Interdisciplinary Research in Terraforming Mars: State of the Profession and Programmatic

White Paper for the Planetary Decadal
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Primary Author:

James L. Green, NASA Headquarters, james.green@nasa.gov, 202-657-2197

Co-Authors:

Vladimir Airapetian, NASA GSFC & American University, vladimir.airapetian-1@nasa.gov,
Ruth Bamford, Rutherford Appleton Laboratory, ruth.bamford@stfc.ac.uk,
Neysa Call, NASA Headquarters/National Science Foundation, neysa.m.call@nasa.gov,
Chuanfei Dong, Princeton University, dcfy@princeton.edu,
Jeffery Hollingsworth, NASA Ames Research Center, jeffery.l.hollingsworth@nasa.gov,
Scott Hubbard, Stanford University, scotthub@stanford.edu,
Melinda Kahre, NASA Ames Research Center, melinda.a.kahre@nasa.gov,
Barry Kellett, Rutherford Appleton Laboratory, barry.kellett@stfc.ac.uk,
Douglas Ming, NASA KSC, douglas.w.ming@nasa.gov,
Tara Ruttley, NASA Headquarters, tara.m.ruttley@nasa.gov,
Raymond Wheeler, NASA KSC, raymond.m.wheeler@nasa.gov,

Endorsements:

Louis Barbier, NASA Headquarters
Shawn Domagal-Goldman, NASA Goddard Space Flight Center
James W. Head, Brown University
Paul Mahaffy, NASA Goddard Space Flight Center
Ralph McNutt, Johns Hopkins University/Applied Physics Laboratory
Doug McQuisition, McQTech, LLC, (NASA MEP Director, Retired)
Lisa Pratt, NASA Headquarters
C. Alex Young, NASA Goddard Space Flight Center

Required Short Abstract (350 characters)

To support NASA's Human Exploration of Mars, programmatic considerations must be delineated in the Decadal. This white paper supports closing all strategic knowledge gaps. A sustainable human presence on Mars encompasses data, simulations, models, and considerations on how, with humans on the surface, Mars will be transformed or terraformed.

Executive Summary

To fully support NASA's Human Exploration of Mars, programmatic considerations must be delineated in the Planetary Decadal. This paper supports closing all strategic knowledge gaps (SKG) through observations required in this new decade. The Planetary Science Division (PSD) must make these new observations, provide accommodations for others to make these observations, or partner with the international and commercial communities to get these observations as part of their Mars exploration plans. The decadal must support this *new initiative* and allow PSD to accomplish this important task by any means possible. In addition, we must be prepared for creating a sustainable human presence on Mars encompassing not just data, but simulations, models, and considerations on how, with humans on the surface, Mars will be transformed or, as some would say, terraformed.

1.0 Introduction

Humans are terraforming the Earth and when they arrive at Mars their influence will begin that process on the red planet. While many in the community reject terraforming, as human exploration of Mars comes closer, it is clear that the topic deserves more rigorous attention. We do not know if Mars supported life in its past or even today. Recent studies, 2 by the NAS and 1 by a NASA Independent Review Board, have all concluded that human exploration of Mars could very well alter the scientific search for life and thus a new set of planetary protection guidelines and scientific approaches are needed. A new, forward looking research initiative is needed that would enable long-term, sustainable human science and exploration of Mars in a way that human influences on the environment are planned, under control over time, and evolves utilizing the best science knowledge. One goal of this white paper is to identify the following research aspects of Mars terraforming: 1) areas where knowledge gaps exist; 2) new capabilities that need to be developed; 3) areas in which coordination with planetary science on related research by other disciplines that must occur. As input to the planetary decadal it is important to assume that the Human Exploration Office (HEO) will develop systems supporting humans on Mars such as: habitats, waste management, etc. Other disciplinary research must also support and connect with HEO in the areas that they are the subject matter experts.

