47th International Conference on Environmental Systems
16-20 July 2017, Charleston, South Carolina

ICES-2017-285

Planetary Protection Considerations of Mars Dust in the Context of Current Human Exploration Concepts

J Andy Spry[1], Angela Zalucha[2] and Lori Fenton[3]
SETI Institute, Mountain View CA 94043

One of the features of the Apollo missions was the pervasiveness of the lunar regolith on the spacecraft systems exposed to the lunar environment, including the astronauts' suits, and on the astronauts themselves. So much so, that the expectation is that for martian exploration, it will be impractical for astronauts to be fully isolated from the martian dust environment for the entirety of their time on the red planet, at least not at the level of the 1x10e-6 probability of exposure that is the current planetary protection requirement for avoidance of release into the terrestrial environment of martian material from a robotic sample return mission. In addition, all human exploration activities carry the threat of leakage of terrestrial material as a result of nominal (e.g. airlock) and non-nominal operational conditions.

So, given that some (tbd) level of material exchange will occur, what are the ramifications for a human exploration mission, as envisaged in NASA's "Journey to Mars"? This paper will consider first, the issues and mitigations from a planetary protection perspective, considering release of terrestrial material at Mars ("forward" contamination); its fate based on physico-chemical properties of the martian environment; near- and far-field dispersion; and its impact on zoning models for managing exploration, particularly at the surface regions on Mars (so-called Special Regions) that may be habitable for terrestrial hitchhikers on such materials. Second, the issues and mitigations around the ingress of/exposure to martian dust ("back" contamination) are considered, in particular those related to astronaut health and the return to Earth.

The discussions in this paper will also reflect a subset of the findings of the 2016 COSPAR workshop on Refining Planetary Protection Requirements for Human Missions.

Nomenclature

ATP	*Adenosine triphosphate*
COSPAR	*Committee on Space Research; part of the International Council for Science*
EVA	*Extra-Vehicular Activity*
GCR	*Galactic Cosmic Rays*
HEPA	*High Efficiency Particulate Air(filter)*
ICES	*International Conference on Environmental Systems*
ISRU	*In-situ Resource Utilization*
NASA	*National Aeronautics and Space Administration*
SETI	*Search for Extraterrestrial Intelligence*
ULPA	*Ultra Low Penetration Air(filter)*
UV	*Ultra-violet*
ZMBR	*Zone of Minimum Biological Risk*

I. Introduction

ONE of the features of the Apollo missions was the pervasiveness of the lunar regolith (in particular, dust) on the spacecraft systems exposed to the lunar environment, including the astronauts' suits, and on the astronauts themselves. About the albedo of asphalt, astronauts commented that after EVAs to the lunar surface, the particles

---

[1] Senior Scientist, 189 Bernardo Ave., Mountain View CA94043.
[2] Research Scientist, 189 Bernardo Ave., Mountain View CA94043.
[3] Senior Research Scientist, 189 Bernardo Ave., Mountain View CA94043.

from the lunar surface made their features look more like those of coal-miners than high technology explorers of a new world. In addition, the nature of the dust particles on the moon, sharp-edged and abrasive, caused significant degradation to their equipment during the course of the missions, including operational failures of camera fittings, Velcro fixings and so on. In particular, the late Apollo 12 astronaut Pete Conrad found that the abrasive effects on his suit joints were so extensive that after eight hours of EVAs on the surface, wear was greater than that experienced in 100 hours in training, and having worn through the outer layer, it was considered likely that a pressure failure would have been experienced after one or two more EVAs. In the late Apollo 17 Commander Gene Cernan's words, "I think probably one of the most aggravating, restricting facets of lunar surface exploration is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and its restrictive friction-like action to everything it gets on".[1]

Finally, there were significant acute health issues with the dust: eye irritation, lung irritation and hay fever symptoms, which may also be indicators for chronic conditions, such as silicosis, had the missions been extended from 75 hours (the longest Apollo era stay on the lunar surface) to the 500-day durations planned for in current Mars exploration architectures.[2]

II. Expectations for Martian Exploration

The experiences of the Apollo crews, and the fact that any near-term crewed exploration of Mars will be based on similar kinds of hardware and operational concepts (sorties from a habitat, with EVAs performed in suits and/or pressurized/unpressurized rovers), means that it will be impractical for astronauts to be fully isolated from the martian dust environment for the entirety of their time on the red planet. Certainly, it will not be practical at the level of the 1x10e-6 probability of exposure that is the current planetary protection requirement for avoidance of release into the terrestrial environment of martian material from a robotic sample return mission. This is recognized in the COSPAR policy for planetary protection of crewed missions, which provides the international guidelines adhered to by all spacefaring nations. Here, the COSPAR policy[3] notes that: "The intent of this planetary protection policy is the same whether a mission to Mars is conducted robotically or with human explorers. Accordingly, planetary protection goals should not be relaxed to accommodate a human mission to Mars. Rather, they become even more directly relevant to such missions—even if specific implementation requirements must differ." The policy goes on to note that: "Safeguarding the Earth from potential back contamination is the highest planetary protection priority in Mars exploration; the greater capability of human explorers can contribute to the astrobiological exploration of Mars only if human-associated contamination is controlled and understood. For a landed mission conducting surface operations, it will not be possible for all human-associated processes and mission operations to be conducted within entirely closed systems," and: "Crewmembers exploring Mars, or their support systems, will inevitably be exposed to Martian materials."

