Published in final edited form as:
Adv Space Res. 2019 March ; 63(5): 1491–1497. doi:10.1016/j.asr.2019.01.011.

Planetary Protection and the astrobiological exploration of Mars: Proactive steps in moving forward

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Abstract

Future efforts towards Mars exploration should include a discussion about the effects that the strict application of Planetary Protection policies is having on the astrobiological exploration of Mars, which is resulting in a continued delay in the search for Martian life. As proactive steps in the path forward, here we propose advances in three areas. First, we suggest that a redefinition of Planetary Protection and Special Regions is required for the case of Mars. Particularly, we propose a definition for special places on Mars that we can get to in the next 10–20 years with rovers and landers, where try to address questions regarding whether there is present-day near-surface life on Mars or not, and crucially doing so before the arrival of manned missions. We propose to call those special places ‘Astrobiology Priority Exploration” regions (APEX regions). Second, we stress the need for the development of robotic tools for the characterization of complex organic compounds as unequivocal signs of life, and particularly new generations of complex organic chemistry and biosignature detection instruments, including advances in DNA sequencing. And third, we advocate for a change from the present generation of SUV-sized landers and rovers to new robotic assets that are much easier to decontaminate such as microlanders: they would be very small with limited sensing capabilities, but there would be many of them available for launch and

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coordination from an orbiting platform. Implementing these changes will help to move forward with an exploration approach that is much less risky to the potential Mars biosphere, while also being much more scientifically rigorous about the exploration of the 'life on Mars" question – a question that needs to be answered both for astrobiological discovery and for learning more definitive lessons on Planetary Protection.

1 Statement of the problem

The first page of the document *Proposed new terms of reference for the COSPAR Panel on Planetary Protection*, presented at the COSPAR meeting in Paris, France, 2017, and approved by the COSPAR Bureau on March 22, 2017, included the sentence: 'Planetary Protection should enable the exploration of Mars and not prohibit it". We enthusiastically endorse this quote. Regrettably, current Planetary Protection policies require that strict measures should be applied before sampling regions on Mars which could be a habitat for certain types of microorganisms, either native from Mars or brought there from Earth. COSPAR defined such regions 'within which terrestrial organisms are likely to propagate, or a region which is interpreted to have a high potential for the existence of extant martian life forms" as *Special Regions* (COSPAR, 2003). Given the current understanding, this is to apply to regions where liquid water is present or may occur (COSPAR, 2003). Otherwise, the argument is that (1) terrestrial biological contamination could jeopardize a possible extant martian biosphere, and (2) it might be difficult to distinguish between any indigenous Martian life forms and life that arrived as contamination from Earth aboard our spacecraft.

We disagree with this hesitant vision. The main point we made in three recent publications (Fairén and Schulze-Makuch, 2013; Fairén et al., 2017, 2018) is that we are being overprotective of Mars. There are several reasons why this situation needs to change, so we can resume a true biological exploration of Mars right away. Succinctly, these reasons can be summarized in five categories, as follows.

1.1 The previous history of cross-contamination

If Earth life cannot survive and most importantly reproduce on the surface of Mars today, our concerns about forward contamination of Mars with terrestrial organisms are unwarranted. On the other hand, if Earth microorganisms can, in fact, survive and create active microbial ecosystems on present day Mars, we can presume that they already have (Fairén and Schulze-Makuch, 2013), carried by dozens of uncleaned or poorly cleaned spacecraft sent from Earth over the last decades, ranging from the first Soviet spacecraft decades ago to SpaceX's Tesla launched last year. This would specially be the case if we consider that potential contaminants on these rovers and landers (and the discarded landing material) could have been widely dispersed by planetary-level dust storms (Zurek and Martin, 1993). Earth contaminants may have also arrived on Mars by the common exchange of planetary material on geological timescales (Gladman et al., 1996). And the situation is getting even more complicated now with the rise of private spaceflight companies (Profitiliotis and Loizidou, 2019), and development of CubeSats, often not hardy enough to withstand rigorous cleaning.