1.1 Planetary Protection and Exploration

In the latest 2 NAS studies on planetary protection (PP), the panel members elected to deliberately avoid the questions of ethical considerations about indigenous Martian life. These panels argued that the membership was not properly constituted and that such issues were not directly part of their study charters. Such considerations cannot be sidestepped forever, so panels with a membership that can address these questions are necessary. Between the missions traveling to Mars now and Mars Sample Return (MSR), there is a growing possibility that the fingerprints of past Mars life will be discovered. Sporadic releases of methane, oxygen, and other evidence points to searching for life underground. What are the legal and moral rules and guidelines for terraforming should contact with microbial life be made? Can Mars be shared and if so, what are the constraints of such a relationship? Answering these questions is a necessary prerequisite to these activities. Thus, we need to enhance our investment in PP techniques and methodologies, complete our detection of life program, and seek NAS guidance, involving experts from the relevant domains. We must move forward. Therefore, we fully endorse the White Paper [1] on identifying and closing PP knowledge gaps.

1.2 A Vision of the Future

NASA's strategy for Human Exploration is to land first on the Moon and then on Mars. The Moon is an important location for humans to learn how to live and work on a planetary surface. The approach for Mars starts out with defining an exploration zone (EZ). Within the ~200 km diameter EZ are the landing sites, habitat, science sites, and *in-situ* resource utilization (ISRU) sites that will be in use for decades. NASA is just beginning to grapple with the issue of whether an EZ can be properly defined as to allow human visits while also maintaining the ability to conduct comprehensive astrobiology research. It is a view of a growing number of scientists that terraforming Mars on a local or regional scale should be part of these discussions since a sustainable human presence will undoubtedly modify the environment. We should not "back in" to these alterations of the planet, but rather face them head on.

The NASA led Human Exploration of Mars will be both an international space agency sector and a commercial endeavor. All sectors must provide significant resources and capabilities to support this endeavor in a highly coordinated way. A series of key infrastructure missions are anticipated including: 1) next-generation STEREO solar observations; 2) Mars L1 solar and solar wind observations; 3) low-altitude planet-asynchronous orbiter observations monitoring dynamical phenomena rapidly evolving in space and time; and 4) planet-wide array of ground-based magnetometers, seismic sensors, and other meteorological instruments. We must be able to fully understand the near-surface planetary environment (e.g., temperatures, surface pressures, surface wind regimes and their variabilities, net radiation fluxes at the surface, etc.), both regionally and globally. At least three spacecraft at areostationary orbit perform the following functions: 1) relay all surface voice/video/data back to Earth; 2) provide Earth to EZ relay capability; 3) communicate atmospheric weather observations relayed to EZ and Earth; 4) acquired particles and field data relayed to the EZ and to Earth.

2.0 Planetary Science with Human Exploration

With Perseverance on its way to Mars the next missions being planned with the international space agencies are to bring back samples in a series of missions called Mars Sample Return (MSR) campaign. The Mars Exploration Program (MEP) has also set up the Mars Architecture Strategy Working Group (MASWG) to delineate a Mars robotic program distinct from MSR. A white paper has been submitted to the NAS that puts forward a plan for a series of missions to "accomplish compelling science and as part of preparations for human missions" [2]. This architecture calls for MEP to select two or more mission arcs (or series of connected missions over a range of cost classes) from the four suggested arcs: 1) diverse habitable environments; 2) subsurface, composition and life; 3) recent climate change as recorded in ice; 4) climate variability and process.

Currently 37 white papers about Mars science missions have been submitted to the NAS in support of the Decadal development. Several missions clearly show a need for observing Mars from a variety of orbits ranging from low altitude, areostationary, and out to Mars L1. Expecting that some of these missions will be included in the Decadal, an extremely important analysis should determine how these missions could be augmented with critical measurements to support other disciplinary work that would go into supporting human exploration of Mars. The importance of those missions that fulfill SKGs, as noted in this white paper should be elevated and considered for execution. As other space agencies and commercial missions arrive and operate at Mars, PSD should work with those groups to obtain SKG observations. It is important to understand that NASA's open data policy does not necessarily occur for missions from others. The PSD is in a unique position to coordinate these activities. If PSD does not do this, we will have lost valuable time and momentum, perhaps by decades, to the detriment of future transformational science that would be accomplished by humans on Mars.

2.1 Surface and Subsurface Features

Significant progress has been made in identifying the EZ for Mars. Features and resources on Mars for supporting humans include, just to name a few: 1) lava tubes and their accessibility – what are the environments like inside them and how can they be used?; 2) aquifers – how accessible are they and how much water do they contain?; 3) buried ice resources - is there a supply at mid to low latitudes?; and 4) geothermal activity - does any exists that might be exploited? The October 2015 EZ workshop identified ~45 potential sites. An ongoing, intense international effort, with significant PSD involvement, has been tasking orbital assets and obtaining high resolution data in support of evaluating these proposed regions. The next workshop is planned for May 2021 to downselect the number of sites.