The effects of these last two points are those that would be mitigated by use of approaches such as suit ports, vacuuming or "air" showers, which will mitigate but not entirely remove the dust. Even though the dust particles themselves on Mars will be very different from the moon having been altered by water and wind processes that reduce the abrasiveness compared to the lunar dust, the long duration of the Mars exploration missions under study will necessitate servicing and repair of suits and other articles exposed to the surface dust, requiring astronauts to be in direct contact with surfaces exposed to the martian dust.[4] Clearly the ramifications of that contact (both in terms of astronaut health and the contamination of Mars by exposure to terrestrial organisms) need to be understood before exploration is allowed to happen. Further, it is not only the biophysical effects (particulates in lungs, etc.) of the dust that needs to be dealt with; the chemical nature of the martian dust needs to be understood so that both acute and chronic effects of topical exposure and ingestion (if any) can be appropriately mitigated or prevented. While such biophysical effects are not a planetary protection issue per se, the ability to discern between an astronaut who is sick due to exposure to martian chemistry from one who is sick due to exposure to martian biology is a planetary protection issue, and an important one in the context of decision-making about whether such a sick individual is allowed to return back to Earth or not, in the context of "Safeguarding the Earth" language that the policy[3] specifies.

III. Exploration Systems as Biocontaminant Sources

In addition, the control of the reverse phenomenon, namely human-, habitat- and other terrestrial-associated contamination reaching the Mars environment, also needs be addressed by appropriate mitigation strategies. To date, all human exploration system concepts carry the threat of leakage of terrestrial material as a result of nominal (e.g., airlock) and non-nominal operational conditions. For example, Apollo-era EVA suits had an astronaut-operated release valve in case of an overpressurization or other anomaly, venting to the local environment. Applied to Mars, this procedure would result in the astronaut introducing a personal plume of contaminant particles, with microbial populations based on his/her microbiome, into the martian environment. Is that acceptable? Under present robotic planetary protection policy, that would not be acceptable, though this policy will not be relaxed without data to support that the martian environment can "cope" with release of such particles without causing the "harmful contamination" event that international treaty seeks to avoid. Similarly, habitat systems with an overpressure relative to the local environment will leak and potentially have vent paths that will need contamination prevention strategies similar to those used for microbial containment and isolation systems on Earth, likely based on HEPA and ULPA filtration technologies.

While accommodating and constraining the "forward" contamination in this way, it is intended to develop a "zoning" strategy, of the kind described in the Safe on Mars report[5], which can be used to determine cleaner, less clean, and pristine zones on Mars during the period of crewed exploration. This strategy can be viewed as effectively adding a "less clean" option to the current zoning of Mars for robotic missions, sites that are Special Regions (kept pristine) and sites that are not (clean). Currently, most of Mars is thought to be able to tolerate introduction of a low number of organisms (5x10e5 spores/spacecraft), equivalent to the pre-sterilization cleanliness of the Viking spacecraft after building in a class 100,000 cleanroom. However, some regions of Mars (areas/volumes where terrestrial organisms may propagate, currently known as "Special Regions"[3]) need to be protected at a higher level, permitting no more than around 30 surface spores/spacecraft. The boundaries (physical and temporal) for a less clean region, proposed as zones of minimum biological risk (ZMBR) in the Safe on Mars report, need to be defined based on the ability of the martian environment to kill released organisms to an acceptable degree before they reach and contaminate any "Special Region".

The key to defining these boundaries is having the information required to *allow* an environment at Mars to become contaminated with viable terrestrial organisms, but to still know that harmful contamination is not going to result. For this situation we need to know what happens to a terrestrial organism when it is introduced into the martian environment and over what time period. At the present time, there is a working assumption that the aggressive nature of the Mars environment will kill all terrestrial organisms before they can migrate via natural processes to a location where they can survive and, subsequently, replicate, although the number of organisms that can be accommodated in this way, and over what time period and what distances is still unknown.

IV. The Fate of Terrestrial Biological Contaminants in the Martian Environment

Several studies suggest that viable microbes have already reached the martian surface, having survived sterilization efforts on Earth, interplanetary transport, and the heat of re-entry during the landing of spacecraft.[6-8] Once on the surface, the most important and best-studied biocidal factor has been that of UV irradiation. Unlike Earth's atmosphere, the thin martian atmosphere does not substantially attenuate UV radiation, particularly at the lethal UVC wavelengths ranging from 190 to 280 nm.[9,10] Several studies have concluded that the resulting UVC fluence rates at the surface of Mars would rapidly kill unshielded microorganisms, even UV-resistant spores, reducing the exposed bioburden by several orders of magnitude on timescales ranging from minutes to hours (e.g., refs. 7, 11 and 12). This finding holds true even on the undersides of spacecraft[11] and in small pits and cracks of spacecraft materials,[13] although some interior and/or shielded niches may be better protected. At first glance, it seems that forward contamination of Mars is unlikely.

