilicates, silica and Fe-oxides). This suggests that liquid water was once widespread over the Martian surface and was, at times, actively cycled between the surface and shallow subsurface hydrosphere, cryosphere and atmosphere, similar to Earth's hydrological cycle. The highly successful Mars Exploration Rovers, Spirit and Opportunity, were targeted to sites previously assigned a high priority for past water activity based on orbital observations. This led to the discovery of extensive outcrops of bedded, hematite-bearing sulfates at Meridiani Planum by Opportunity and water-formed Fe-oxides, sulfates and silica in the Columbia Hills of Gusev Crater by Spirit. Efforts are now underway to select possible landing sites for the 2011 Mars Science Laboratory mission, based on orbital data from ODY, MRO and Mars Express. We must continue to build on these successes through focused site evaluations from orbit and with landed assets, in order to identify the best landing sites to explore for fossil biosignatures preserved in water-formed sedimentary deposits and ground ice.

B) Follow the biological elements – Life as we know it requires carbon, along with the essential elements H, N, P, S. Terrestrial life forms also require a number of transition metals, that have well understood catalytic roles in enzymes. Understanding the processes that control the distribution of bioessential elements on Mars is considered key for a more refined understanding of habitability. In the coming decade, we must improve our understanding of how geological processes (e.g. hydrothermal circulation, evaporation, weathering, etc.) may have shaped surface and subsurface habitats on Mars, potentially creating conditions favorable for the origin and persistance of life. This includes a characterization of carbon reservoirs in the crust (e.g. carbonates, CO_2 clathrates, etc.), as well as atmospheric fluxes of key carbon containing volatiles (CO, CO_2, CH_4, etc.) needed to better constrain the carbon cycle and how it has changed over time.

Priority 1) Distribution and abundance of carbon compounds: We need to refine our understanding of carbon sources and sinks (organic and inorganic) on Mars, including the endogenic processes that synthesize carbon molecules *in situ* and exogenic processes that deliver carbon compounds to Mars via IDPs, meteorites and comets. This will require the detailed characterization of both the molecular structure and isotopic composition of organic compounds present in soils and ices, as well as biogenic gases in the atmosphere.

Priority 2) Nature, distribution and concentration of oxidants: The failure of the Viking experiments to detect measurable carbon in the Martian regolith is consistent with a highly oxidizing surface environment, although the exact nature of the oxidants and their interactions are, as yet, poorly constrained. In addition, it has been pointed out that the

Viking GCMS experiments would have been unable to detect certain relcalcitrant carbon compounds derived from the diagenesis of meteoritic organics (e.g. nonvolatile salts of benzene carboxylic acids, and perhaps oxalic and acetic acids). Thus, such compounds are likely to be present in the Martian regolith today. Redox is considered to be a fundamental dimension of habitability. To understand the processes that have controlled the distribution and availability of carbon and the biogenic elements in the Martian crust, it will be necessary to understand basic redox processes and pathways.

C) Follow the energy - To advance Mars Astrobiology in the coming decade will require models for habitability that are both inclusive (with respect to alternative possibilities for life) and quantitative. In particular, we need models that predict not only whether life could exist in a particular environment, but *how much life* could be supported. In most chemotrophic biological systems on Earth, energy availability constrains biomass abundance over many orders of magnitude. Characterizing and quantifying energy sources on the Martian surface may thus, provide a key observation for prioritizing future landing sites, based on the potential magnitude of the energy "signal" they may harbor. For organisms on Earth, the relationship between energy flux and biomass abundance varies with the physicochemical environment (e.g. temperature, water activity, pH). For example, the amount of biomass supported at steady state by a given energy flux can be expected to decrease as temperatures increase, as water activity decreases, or as pH deviates from an optimal range. This observation presents a means for weighing, on a common basis, the individual and compounded effects of a variety of physical and chemical factors that influence habitability. To take such factors into account requires a means for constraining the effects of these factors over a range of environments. This may be particularly challenging when assessing the habitability of ancient surface environments on Mars. Nonetheless, the rock record may preserve evidence of paleoenvironmental conditions in the mineral assemblages and elemental signatures present, which, in turn, can help constrain the temperature, water activity and pH of the environment.