1.2 The biological adaptation of life to its environment

Any indigenous life on Mars, by definition, should be much more adapted to Martian stresses than Earth life, and therefore would outcompete any possible terrestrial newcomers. For example, it has been argued that the salinity of past surface waters on Mars would probably exceed levels tolerated by most terrestrial organisms (Tosca et al., 2008). However, we know that a significant number of microorganisms on Earth have evolutionary adapted to thrive exclusively in places with inherently very high salinity (such as some lakes in Antarctica or salty soils in the Atacama Desert, e.g. Rothschild and Mancinelli, 2001; Schulze-Makuch et al., 2018; Azua-Bustos et al., 2018), similar to that estimated for ancient water solutions or extant brines on Mars. Following this reasoning, we can expect that any potential Martian biosphere would have been subjected to an enormous evolutionary pressure during billions of years to become specialized in inhabiting extremely saline environments. Indeed, the same argument would be applicable for the adaptation of the Martian organisms to extreme cold, radiation, oxidative environments and any other stresses common on the Mars surface, including the recently identified abrasion mediated by wind-driven saltation (Bak et al., 2018). The microorganisms hitchhiking on our spacecraft would not be able to compete against these potential super-specialized Martian organisms in their own territory, as contemporary terrestrial microorganisms have never experienced the combination of all the extreme environmental stresses prevailing on Mars.

1.3 The flawed bioburden controls

Current bioburden reduction methods applied to our spacecraft do not actually ‘sterilize” them, as we still do not know how to accomplish true sterilization (Nicholson et al., 2009), defined as completely killing of 100% of the microbial life in a given sample: we can meticulously clean our robots at best, killing only those microorganisms with no chance of surviving on Mars anyway. This is because the cleaning procedures rely basically on some of the same known environmental stresses prevailing on the Martian surface, such as oxidizing chemicals and radiation. In addition, despite continuous cleaning efforts, microbiomes in clean rooms are dominated by *Acinetobacter* capable of growth even on anti-microbial cleaning reagents such as ethanol (Mogul et al., 2018). Therefore, current cleaning protocols are essentially conducting an artificial selection experiment, with the result that we have been sending to Mars only the really resilient microorganisms with the exact characteristics that might allow them to survive on Mars. This reality should put into question the whole cleaning procedure as the preeminent component of the planetary protection measures.

Following the previous arguments, the current robotic exploration of Mars will have little (if any) impact on potential Mars biospheres or on our efforts to search for active life on Mars. After the interplanetary trip and just a few days on Mars, the exposed parts of our rovers and landers will be as biologically clean (and maybe even more so) as the Viking probes were when they left Earth (Khodadad et al., 2017). Direct exposure to the martian surface environment would kill any terrestrial microorganism within seconds. Indeed, microbes initially hiding deep within the electronics and mechanics of a lander or rover will suffer the same fate as soon as they become eventually exposed. As such, the odds of microorganisms surviving near the surface of Mars are negligible, both when considering individual environmental parameters (temperature ranges and circadian oscillations, relative humidity, ionizing radiation, oxidizing regolith chemistry), but particularly when considering multiple extreme conditions acting synergistically. Therefore, MER- and MSL-like cleanliness levels should be sufficient to allow a robot to search for life on Mars as soon as the first significant drive decision is made around Sol 10-20.

Related to this, a common misconception in Planetary Protection policies is that searching for martian life using spacecraft that carry Earth contamination could result in the ‘inadvertent finding” of Earth contamination, which could be confused with indigenous Martian life (Rummel and Conley, 2018). The reality is that microbial contamination can contribute rather infinitesimal levels of biochemicals, but those biochemicals are not removed from the spacecraft by our current cleaning procedures required by Planetary Protection protocols. Each bacterium is a cubic micron, or 10^{-12} g (i.e., a picogram of contamination per bacterium), or a microgram of total bioburden spread out in one million individual picogram packets across the surface of the spacecraft, if the craft carries 10,000 cultivatable and 100× more uncultivatable bacteria. When these bacteria are heat-killed, the biochemicals that make them up are not actually neutralized. Therefore, it is not worth the costs and, most importantly, the degradation of onboard electronics and the time delays that cleaning implies, when the biochemicals will remain anyway in the spacecraft to be ‘inadvertently found”.