Many other biocidal factors in the martian environment may also reduce the bioload,[14-17] including desiccation, an anoxic carbon dioxide atmosphere with low air pressure, and low temperatures. However, some bacterial strains have been found capable of metabolizing in carbon dioxide in laboratory environments with martian atmospheric pressures and temperatures.[17-19] Other suggested inhibitors of microorganism metabolism and propagation include extreme temperature fluctuations, soil geochemistry (including oxidants, heavy metals, high salinity, perchlorate, and acidity), galactic cosmic rays (GCR), solar particle events, glow discharge plasmas created within lofted dust, and a shortage of energy and nutrient sources. The combined biocidal impact of these factors on Mars are not easily modeled and they are largely unconstrained. However, some factors have been suggested to play a more minor role compared to UV irradiation, such as soil geochemistry[20] and GCR.[21-22] The microbial inhibition resulting from local soil and atmospheric properties is expected to vary considerably with location on Mars and in some cases with season[15], suggesting that each potential landing site must be investigated in detail prior to any landed mission, particularly that involving human habitation. In addition, some microbial species are more resistant than others to UV irradiation, as well as to other biocidal effects, for example as described in refs. 7 and 23. A major limitation of the current state of knowledge is the vast numbers of microbial taxa yet untested for their resilience in Mars-like conditions, including noncultivable bacteria as well as archaea and eukarya, that are only identifiable with modern molecular methods.[24]

Is solar UV irradiation on Mars alone sufficient to remove any potential forward contamination by terrestrial microorganisms? The answer emerging from lab studies appears to be "no". Even when protected by Earth's atmosphere, terrestrial bacterial survival is diminished by exposure to UV radiation. However, their survival is enhanced when they are "rafted" on suspended aerosols, particularly on larger grains.[25] Such findings suggest that suspended aerosols may extend microorganism lifetimes partly because they provide a physical shield from UV irradiation, and partly because they retain moisture that microorganisms need to survive. On Mars, this shielding could provide microorganisms enough time to be lofted by dust-laden winds and then transported to distant sheltered locations where they could survive and, under the right conditions, even proliferate. A preliminary lab study by Mancinelli[26] indicated that lofted dust would indeed shield rafted microorganisms from the harsh martian environment. However, sufficient protection may only occur on relatively large lofted grains (~3-45 μm), rather than on the smaller grains (<~3 μm) that comprise large dust storms on Mars.[26] Larger grains are not typically transported far from their source regions, so that locally-lifted particles may be the most important contribution to forward contamination.

Should microorganisms survive aeolian transport, their likelihood of contaminating Mars increases. Simulations of martian conditions suggest that a thin (>~1 mm) surface coating of dust overlying a microbial sample would protect it against UV irradiation as shown by multiple researchers, e.g., refs. 7, 20 and 27. When mixed with analog soils, the shelter provided by these grains permitted vegetative cells and even multicellular organisms (tardigrades) to survive Mars-like conditions (UV radiation, desiccation, low air pressure, and low temperatures), suggesting that the potential issue of forward contamination in martian soils may be more likely than previously thought.[28-29]

A further complicating factor is that biogenic signature molecules, such as amino acids and adenosine triphosphate (ATP), would require days to years to break down by UV irradiation on Mars, particularly if they became embedded in the soil.[29-33] These molecules do not present a direct forward contamination problem by microorganisms. However, biogenic signature molecules could be rafted on aerosols and dispersed by the wind, only to settle in a protected area or be subsequently buried by airfall dust, so that an instrument searching for martian life might then identify them as false-positives. Halting completely all release of such molecules would be difficult for landed robotic spacecraft, and all but impossible for a long-term crewed mission. Rather, the methods used to identify the signatures of life in situ on Mars must appropriately account for such contamination factors.

V. Near- and Far-Field Dispersion

Culturable bacteria has been discovered on Earth at altitudes up to 80 km[34], which on average corresponds to an atmospheric pressure of 0.01 hPa (c.f. the surface pressure of Mars is on average 6 hPa). Thus, with regards to low atmospheric pressure environments, bacteria have the potential to survive on the surface and in the atmosphere of Mars. In Earth desert dust, bacteria are often found to be attached to mineral dust, and bacterial concentrations in the air have been observed to increase during dust storms.[34] Meteorological conditions on Mars (see below) are not thought to be suitable to directly lift microorganisms; rather, the microorganisms may become attached to dust particles that are themselves entrained.

Mineral dust, i.e., particles less than 10 microns in diameter, is ubiquitous in the martian environment at the surface, suspended in the air, and lofted into the air during dust storms.[35] The seminal work by Toon et al. (ref. 36) using Mariner 9 data showed that the martian dust particle size distribution between 1 and 10 microns had a size distribution similar to that of terrestrial dust. The dust was determined to be composed of a combination of primarily granite, basalt, basaltic glass, obsidian, quartz, andesite, and montmorillonite. The work of Berger et al. (2016)

provides a more up-to-date assessment of mineral concentrations based on in situ measurements from the Curiosity Rover and Mars Exploration Rovers.[37]

Dust storms occur at many scales on Mars, from planet-wide storms, to regional (>1.6x10e6 km^2) and local storms (<1.6x10e6 km^2).[38] Local dust storms occur in all seasons and both northern and southern hemispheres.[39-40] These are more frequent during southern spring and summer.[38] Mariner and Viking observations indicated that the storms tend to occur in broad latitudinal zones equatorward of the seasonal polar cap edges, more often in the southern subtropics. Storm activity was more common in distinct regions such as Hellas, Noachis-Hellespontus, Argyre, and Solis, Sinai, and Syria Plana in the southern hemisphere, and Chryse-Acidalia, Isidis-Syrtis Major, and Cerberus in the north.[39] Several regions lie along identified storm tracks, experiencing frontal activity that often sweeps through seasonally, both lifting fresh dust from the surface and carrying dust aloft from farther afield.[41]

Most of these local and regional storms do not grow to larger scales,[42] and many individual martian years have no planet-encircling dust storms. However, in years when such dust storms do occur, they begin in the southern hemisphere midlatitudes during local spring or summer, often in the Hellas Basin. Such storms have been observed to notably reduce the amount of sunlight reaching the surface,[43-44] which would affect, for example, the amount of power gathered by solar panels. Once the dust is raised into the atmosphere, in can take months for the atmosphere to clear after a global dust storm. Dust takes longer to sediment out of the atmosphere of Mars compared with Earth. On Earth, dust and other aerosols act as condensation nuclei for water droplets, which are eventually rained out, a process that has no equivalent on Mars. Mitigating the effects of dust storms may include selecting landing [A1]sites for crewed missions that exclude the most storm-prone regions. Where unavoidable, weather monitoring during missions could provide forecasts for the crew to curtail field excursions as needed and to secure identified leaks in the event of a dust storm's passage.