2.2 Atmosphere and Climate Modeling

The Mars Space Weather (SW) environment affects the ionosphere and the lower, middle, and upper atmosphere. The recent Sept. 2017 solar X-flare heated the thermosphere and ionosphere [3] with the solar energetic particles observed by Curiosity rover on the surface [4] and produced a massive aurora [5]. How severe would a Carrington event be at Mars? Initial modeling indicates that the surface would receive a huge 3000 nT field [6]. We need new supporting research to answer that question.

Mars' regional and global topography and its extreme variations in altitude are ubiquitous sources of diurnal, day-to-day, and seasonal atmospheric variability associated with atmospheric waves that inevitably affect the local environment, the EZ regional locales, and then the continental-scale environment [7]. Such atmospheric waves and their effects on the seasonal mean circulations also connect the lower-middle atmosphere with the upper atmosphere and ionosphere. This connection between lower and upper atmospheric physical processes must be measured and fully understood prior to humans staying on the surface of Mars.

Several years ago, PSD established the Mars Climate Modeling Center (MCMC) at Ames. The goals of the MCMC are to develop, maintain, and provide state-of-the-science atmospheric models and full 3D high-resolution global climate models for Mars. The current models that the MCMC supports span from the surface to the homopause. With future missions dedicated to Mars, and with the advancement of atmospheric and global climate modeling for the planet, the Agency will only then be able to understand the human risks. One of the largest sources of atmosphere and environmental variability at Mars are dust storms occurring on various spatial and temporal scales, from local/regional to hemispheric and global [8]. The precise mechanisms that trigger local and regional dust storms to become hemispheric or global is currently not understood. Atmospheric measurements at the near-surface are necessary to provide ground-truth measurements. Coupled with remote sensing by orbiters, developing and dissipating dust storms may be placed in context: geographically, seasonally, and on interannual time scales. Weather modification mechanisms to abate the impact of dust storms on the EZs should be an area of future research.

Only a limited supply of sequestered CO₂ exists within Mars's geophysical environment [9] and the largest sinks have been lost to space via impacts and then via solar wind stripping of the atmosphere [10;11]. Releasing the buried CO₂ under the south polar cap could double the mass of the atmosphere [12]. Some studies [13;9] have promoted candidate chemical species of greenhouse gases that would significantly warm the climate; more research is needed along with coupling the analysis with the ability of the MCMC to predict the outcome.

3.0 Planetary Science with Heliophysics

For the Heliophysics Division (HD), in partnership with PSD, a comprehensive Mars Space Weather and Atmosphere Modeling (MSWAM) system must be developed. No space weather system exists for Mars. The system should start at the Sun, with 360° coverage by observations and models that ingest

relevant data streams as more become available. The MSWAM system must employ atmospheric models starting with those developed in the MCMC and extend those outward by coupling to space environment models. The MCMC must continue to be updated and improved providing detailed surface weather status and predictions. This total system then provides the breadth of relevant space and Mars weather information as well as output suitable for scientific research, validation, and verification.

3.1 Mars Space Weather Predictions

The MSWAM and MCMC systems should be designed to provide rapid dissemination of information to Earth controllers, astronauts in transit, and those in the EZ by producing alerts that are delivered rapidly and are actionable. A series of key measurements must exist that are fed into the MSWAM and MCMS system that include at least the following: 1) solar observations; 2) Mars L1 solar wind observations; 3) low-altitude orbiter observations monitoring dynamical phenomena rapidly evolving in space and time; and 4) planet-wide ground-based magnetometers and seismic instruments.

Compelling planetary science missions will be delineated in the decadal, which presents the perfect opportunity to cooperate on Mars missions with PSD by providing key heliophysics payloads. These missions are trying to fill critical science gaps, including understanding solar activity effects on Mars' system, the coupled solar wind - magnetospheric, ionospheric and upper atmosphere dynamics, and exploring the interior structure through magnetosphere-interior coupling during extreme events.