1.4 Our enhanced biomolecular identification tools

Technology has advanced enough that distinguishing between Earth organisms and Martian organisms is no longer a problem (NASEM report, 2018), assuming that some Earth microbes could still get to and survive on the surface of Mars, which is very doubtful based on the previous arguments. If Martian life is biochemically similar to Earth life, we could add Martian life to the tree of DNA-based life that we already know, probably somewhere on its lower branches; and if it is different, we would be able to identify such differences based on its building blocks (Fairén et al., 2017).

In addition, we can discriminate between Mars and Earth life because we can identify and control the diversity and quantity of microbial populations in our clean rooms, and therefore the microorganisms potentially travelling in our spacecraft can be easily identified as such (van Heereveld et al., 2016). Consequently, the microbes we know persist in clean spacecraft assembly rooms provide an excellent control with which to monitor potential contamination. Any microorganism found in a Martian sample identical or highly similar to those present in the clean rooms would very likely indicate contamination – and not an indigenous Martian life form.

Importantly, surveys of spacecraft assembly rooms for any organisms, as are current Planetary Protection assays, treat every bacterial species as a potential growing pathogen for Mars. This is a flawed approach, because (1) spacecraft assembly room organisms are not found and do not grow in cold/dry/UV rich environments on Earth, and (2) sporulating bacteria are a relatively uncommon form of bacteria and not found in icy lakes or oceans on Earth. Planetary Protection protocols fail to distinguish between the small level of biochemical contamination that the microbial load on a spacecraft brings to another planet and the infinitesimally small probability that one or more of those microbes will grow and reproduce on Mars. Thus, rather than limiting the bacterial load of a spacecraft to 300,000 spores, the limits should be on the short list of particular species of bacteria that we could reasonably expect to grow on Mars (if any).

1.5 The impending impact of human exploration

Given NASA's (and other agencies as well as the private sector) hope to send human missions to Mars in the 2030s or even earlier, current planetary protection guidelines applied to today's unmanned robots are impractical: humans would inevitably bring microbial hitchhikers with them very soon, because we cannot conduct a bioburden reduction process on humans. A high degree of forward contamination associated with human astronaut explorers will be inevitable (Conley and Rummel, 2010), as it will be impossible for all human-associated processes and operations to be conducted within entirely closed systems (Rummel et al., 2014). No matter what strategy we choose to follow, the instant we have humans in an area on Mars we have a less clean state of that area. Therefore, the continued delaying of the robotic astrobiological exploration of Mars because we do not want to contaminate the planet now with microorganisms hiding aboard our unmanned spacecraft is not reasonable. Human contact with Special Regions is not the most intelligent way to make a first contact, if there is something there to make contact with in the first place. We urgently need to know before humans get there, if there are extant microbial ecosystems at or near the surface. This is a one-time only chance for humanity, and thus of paramount importance.

Related to this, should we not find out prior to sample return missions and human landings whether there is indigenous life on Mars? The answer is a resounding yes, we absolutely need to have a better idea as to whether there is life on Mars or not, and what robots or astronauts might find there and/or purposely or inadvertently bring back to Earth. Doing so, we will contribute to increasing the safety of Earth´s biosphere (planetary protection of our home planet). After all, we still do not know if returning samples could endanger humanity and the terrestrial biosphere if there is life on Mars.

2 Proactive steps in moving forward

Worries of contamination with Earth microorganisms have delayed *sine die* a thorough astrobiological exploration of Mars. As a result, since Viking no other Mars mission carried true life-detection instrumentation. We advocate here for a substantial change of direction in the exploration of Mars. The change of strategy we propose is threefold, as follows.