Dust devils are dust-laden vortices produced by intensive convective activity. They are small-scale phenomena relative to dust storms (with diameters ranging from ~10 m to ~1 km), but as reviewed in Fenton et al.,[45] they have been observed on Mars from nearly every orbiter and lander, and have been observed at nearly all elevations and latitudes. It is difficult to make quantitative estimates of how much material Martian dust devils can entrain as there have been no in situ measurements of their dust loading,[46] but atmospheric models and observations suggest that they are responsible for contributing to 25-75% of the atmospheric dust load, making their occurrence as important as that of dust storms.[47-49] Dust devil activity peaks in the season and local time of maximum insolation, i.e. regional spring and summer, during late morning and early afternoon.[50] The data show "bursts" of dust devil formation with fewer events in the half hour after a period of intense activity. Some particularly active dust devil regions that have been identified include northern hemisphere low-lying regions such as Amazonis Planitia, Casius, and Argyre Planitia. Observations on Earth and Mars suggest that modal dust devil diameters on Mars may be ~3x larger than those on Earth.[51] Further, observations of martian dust devils towering several kilometers high[52] also suggest that they might loft dust higher into the atmosphere than most terrestrial dust devils. Dust devils are electrified and may produce oxidants, especially hydrogen peroxide, further contributing to the inhospitable nature of the Martian surface to terrestrial organisms.[53] Because of their ubiquity on Mars, dust devils are likely unavoidable during any extended mission, although they appear to occur less frequently in local low-lying areas where the convective boundary layer is supressed (e.g., the floor of Gale crater)[62-65a-d][A2]. Thus, careful selection of landing sites could help reduce the likelihood of forward contamination from dust devils.

The transport of dust or larger particles by wind can be separated into several physical regimes, dependent on particle size and wind speed: long-term suspension, short-term suspension, saltation, reptation, and creep.[54] On Mars, the term "dust" typically refers to clay-sized grains lofted into suspension, either indirectly by saltating sand grains bombarding the surface and kicking up smaller grains, or directly by saltation of sand-sized agglomerates of clay-sized grains held together by electrostatic forces. The horizontal and vertical distance to which dust particles are carried depends on grain size, wind speed, and sedimentation rates. Background wind speeds on Mars near the surface are typically of order 10 m/s, but the magnitude varies widely due to local topographical effects, thermal tides, frontal storms, and turbulence. Thermal tides in particular follow a diurnal timescale. Variations in the background wind with season (e.g., large scale wind events are stronger during the winter in midlatitudes and at the poles) may influence the local wind speed and direction subsequently caused by topography and turbulence. With careful modeling and an understanding of local flows, natural topography could be used to block the strongest winds from impinging on a crewed mission habitat, limiting the likelihood of transport of released microorganisms.

Topographical effects on wind, such as downslope flow from mountains, and flow around craters and thermal tides can be modeled with much more ease than turbulence.[55-56] Turbulence occurs at very small scales (10 m or less), which presents a practical challenge for measurement. A theory for turbulence has not yet been developed that relates easily measured variables (3D wind, temperature, and pressure) on larger background scales, that are more easily determined through observation or modeling, to local turbulent scales. Boundary layer similarity theory can be used to determine the functional dependence of boundary layer (i.e. small-scale, near-surface) variables on each other. According to similarity theory, relationships between variables must be empirically determined. Due to the scarcity of Martian wind data, turbulent wind speeds have only been calculated to about an order of magnitude, which is not much help in trying to establish planetary protection risk. Sutton et al. (ref. 57) calculated maximum values of friction velocity of 0.4-0.6 m/s that occur during late morning at the Viking 1 lander site, and for the Viking 2 landing site where they occur shortly after dawn with peak values estimated to be in the range 0.25-0.35 m/s, emphasizing the site-specific nature of these effects. A more complete characterization of boundary layer turbulence on Mars would require detailed monitoring at any potential landing site prior to human habitation for at least one full Mars year (ideally for a longer time). In the meantime, similar measurements obtained at any site on Mars would present a significant improvement over the current state of knowledge, aiding future landing site selection.

VI. Impact on the Exploration Activity

It is clear that these multiple, complex and interrelated factors associated with dust and transport will impact zoning models for managing exploration on and at near-surface regions on Mars (so-called Special Regions, that may be habitable for terrestrial hitchhikers conveyed there on materials released from crewed systems). The fact that so many of these factors are so poorly constrained means that, using only current data, it would only be a guess as to whether the location of a habitat relative to a potential Special Region or exploration site would be sufficient to prevent contamination. The precautionary principle[58] (that planetary protection policymakers and implementors have traditionally followed) would require use of conservative assessments of the permitted proximity of habitats to sensitive sites. This would have significant impact on travel to/from such sites (and hence the amount of work that could be performed at the site on any particular sortie); the closest approach permitted for mobile contaminant sources, e.g. pressurized rovers and suited astronauts, to a sensitive site; and whether certain activities would be permitted at all, for example whether or not an astronaut could approach hardware being used for harvesting ice at an ISRU site in order to perform a maintenance activity.