3.2 Magnetic Field Considerations

Mars lost its intrinsic dynamo field over 4.0 Ga. A magnetosphere is known to provide resilience against solar storms removing the outer layers of the atmosphere [14]. There is compelling evidence that Mars has lost a significant amount of atmosphere to outer space [15]. Partial protection of the Martian atmosphere from the solar wind is provided by the strong, localized remnant crustal magnetic fields [16; 17]. How these magnetic bubbles interact with the solar wind/atmosphere interaction region adds a complexity that must be investigated in greater detail.

Current monitoring of Mars shows an ongoing loss of key atmospheric elements, such as oxygen, due to solar short wavelength radiation (EUV and X-rays) and solar wind energy inputs [18]. The mass of Mars is another important parameter, leading to an extended hot oxygen corona [19; 20]. Therefore, creating a sizable magnetospheric cocoon around the EZ or Mars to help retain a denser atmosphere in future may be vital. When considering an artificial magnetic field, the size, location, intensity, and topography of the magnetic field are all free parameters. Analysis of the engineering, resources available, and power needed as well as the economic and energy requirements for both the construction phase and the maintenance of a magnetic field capable of creating an artificial magnetosphere would need to be modelled in detail.

4.0 Planetary Science with Biological & Physical Sciences

The Biological and Physical Science Division (BPSD) is a new division in the Science Mission Directorate which performs space biology research ranging from microbes to plants and animals. BPSD will play a critical role in developing capabilities necessary to support humans on Mars. PSD should provide critical Mars environmental data and by deliberate planning and developing research objectives.

4.1 From the Study of Dust and Soils to Agriculture

The dust and soils on Mars are largely basaltic in composition. All 16 essential elements for plants have been identified in Martian soils, so in theory, they may be bioavailable for plant growth. Nitrogen (N) is present in surface soils and some of the sedimentary rocks that have been examined by Curiosity.

N and other essential elements would be quickly depleted in plant growth so fertilizer will be required. At this time, current research indicates that we do not expect major toxicological issues, but several related areas will need further study. Toxic effects of Martian dust on humans is unlikely to be an issue for human health based upon the iron state in surface materials [21]. Another major issue concerning toxicologists is plant uptake and accumulation of perchlorate in plant biomass, thereby eventually passing the toxin into the human food chain. This fundamental area of research needs to be addressed. It is also important to understand the distribution of surface perchlorates since they are not ubiquitous.

Specialized simulants are made to mimic a wide range of chemical variability observed at the various landing sites on Mars. A new simulant has been developed that not only has the chemistry, but also the volatile content as identified from the Curiosity-SAM instrument datasets [22]. The simulant was developed in quantity (800 kg) for testing water extraction techniques. Additional research is needed on what can and cannot survive under Martian surface conditions. The impacts of dust and soil on human missions must be addressed, but we do not foresee “show-stoppers” based on available data. We need to define the types of experiments for testing and evaluation of Mars soils that should be implemented on the surface of Mars, in the laboratory using simulants, and with returned soil samples.

4.2 Vegetation for Food and the Environment

Plants play an important role in life-support systems because they recycle water and oxygen and filter out CO₂ while generating food [34]. Humans will need both closed and open systems. How these systems will operate and when, will require knowledge of the evolving environment that can only come from PSD.

Closed Environments: Initial attempts to grow plants and other photosynthetic organisms on Mars will require protected habitats where pressure, gas composition, temperature, and relative humidity can be controlled. The resilience of plants to Mars levels of radiation or various levels of attenuated radiation needs further study and these findings could help define structural requirements and shielding to protect plants. Ambient solar lighting would be sufficient for many plants but collecting the light and transmitting it to the plants will require further developments in sturdy transparent materials and solar light collection systems [23; 24]. Other than dormant phases or extremely hardy species, temperatures must be kept above freezing (0°C) for most actively growing plants, and below ~35°C for optimal growth. Plants can tolerate and grow well at reduced pressures (down to ~20 kPa or 200 mb) provided sufficient pO₂ (~10-15 kPa), water vapor (~0.5 – 2.0 kPa), and CO₂ (~0.1 - 1.0 kPa) [25; 26]. This tolerance of plants to reduced pressure could allow the use of independent structures with lower mass and reduced gas leakage. More research is needed in this area. Plants will require a constant supply of water and nutrients to sustain good growth.