Priority 1) Biological energy sources: To attain a useful understanding of energy sources on Mars, we must map the geochemistry of the surface and shallow subsurface to better understand the nature of past and present rock-water interactions in the Martian crust. We need to measure the temperature, heat flow and pH of modern surface environments on Mars and map spatial variations in the geothermal gradient of the Martian crust. Finally, we need to develop better geochemical and mineralogical proxies for inferring the temperature and pH of paleoenvironments recorded in the geological record.

II. Understand how changes in climate have affected the surface habitability of Mars over the planet's history

Arguably the three most important influences affecting the present Martian climate and habitability of Mars are the planet's orbital configuration (obliquity, eccentricity, etc.), atmospheric composition and the global water cycle. Changes in the planet's orbital configuration drive the global water cycle, which in turn drives atmospheric composition. To improve our understanding of past habitability on Mars, we will need to advance our study of past and present climate.

A) Changes in the composition of the Martian atmosphere - Coupling studies of the geological history and paleoclimate of Mars is regarded as crucial for an understanding long-term habitability of the planet. Under the present Martian atmosphere the greenhouse warming effect induced by the atmosphere is small (~5°K). However, the existence of liquid water at the surface early in Mars' history requires substantially warmer surface temperatures, which has led to the conclusion that the atmosphere must have either been substantially thicker in the past, or contained some admixture of potent greenhouse gases.

Hitchcock & Lovelock (1967) suggested that the presence of a gaseous atmospheric disequilibrium could be a signature for the presence of life. Methane, which cannot be formed by any known atmospheric chemical process, has a photochemical lifetime of, at most, hundreds of years. Reports of methane in the current Martian atmosphere have raised prospects for the existence of an active subsurface biology and may also be key to unlocking the mystery of the transition from 'warm and wet' to 'cold and dry' Martian climates. Approaches for identifying the processes responsible for producing methane on Mars have centered on the detection of methane isotopologues, but, based on terrestrial experience, could be enhanced by studying the nature of different co-generated species (e.g. ethane, reduced sulfur- and nitrogen-containing compounds), which can more effectively discriminate between biological and non-biological sources and processes.

Priority 1) Atmospheric composition: In the coming decade of exploration a high scientific priority is given to broad, high sensitivity surveys of the atmospheric composition of Mars over a period of one or more Martian years. These surveys should include 4-D variability in methane concentrations, the search for methane isotopologues and other compounds that do not form within the atmosphere. The atmospheric lifetimes of trace gases, including methane, directly influence quantitative simulations of how gas discharge plume evolve in space and time and such information can be used to infer the surface locations of gases being discharged to the atmosphere.

B) Changes in the Martian orbit and spin axis configuration - With its proximity to Jupiter and absence of large, stabilizing moons, Mars experiences significant oscillations in its orbital and spin-axis configurations. Presently, Martian obliquity, or axial tilt, is a very Earth-like 25°, although over the past 10 My, this value has oscillated between extremes of 15°-45°, with a ~100,000 yr period. Obliquities may have been as high as 80° during early periods of Martian history. These variations in obliquity have produced major changes in the strength of the Martian water cycle, both in the magnitude of water vapor transported by the atmosphere, and in the distribution of water ice at the Martian surface.

Priority 2) Orbital history of Mars: Changes in the eccentricity of the Martian orbit are an important factor in driving past climate change by changing the level of seasonal insolation experienced at the surface. Periods of high eccentricity enhance seasonal extremes, resulting in warmer (and wetter) summers and colder (and drier) winters. Orbital eccentricity has ranged, through recent history, from 0.0 (circular) to 0.13 with ~100,000 yr periodicity. Probabilistic approaches suggest a mean eccentricity over Martian history that is about 25% less than the present value (0.069 vs. 0.093), indicating lower seasonality than at present. Over the next decade, we must improve our efforts to model changes in orbital and spin axis configurations over time and their affects on surface habitability.