VII. Astronaut Health and the Return to Earth

Returning to the issue of astronaut health, it is worth considering the impact of, e.g., a 500 day exposure to martian material and what we know about it. Based on the properties of dust we have seen displayed during robotic explorations[53] and the chemistry of the dust, some ingestion of perchlorates by astronauts would seem to be an extremely likely scenario. As a cause of goiter by depleting iodine absorption,[59] perchlorate is most well-known on Earth for causing a swelling in the thyroid but it can also be responsible for fatigue, weight gain and depression in sufferers, with severe cases resulting in serious mental health problems, brain damage and death. Clearly, such severe health consequences would want to be avoided in the management of a successful crewed mission to Mars. Not only as a result of the presence of perchlorate, but also hexavalent chromium or any other toxic trace contaminant that may be present in the martian environment. As previously commented, discrimination between a known condition and one which might be resulting from exposure to martian biology is an important one in the context of decision making about whether such a sick individual is allowed to return back to Earth or not.

With these unknowns hanging over the potential future crewed exploration of Mars, stakeholders from the United States and the international space exploration communities have held workshops to address the issues. Reports from these meetings have identified and prioritized knowledge gaps to be addressed in the course of planning and executing a crewed mission to Mars[60-61]. The 2015 NASA workshop held at Ames Research Center parsed the subject into three broad topic areas: Microbial and Human Health Monitoring, Technology and Operations for Contamination Control, and Natural Transport of Contamination on Mars. The later 2016 COSPAR workshop endorsed and added to the 2015 findings, and suggested prioritization.

Six of the nine identified knowledge gaps in the micro/human health group focused on questions typically associated with microbial research per se—such as understanding the microbes themselves and the diverse populations to be monitored, as well as how to monitor, collect and process data about them during the missions. Another gap focused on developing novel approaches for low-toxicity microbial disinfectants and addressing problems associated with microbial biofilms, such as induced corrosion and fouling of equipment. The final two gaps related to biomedical considerations associated with microbes, including the need to develop diagnostic options for crew microbial and health exposures, and to develop operational guidelines for how to integrate data with ethical and operational considerations during Mars missions.

Knowledge gap discussions in the technology and operations group focused mainly on measures for mitigating and controlling contamination—both microbial and organic. The majority of identified knowledge gaps applied to mission-related questions, including the implications of mission duration, the escape of viable microbes, understanding what vents from each hardware component, containment needs for both planetary protection and science considerations, and the development of procedures for decontamination and verification. Two gaps centered on questions about operations and microbial vulnerability—specifically on acceptable containment of wastes and constraints on vented materials near infrastructural elements and on similar considerations related to EVA systems, where mobility presents a particular concern.

The main conversation in the dust/transport area was the trade between the lethality of the UV environment to organisms released versus the potential for dust relocation to a "safe" place where organisms would be able to grow. At the present time our knowledge of both the lethality and the relocation processes are not well enough constrained to make predictions of the distributions of how long a viable microorganism would survive or how far it could travel. Therefore, for any given landing site, it is not possible to say with confidence whether a "downwind" Special Region would or would not become contaminated. The kinds of data needed to inform these considerations would require data collection from instruments at the martian surface, ideally at the location where the human landing site is to be situated.

VIII. Summary and Conclusion

With current planning for human exploration of Mars goes a two-way contamination threat. First, there is the threat of dust contaminated by terrestrial organisms being released and dispersed in the martian environment, threatening our ability to determine whether Mars has (or ever had) its own biosphere, and potentially compromising our ability to exploit Mars' natural resources, should they become contaminated. Second there is the threat that astronauts, affected by the Mars environment, might be unable to ascertain whether their ailment is simply due to exposure to chemical irritants or due to exposure to an environmentally-encountered martian organism.

Mitigation of both of these threats comprises a three-part solution. First, a significantly enhanced knowledge (compared to the current state) of the martian environment and its effects, particularly the dust environment, its chemistry and habitability is required. Second, a more complete understanding of the release, processes and fate affecting terrestrial biota introduced into the martian environment as a result of human space exploration activities, including the ability to monitor those biota and to discriminate them from putative martian biota is required. Third, the modification of performance requirements for the systems and operations of the mission architecture is needed to appropriately control the ingress and egress of martian and terrestrial material respectively, so that harmful contamination of the martian environment does not occur and so that the environment of the Earth (on which we all depend) is protected.

Precursor missions to the surface, ideally with instruments deployed in close proximity to the planned human landing site, will be necessary to get the best information to inform these knowledge gaps.

Acknowledgments

Part of this work was funded by NASA grant number NNX15AV46A to the SETI Institute.

References

[1]Gaier, J. (2005) The Effects of Lunar Dust on EVA Systems During the Apollo Missions. NASA/TM—2005-213610.

[2]National Aeronautics and Space Administration. (2009). *Human exploration of Mars: Design reference architecture 5.0* (NASA Publication No. NASA-SP-2009-566). Retrieved from http://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf.

[3]Kminek, G. & Rummel, J.D. (2015) COSPAR's Planetary Protection Policy; Space Research Today 193 pp7-17.

[4]Gromov, V (1999) Physical and Mechanical Properties of Lunar and Planetary Soils *in* Laboratory Astrophysics and Space Research Vol 236 pp 121-142.