2.1 New and meaningful rules for Planetary Protection and Special Regions

We advocate for allowing immediate access to the Special Regions for vehicles with the cleanliness level of Curiosity, Mars2020 or ExoMars. Special Regions could hold a sluggish extant biosphere able to produce biomarkers even under current Martian radiation, because viable microorganisms would repair cellular damage resulting from ionizing radiation; on the contrary, biomarkers of extinct life would simply degrade in several hundred millions of years in the top meter of Martian surface due to exposure to cosmic rays (Pavlov et al., 2012) and the oxidizing surface chemistry (Mancinelli, 2017). Therefore, focusing on the detection of evidence for extant life in sub-surface and surface rocks and regolith in Special Regions may be more realistic than the hopes of detecting ancient and highly degraded organic biomarkers at or near the Martian surface on the long timescale.

We urgently need to designate, describe and analyze a few special places on Mars that we can get to now (i.e., in the next 10–20 years) with rovers and landers, and try to do a better astrobiological job asking and addressing questions regarding whether there is present-day nearsurface life on Mars or not, *before* the arrival of manned missions. We propose to call those special places ‘Astrobiology Priority Exploration” (APEX) regions. Examples of APEX regions are possible aquifers hidden under ice masses, similar to those reported to exist beneath the south polar cap (Orosei et al., 2018), but located in places where ice sheets have been identified at more accessible latitudes (Dundas et al., 2018); or salt crusts (Hynek et al., 2015) with low eutectic points, in which temperature and relative humidity (RH) fluctuations could promote transient deliquescence processes and solution formation (Chevrier et al., 2009).

Indeed, to allow spacecraft access to APEX regions, it would be necessary to reevaluate the current Planetary Protection restrictions and make sure they are properly adapted for the new space age we are entering, particularly distinguishing clearly between spacecraft cleanliness for biological reconnaissance and spacecraft cleanliness for planetary protection. This will reduce the likelihood that spacecraft cleanliness issues create conflicts between planetary protection efforts and science objectives. These proposed changes would require COSPAR to re-evaluate and update the rules governing the robotic exploration of Mars. Moreover, although the United Nations Outer Space Treaty does not need to be amended, because these international law bodies provide just guidance and not legal requirements, and apply only to States and not to private companies (Montgomery, 2018), a clear redefinition would help the upcoming astrobiological exploration of Mars. Especially considering that the relevant provision in the Treaty, Article IX, is very vague, and crucially the term “harmful contamination” is not defined (UN Treaty).

2.2 New exploration strategies in biosignature detection

We urge that our existing laboratory robotic technology is made flight ready in the search for biochemical evidence of life (e.g., McKay et al., 2013) in APEX regions. In particular, we advocate the development of robotic tools for the characterization of organic compounds as unequivocal signs of life. Arguably, the characterization of complex organic chemistry should be the relevant astrobiology science at this point for Mars. The organic characterization should be adequate to determine if the organics recently found on Mars (Freissinet et al., 2015; Eigenbrode et al., 2018) result from biological processes rather than being part of the abiotic organics that are ubiquitous in the Solar System (Kwok, 2009). Natural selection has resulted in life on Earth specializing in the use of certain organic molecules in the construction of biomass. The basic ingredients for life on Earth are the 20 L amino acids, the pyrimidines (U, T, C) and purines (A, G), the D sugars, and a few lipids. A collection of similar (not necessarily the same) basic ingredients is likely to be common to any life form that could have developed by natural selection on Mars. Hence one way to determine if a collection of organic material from an APEX region is of biological origin, is to look for a selective pattern of organic molecules similar to, but not necessarily identical with, the selective pattern of bio-chemistry in life on Earth.