C) Changes of the Martian climate system over geological time - The history of Martian surface water is recorded in the geomorphology, mineralogy and structure of sedimentary deposits exposed at the planet's surface. In the coming decade, *integrative studies* of the geology, paleoclimate and atmospheric composition of Mars will allow us to 'tease' out information about how climate and habitability have changed over the history of the planet. In conjunction with high latitude, polar-layered deposits, the observation of mid-latitude glacial deposits provides a window into the climate history of Mars. Understanding the origin and emplacement of near surface ice deposits requires an understanding of the relationship between the Martian water cycle and the orbital configuration. For example, during periods of higher obliquity, mixed surface ice/dust deposits appear to have been preferentially deposited on poleward-facing slopes and other thermally advantageous locations. With decreases in obliquity, the upper-most layers of these deposits sublimed, leaving behind a mantle of residual dust that has since protected subsurface ice against further sublimation.

Priority 2) History of the hydrological cycle and climate and their effects on habitability: To progress in our understanding of the biological potential of Mars over the next decade, it will be important to achieve a more integrated understanding of how cyclical changes in the hydrological cycle and climate of Mars have altered habitability at both planetary and local scales.

III. Explore for evidence of past, or present Martian life.

The exploration for Martian life involves two distinct pathways of investigation: The search for a fossil record of ancient life (exopaleontology) and the search for extant life forms (exobiology). The search for a fossil record of past Martian life requires access to ancient sedimentary deposits that represent environments favorable for the capture and long-term preservation of fossil biosignatures. In contrast, the exploration for extant Martian life depends on the discovery of subsurface oases of liquid water where the basic building blocks of life and energy coexist.

A. Explore for a Martian fossil record - The ancient highlands of Mars appear to preserve a record of geological environments far older than anything on Earth. Even if life never developed on Mars, the search for evidence of pre-biotic organic chemistry preserved in ancient aqueously-formed sedimentary rocks could provide important constraints for understanding how life first emerged on Earth, where the pre-biospheric rock record has been largely destroyed by crustal recycling. During the coming decade, missions should expand our knowledge of the ancient sedimentary record on Mars, by interleaving orbital and landed missions designed to progressively focus and intensify the search for fossil biosignatures at sites that are most promising for preserving a fossil record. An implicit requirement for achieving this objective is the ability to gain access to the highest priority landing sites with mobile platforms (rovers), properly instrumented for obtaining definitive mineralogy and biogeochemistry, over a broad range of geological conditions. Precision landing and sustainable (e.g. nuclear) power sources are highly desirable technology developments that will be needed to enable *in situ* life detection missions and targeted sample returns.

Priority 1) Explore for fossil biosignatures and/or pre-biotic organic chemistry: In the coming decade it will be important to carry out life detection and/or sample return missions at well-characterized sites on Mars where water-formed sedimentary deposits have accumulated under paleoenvironmental conditions favorable for the preservation of fossil biosignatures. Providing a proper context for interpreting sample measurements will require mobile platforms (rovers) equipped for scale-integrated analyses of sites, including the local geological context, mesoscale outcrops and structures, microscale textures, elemental and isotopic geochemistry, with high resolution organic analyses carried out on a variety of high priority target minerals (e.g., sulfates, halides, silica, phyllosilicates, etc.). This approach, which is foreshadowed in the MSL (2011) rover and its payload, will provide important constraints for assessing the biogenicity of potential biomarkers, biofabrics and biomediated minerals preserved in sedimentary rocks. The discovery of past life on Mars may ultimately require one or more targeted sample returns. Thus, the caching of promising samples during future landed missions is regarded to be a highly desirable strategy for ensuring future progress.

B. Explore for an extant Martian biota - The absence of liquid water, combined with a high radiation flux and a highly oxidizing regolith, suggests that the surface of Mars is presently unfavorable for life. On Earth, microorganisms have been shown to occupy a broad array of extreme habitats, including subsurface environments where life is sustained entirely by chemical energy. Such discoveries have dramatically increased the potential for subsurface habitable zones on Mars that might sustain an extant Martian biota. Access to subsurface environments through robotic drilling (meters to hundreds of meters) is regarded as an essential technology development that will be needed to explore for subsurface life. If extant life exists on Mars today, it is likely to be found in association with deep subsurface aquifers where habitable zones of liquid water are present, or perhaps within ephemeral, near surface microhabitats where microzones of liquid water may exist as thin films (e.g. surrounding sediment grains in soils), or as fluid inclusions within evaporites (salts), or ice crystals.