[5]National Research Councils (2002) Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface; National Academies Press, Washington DC.

[6]Schuerger, A.C. (2004), Microbial ecology of the surface exploration of Mars with human-operated vehicles. In: Cockell, C.S. (Ed.), Martian Expedition Planning. Univelt Publishers, Escondido, CA, pp. 363–386.

[7]Schuerger, A. C., J. T. Richards, D. A. Newcombe, and K. Venkateswaran (2006), Rapid inactivation of seven Bacillus spp. under simulated Mars UV irradiation, Icarus, 181(1), 52–62, doi:10.1016/j.icarus.2005.10.008.

[8]Fajardo-Cavazos, P., Schuerger, A.C., Nicholson,W.L. (2007), Testing interplanetary transfer of bacteria between Earth and Mars as a result of natural impact phenomena and human spaceflight activities. Acta Astronaut. 60, 534–540, doi:10.1016/j.actaastro.2006.09.018.

[9]Kuhn, W.R. & Atreya, S.K. (1979) Ammonia Photolysis and the Greenhouse Effect in the Primordial Atmosphere of the Earth; ICARUS 37 pp207-213.

[10]Gómez-Elvira, J. et al. (2014), Curiosity's rover environmental monitoring station: Overview of the first 100 sols, J. Geophys. Res. Planets, 119, 1680–1688, doi:10.1002/2013JE004576.

[11]Cockell, C. S., D. C. Catling, W. L. Davis, K. Snook, R. L. Kepner, P. Lee, and C. P. McKay (2000), The Ultraviolet Environment of Mars: Biological Implications Past, Present, and Future, Icarus, 146(2), 343–359, doi:10.1006/icar.2000.6393.

[12]Mancinelli, R. L., and M. Klovstad (2000), Martian soil and UV radiation: microbial viability assessment on spacecraft surfaces, Planet. Space Sci., 48(11), 1093–1097, doi:10.1016/S0032-0633(00)00083-0.

[13]Schuerger, A. C., J. T. Richards, P. E. Hintze, and R. G. Kern (2005), Surface characteristics of spacecraft components affect the aggregation of microorganisms and may lead to different survival rates of bacteria on Mars landers, Astrobiology, 5(4), 545–559, doi:10.1089/ast.2005.5.545.

[14]Beaty, D.W., Buxbaum, K., Meyer, M., Boynton, W.V., Clark, B.C., Deming, J.W., Doran, P.T., Edgett, K.S., Hecht, M.H., Hipkin, V., Kieft, T., McDonald, E., McKay, C.P., Mellon, M.T., Newsom, H.E., Ori, G., Paige, D., Schuerger, A.C., Sogin, M., Spry, A., Steele, A., Tanaka, K.L., and Voytek, M.A. (2006), Findings of the Mars Special Regions Science Analysis Group. Astrobiology 6, 677–732, doi:10.1089/ast.2006.6.677.

[15]Stoker, C.R., Zent, A.P., Catling, D.C., Douglas, S., Marshall, J.R., Archer, D., Jr., Clark, B.C., Kounaves, S.P., Lemmon, M.T., Quinn, R., Renno, N.O., Smith, P.H., and Young, S.M.M. (2010) Habitability of the Phoenix landing site. J Geophys Res Planets 115, doi:10.1029/2009JE003421.

[16]ten Kate, I.L. (2010), Organics on Mars?, Astrobiology, 10(6), 589–603, doi:10.1089/ast.2010.0498.

[17]Schuerger, A. C., R. Ulrich, B. J. Berry, and W. L. Nicholson (2013), Growth of Serratia liquefaciens under 7 mbar, 0°C, and CO2-enriched anoxic atmospheres., Astrobiology, 13(2), 115–131, doi:10.1089/ast.2011.0811.

[18]Schuerger, A. C., and W. L. Nicholson (2016), Twenty-three species of hypobarophilic bacteria recovered from diverse ecosystems exhibit growth under simulated martian conditions at 0.7 kPa, Astrobiology, 16(5), 1–13, doi:10.1089/ast.2015.1394.

[19]Nicholson, W.L., Krivushin, K., Gilichinsky, D., and Schuerger, A.C. (2013) Growth of Carnobacterium spp. from permafrost under low pressure, temperature, and anoxic atmosphere has implications for Earth microbes on Mars. Proc Natl Acad Sci USA 110:666–671, doi:10.1073/pnas.1209793110.

[20]Schuerger, A. C., D. C. Golden, and D. W. Ming (2012), Biotoxicity of Mars soils: 1. Dry deposition of analog soils on microbial colonies and survival under Martian conditions, Planet. Space Sci., 72(1), 91–101, doi:10.1016/j.pss.2012.07.026.

[21] Horneck, Gerda, David M. Klaus, and Rocco L. Mancinelli. "Space microbiology." Microbiology and Molecular Biology Reviews 74.1 (2010): 121-156.

[22] Hassler, Donald M., et al. "Mars' surface radiation environment measured with the Mars Science Laboratory's Curiosity rover." science 343.6169 (2014): 1244797.

[23] Newcombe, D.A., Schuerger, A.C., Benardini, J.N., Dickinson, D., Tanner, R.,Venkateswaran, K. (2005), Survival of spacecraft-associated microorganisms under simulated martian UV irradiation. Appl. Environ. Microbiol. 71, 8147–8156, doi:10.1128/AEM.71.12.8147-8156.2005.