Open Environments; Very hardy photosynthetic organisms such as cyanobacteria and lichens may be good candidates as early pioneers for surviving in external Mars environments, but all would require reduced levels of UV radiation. The resilience of these organisms to very low partial pressures O₂ and H₂O is an area needing further study. If such hardy species could become established along with an associated microflora, the basis for expanding vegetative cover would be revolutionary. This would be closely linked to the establishment of a diverse “soil” microbiome with increasing organic matter in surface regolith, and continued mineralization. Among the most promising Earth plants expected to survive were in the *Bryophyte* phyla—small plants like mosses, liverworts, and hornworts—and the *Tracheophyta* phyla—vascular plants such as ferns, selaginellas, and horsetails [27], again with reduce UV. A promising group of higher plants could be the genus *Poa*, a group of perennial grasses with hundreds of different species. In addition to being able to handle frigid temperatures and intense solar radiation, *Poa* would take up minimal space, require little maintenance, and could produce large

quantities of seeds [27]. Another line of research is examining the feasibility of growing snow algae at Mars pressures and low temperatures [28]. The research is in progress and shows that these remarkable organisms not only survive, but flourish under near-Mars challenging conditions.

4.3 Use of Synthetic Biology

Synthetic biology allows biological organisms to be optimized for human use. The scientific community has pursued synthetic biology overwhelmingly for beneficial purposes on Earth ranging from reducing the burden of disease to improving agricultural yields - all necessary for supporting humans on Mars. Mars conditions are extremely harsh. Thus, the utilization of biological systems for production of resources on Mars is not just appealing but a necessary approach. Future Mars settlers will need habitats, clothing, food, water, medicines, waste removal, recycling, propellant, and more.

Synthetic biology methods use biological intermediates to create fundamental necessities utilizing *in situ* resources. For example, Martian CO₂, N, H, and O could be converted to important target areas of propellant, food, biopolymers, and pharmaceuticals with the introduction of biological intermediates [29]. Synthetic biology could be used for propellant produced on Mars to satisfy local needs as well as to support the return trip, decreasing the Earth-supplied fuel mass by as much as a factor of three [29]. Based on food sent to the ISS, 1.83 kg of food per person, per day, would need to be shipped to Mars from Earth [30; 31]. On-site food production becomes a game-changer. Biologically derived biopolymers could be used for on-demand plastic production in housing, tools, and critical infrastructures on the surface, potentially saving up to 30% of launch mass [32]. Regarding medical needs, pharmaceuticals under high-radiation levels lose effectiveness by ~70% on missions lasting 880 days. On-demand synthetic manufacturing of a wide range of medicines would be required [32]. Synthetic biology approaches transformed astronaut waste into practical products with less mass as compared to conventional abiotic means [29]. The PowerCell payload on the EuCROPIS satellite also informed genetic engineering and bioprinting beyond Earth as well as the effectiveness of photosynthetic and nitrogen-fixing cyanobacterium engineered to secrete sucrose and protein production under a Martian gravity regime [33].

Using biological systems to produce needed resources on Mars is envisioned to provide substantial benefits. However, full reliance on modified organisms requires additional research and dramatic advances. Challenges and opportunities include improving biological extraction and utilization of limited space resources; the manufacture and construction of products useful in space; support of human life; the treatment of human health; and even the development of biological devices that can emulate and interact with non-biological components. Future biological processing, anaerobic or aerobic, must be developed for each kind of space resource, e.g., solid waste, volatiles and minerals, and other geological materials. The PSD in concert with others, must be able to help create a focus for this research effort to the point of defining and executing critical experiments on the surface of Mars.

5.0 Conclusions

NASA is in the process of creating a vision of future exploration to live and work on Mars. Scientifically, we should move boldly into joining this vision ensuring that the first humans on Mars have significant science backgrounds with meaningful work to perform on the surface. Therefore, the new decadal survey must include closing all SKGs and begin to develop sustainable technologies to support the Moon-Mars vision and humanity's expansion into the solar system. To achieve NASA's objective of developing sustainable capabilities for the long-term human exploration of Mars, cross-discipline research needs to be accomplished. The process of developing the programmatic requirements must begin in this decade if humanity will walk on the surface of Mars by mid-century. Because of the

magnitude of the research efforts, multi-year funding will be needed. This decadal survey should strongly support and recommend funding new programmatic elements designed to work between the science disciplines and to greatly encourage PSD to aggressively pursue all programmatic options with other organizations, space agencies, and the commercial sector that will lead to supporting humans on Mars and understanding of the effects they will have on the red planet.

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