Priority 2) Explore for a subsurface biosphere: Gain access to subsurface habitable zones of liquid water, or ices that have formed recently in association with upwelling hydrological (e.g. hydrothermal) systems. Develop robotic systems capable of reliably drilling to depths of meters to hundreds of meters, with coupled life detection experiments that will analyze cuttings of ice/regolith and melt water for evidence of organic compounds and biosignatures. Some of these ideas are central elements of the ESA's planned ExoMars mission.

C. Develop Definitive Methods for Life Detection

Approaches to extraterrestrial life detection are still in their infancy. So far, life detection methods have followed a terracentric path, assuming that putative Martian life will be Earth-like, perhaps as a result of the transfer(s) of viable organisms between the two planets (i.e., 'panspermia'). However, if a presumed Martian life form(s) developed independently, or evolved along pathways dramatically different from terrestrial life, then definitive life detection will require the development of more universal methods.

Given the high sensitivities required to measure potentially low abundances of bio-organic components in Martian materials, forward contamination (organic compounds and/or microorganisms carried to Mars on various spacecraft and instrument components) must be carefully controlled, to minimize the chances for a false positives. Missions that will search for the elemental and molecular signatures of Martian life will needed to follow stringent protocols for minimize the impacting of forward terrestrial contamination. This will require high levels of spacecraft cleanliness (to reduce bioloads to an acceptable level), plus reliable *in situ* methods (e.g. witness plates, etc.) to identify the nature of any forward contaminants present. Planning for *in situ* life detection missions during the next decade should include the parallel development of both terracentric and universal methods for life detection.

Priority 1) Develop methods for in situ life detection: Develop both terracentric and universal approaches for the detection of extant life forms on Mars that can be applied over a broad range of surface conditions and materials. Define protocols to distinguish between terrestrial forward contaminants and putative Martian life forms.

D. Return Astrobiological Samples to Earth

The technology challenges associated with gaining access to deep (100s to 1000s of meters) subsurface zones of liquid water on Mars by robotic drilling are formidable. At this stage, progress on the question of Martian life is likely to come more quickly through the search for fossil biosignatures preserved in ancient, surface exposed sedimentary rocks. While it possible that compelling evidence for fossil biosignatures may be obtained through *in situ* missions, the definitive identification of putative Martian life forms may prove to be impossible using remote, robotic methods. For this reason, targeted Mars Sample Return (MSR) has been broadly advocated as an essential step for the definitive detection of past Martian life. On this basis, MSR provides a logical step in the exploration for an ancient a Martian biosphere, provided that the samples returned have been highly targeted by precursor *in situ* missions.

Priority 1) Targeted MSR for fossil/subfossil biosignatures - On Earth, it is well known that some subsurface hydrological processes (e.g. hydrothermal upwelling, artesian springs, etc.) routinely bring deeply sourced subsurface water (and the associated microbiota) into surface/near surface environments. On Mars, there may be sites where such processes may have operated recently and where subsurface flows have been added to ground or surface ice. It is also known that certain evaporite deposits (e.g. halite salts) may retain microorganisms in a viable state over prolonged periods of time. If discovered, such sites would provide particularly compelling targets for a first life detection missions.

While MSR will provide opportunities for highly sophisticated analyses of Martian materials in terrestrial labs, it will also require the implementation of extensive planetary protection protocols to address international concerns over planetary back-contamination. This reality will add significantly to the cost and complexity of astrobiology missions and may require international partnering to be affordable. Thus, the value of MSR should be carefully weighed against the value of additional *in situ* mission investments. Given the cost and complexity, MSR should be discovery-driven. To effectively address issues of planetary back-contamination, MSR must be preceded by the development of sample containment technologies, sample handling and biohazard testing protocols, specification of criteria for sample release, etc. and completion and staffing of a Sample Receiving Facility prior to sample return. (see “Assessment of Planetary Protection Requirements for Mars Sample Return Missions”. 2009. National Academies Press ISBN: 978-0-309-13073-8, 90 pages.