[24] Venkateswaran, K., La Duc, M.T. and Vaishampayan, P. (2012), Genetic inventory task: Final report, Vol. 1, JPL Publication 12-12, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

[25] Tong, Y., and B. Lighthart (1998), Effect of simulated solar radiation on mixed outdoor atmospheric bacterial populations, FEMS Microbiol. Ecol., 26(4), 311–316, doi:10.1016/S0168-6496(98)00046-4.

[26] Mancinelli, R.L., Klovstad, M.R., Fonda, M.L., DeVincenzi, D. (2000) Survivability of microbes in Mars wind blown dust environment, presented at the 35th ESLAB Symposium, Noordwijk, Netherlands.

[27] Mancinelli, R.L., Klovstad, M.R., Fonda, M.L., DeVincenzi, D. (2000) Survivability of microbes in Mars wind blown dust environment, presented at the 35th ESLAB Symposium, Noordwijk, Netherlands.

[28] Osman, S., Z. Peeters, M. T. La Duc, R. Mancinelli, P. Ehrenfreund, and K. Venkateswaran (2008), Effect of shadowing on survival of bacteria under conditions simulating the Martian atmosphere and UV radiation, Appl. Environ. Microbiol., 74(4), 959–970, doi:10.1128/AEM.01973-07.

[29] Johnson, A. P. et al. (2011), Extended survival of several organisms and amino acids under simulated martian surface conditions, Icarus, 211(2), 1162–1178, doi:10.1016/j.icarus.2010.11.011.

[30] Stoker, C. R., and M. A. Bullock (1997), Organic degradation under simulated Martian conditions, J. Geophys. Res., 102(E5), 10881–10888, doi:10.1029/97JE00667.

[31] ten Kate, I.L., Garry, J.R.C., Peeters, Z., Quinn, R., Foing, B., Ehrenfreund, P., 2005. Amino acid photostability on the martian surface. Meteorit. Planet. Sci. 40, 1185–1193, doi: 0.1111/j.1945-5100.2005.tb00183.x.

[32] ten Kate, I.L., Garry, J.R.C., Peeters, Z., Foing, B., Ehrenfreund, P., 2006. The effects of martian near surface conditions on the photochemistry of amino acids. Planet. Space Sci. 54, 296–302, doi:10.1016/j.pss.2005.12.002.

[33] Schuerger, A. C., P. Fajardo-Cavazos, C. A. Clausen, J. E. Moores, P. H. Smith, and W. L. Nicholson (2008), Slow degradation of ATP in simulated martian environments suggests long residence times for the biosignature molecule on spacecraft surfaces on Mars, Icarus, 194, 86–100, doi:10.1016/j.icarus.2007.10.010.

[34] Burrows, S. M.; Elbert, W.; Lawrence, M. G.; Pöschl, U. (2009) "Bacteria in the global atmosphere - Part 1: Review and synthesis of literature data for different ecosystems" Atmospheric Chemistry and Physics, Volume 9, Issue 23, 2009, pp.9263-9280.

[35] Karunatillake, Suniti; Keller, John M.; Squyres, Steven W.; Boynton, William V.; Brückner, Johannes; Janes, Daniel M.; Gasnault, Olivier; Newsom, Horton E. (2007). "Chemical compositions at Mars landing sites subject to Mars Odyssey Gamma Ray Spectrometer constraints". Journal of Geophysical Research. 112.

[36] Toon, O. B.; Pollack, J. B.; Sagan, C. (1977) "Physical properties of the particles composing the Martian dust storm of 1971-1972" Icarus, vol. 30, Apr. 1977, p. 663-696.

[37] Berger, J. A., M. E. Schmidt, R. Gellert, J. L. Campbell, P. L. King, R. L. Flemming, D. W. Ming, B. C. Clark, I. Pradler, S. J. V. VanBommel, et al. (2016), A global Mars dust composition refined by the Alpha-Particle X-ray Spectrometer in Gale Crater, Geophys. Res. Lett., 43, 67–75, doi:10.1002/2015GL066675.

[38] Cantor, B. A., P. B. James, M. Caplinger, & M. J. Wolff, Martian dust storms: 1999 Mars Orbiter Camera observations, J. Geophys. Res. 106, E10, 23,653-23,687 (2001).

[39] Cantor, B. A., P. B. James, M. A. Caplinger, and M. J. Wolff (2001), Martian dust storms: 1999 Mars Orbiter Camera observations, J. Geophys. Res., 106(E10), 23,653-23,687, doi:10.1029/2000JE001310.

[40] Kahn, R. A., T. Z. Martin, R. W. Zurek, & S. W. Lee, The Martian dust cycle, in Mars (H. H. Kieffer, B. M. Jakosky, C. W. Snyder, and M. S. Mathews, eds.), 1017-1053, Univ. of Arizona Press, Tuscon (1992).

[41] Wang, H., and M. I. Richardson (2015), The origin, evolution, and trajectory of large dust storms on Mars during Mars years 24-30 (1999-2011), Icarus, 251, 112–127, doi:10.1016/j.icarus.2013.10.033.

[42] Zurek, R. W., J. R. Barnes, R. M. Haberle, J. B. Pollack, J. E. Tillman, & C. B. Leovy, Dynamics of the atmosphere of Mars, in Mars (H. H. Kieffer, B. M. Jakosky, C. W. Snyder, and M. S. Mathews, eds.), 835-933, Univ. of Arizona Press, Tuscon (1992).

[43] Smith, M. D., M. J. Wolff, N. Spanovich, A. Ghosh, D. Banfield, P. R. Christensen, G. A. Landis, and S. W. Squyres (2006), One Martian year of atmospheric observations using MER Mini-TES, J. Geophys. Res., 111, E12S13, doi:10.1029/2006JE002770.

[44] Wolff, M. J., et al. (2006), Constraints on dust aerosols from the Mars Exploration Rovers using MGS overflights and Mini-TES, J. Geophys. Res., 111, E12S17, doi:10.1029/2006JE002786.

[45] Fenton, L., D. Reiss, M. Lemmon, B. Marticorena, S. Lewis, and B. Cantor (2016), Orbital observations of dust lofted by daytime convective turbulence, Space Sci. Rev., 203, 89–142, doi:10.1007/s11214-016-0243-6.

[46] Balme, M., and R. Greeley (2006), Dust devils on Earth and Mars, Rev. Geophys., 44, RG3003, doi:10.1029/2005RG000188.

[47] Newman, C. E., S. R. Lewis, P. L. Read, and F. Forget (2002), Modeling the Martian dust cycle, 1. Representations of dust transport processes, J. Geophys. Res., 107(E12), 5123, doi:10.1029/2002JE001910.

[48] Cantor, B. A., K. M. Kanak, and K. S. Edgett (2006), Mars Orbiter Camera observations of Martian dust devils and their tracks (September 1997 to January 2006) and evaluation of theoretical vortex models, J. Geophys. Res., 111, E12002, doi:10.1029/2006JE002700.

[49] Kahre, M. A., J. R. Murphy, and R. M. Haberle (2006), Modeling the Martian dust cycle and surface dust reservoirs with the NASA Ames general circulation model, J. Geophys. Res., 111(E6), 1–25, doi:10.1029/2005JE002588.

[50] Greeley, R., D. A. Waller, N. A. Cabrol, G. A. Landis, M. T. Lemmon, L. D. V Neakrase, M. Pendleton Hoffer, S. D. Thompson, and P. L. Whelley (2010), Gusev Crater, Mars: Observations of three dust devil seasons, J. Geophys. Res., 115, E00F02, doi:10.1029/2010JE003608.

[51] Lorenz, R. D., and B. K. Jackson (2016), Dust Devil Populations and Statistics, Space Sci. Rev., 203(1–4), 277–297, doi:10.1007/s11214-016-0277-9.

[52] Thomas, P., and P. J. Gierasch (1985), Dust devils on Mars, Science (80)., 230(4722), 175–177, doi:10.1126/science.230.4722.175.

[53] Atreya, S.K., Ah-San Wong, Nilton O. Renno, William M. Farrell, Gregory T. Delory, Davis D. Sentman, Steven A. Cummer, John R. Marshall, Scot C.R. Rafkin, and David C. Catling. Astrobiology. June 2006, 6(3): 439-450. doi:10.1089/ast.2006.6.439.

[54] Kok, J. F., E. J. R. Parteli, T. I. Michaels, and D. Bou Karam (2012) Rep. Prog. Phys. 75, 106901.

[55] Rafkin, Scot C. R.; Haberle, Robert M.; Michaels, Timothy I. (2001) “The Mars Regional Atmospheric Modeling System: Model Description and Selected Simulations” Icarus, Volume 151, Issue 2, pp. 228-256.

[56] Wilson, R. J.; Hamilton, K. (1996) “Comprehensive model simulation of thermal tides in the Martian atmosphere.” Journal of Atmospheric Science, Vol. 53, No. 9, p. 1290 – 1326.

[57] Sutton, J. L.; Levoy, C. B.; Tillman, J. E. “Diurnal variations of the Martian surface layer meteorological parameters during the first 45 sols at two Viking Lander sites” Journal of the Atmospheric Sciences, vol. 35, Dec. 1978, p. 2346-2355.

[58] UNESCO–COMEST – World Commission on the Ethics of Scientific Knowledge and Technology (2005) The Precautionary Principle.

[59] Soldin, O. P., Braverman, L. E., & Lamm, S. H. (2001). Perchlorate Clinical Pharmacology and Human Health: A Review. Therapeutic Drug Monitoring, 23(4), 316–331.

[60] Race, M.S., J.E. Johnson, J.A Spry, B.Siegel and C.A. Conley (Eds) (2016). Planetary Protection Knowledge Gaps for Human Extraterrestrial Missions Workshop Final Report. Published by NASA Washington DC NASA/TM-2016 XXXX[tbd].

[61] Kminek, G et al. (2017, in preparation). Report of the COSPAR Workshop on Refining Planetary Protection Requirements for Human Missions, Adv. Space Res. [tbd].

[62] Tyler, D., and J. R. Barnes (2013), Mesoscale modeling of the circulation in the Gale crater region : An investigation into the complex forcing of convective boundary layer depths, Mars, 8, 58–77, doi:10.1555/mars.2013.0003.

[63] Haberle, R. M. et al. (2014), Preliminary interpretation of the REMS pressure data from the first 100 sols of the MSL mission, J. Geophys. Res. Planets, 119, 440–453, doi:10.1002/2013JE004488.Received.

[64] Kahanpää, H. et al. (2016), Convective vortices and dust devils at the MSL landing site: Annual variability, J. Geophys. Res. Planets, 121, 1514–1549, doi:10.1002/2016JE005135.

[65] Steakley, K., and J. Murphy (2016), A year of convective vortex activity at Gale crater, Icarus, 278, 180–193, doi:10.1016/j.icarus.2016.06.010.