Implementing this search in practical terms in near term missions will require a sophisticated ability to separate and characterize organic molecules. Currently the instrument best suited for this task is a GCMS (Gas Chromatograph Mass Spectrometer) with liquid solvent extraction. However, new methods based on fluorescence and Raman spectroscopy could provide similar information, or at least complement GCMS, and may have a role in future mission applications. We will need to understand the nature, complexity and diversity of the organic chemistry found on APEX regions by searching for polymeric sugars, lipids, peptides, and nucleic acids, as well as their building blocks such as sugars, nucleobases, and amino acids (Parro et al., 2011; Benhabib et al., 2010). If any biochemistry is detected, detection and nucleic acid sequencing instrumentations should also be considered for future in-situ detection and/or sample return (Carr et al., 2017; Goordial et al., 2017; Johnson et al., 2018), to analyze and identify any building blocks of life or their remains. All these techniques will help to no longer be concerned about possible false positive life detection in APEX regions. Robotic microscopes with very high resolution to analyze samples could also help to identify different cellular architectures, particularly imaging across orders of magnitude to cover contextual to microscopic imaging (Fink et al., 2013).

2.3 New mission architectures

Concerns regarding APEX regions exploration and the simultaneous concerns of planetary protection can be pragmatically addressed by: (1) introducing mission redundancy through multiple spacecraft/rovers, as opposed to a single spacecraft/rover, such that the loss of equipment can be tolerated in the quest to achieve the maximum possible science return; (2) miniaturization of spacecraft/rovers, to potentially facilitate and enhance the success of cleaning (a smaller spacecraft should be easier to clean than a larger one); and (3) preparing/equipping these investigative robots to minimize their risk at dangerous but potentially scientifically more potent outcrops (Fink et al., 2018).

To further advance the goals of both planetary protection and the search for life on Mars, we propose that a redundant (thereby more robust), minimally-invasive, and highly reactive/responsive (e.g., to transient events such as methane outgassing, recurring slope lineae (RSL), dark slope streaks, fresh meteorite impacts, and others) exploration arrangement is called for, such as the Tier-Scalable Reconnaissance mission architecture (Fink et al., 2005). This mission organization would integrate spaceborne assets (orbiters), airborne elements (aerial platforms such as blimps, balloons, and rotorcrafts) and miniaturized robotic ground units (both mobile and immobile, see for example http://www.spacenewsfeed.com/index.php/news/2059-cuberover-to-develop-next-generation-planetary-rovers-in-luxembourg) for *in situ* investigations. Tier-scalable reconnaissance benefits from multiple perspectives from different vantage points, afforded by the various tiers, allowing for a geologic ‘zoom-in” on spatio-temporal anomalies. Moreover, the miniaturized ground units do not have to be homogeneously equipped with all sensors. Instead, they would be carrying individually different sub-sets of sensors (thereby simplifying these ground units) that would help answer targeted/specific scientific questions at specific locales. As such, only the most suitable miniaturized ground unit(s) would be deployed for *in situ* follow up investigation for any given scenario (e.g., a methane-sensor and/or miniaturized Gas Chromatograph Mass Spectrometer (Fink et al., 2007; George, 2003) equipped rover for methane outgassing in Nili Fossae; a water-, pH-, electrical conductivity-sensor equipped rover for RSLs). As such, tier-scalable reconnaissance mission architectures would have the potential to emulate and thereby support a true geologic approach at APEX regions.

There is also a question of methodology: Geologists commonly make their field discoveries at outcrops (Frodeman, 1996), which are the locations where rocks and strata are best exposed. However, the best outcrops can occur on steep slopes, at the bases of cliffs, along canyon walls, in caves, and at other sites that pose extreme hazards to classic robotic exploration vehicles and their associated missions; arguably, the most interesting APEX regions have a greater potential to occur in or near outcrops. Denial of access to such sites, because of planetary protection and/or operational risk to the spacecraft/rover, will ‘block the way of inquiry” (Haack, 2014). If a field geological investigation is to be truly scientific, and if the search for life on Mars is to be seriously pursued, the investigational efforts must be able to access all accessible out-crops/locales on Mars (Fink et al., 2018).

3 Conclusions

We have stated here our position that a number of special places on Mars, which we refer to as ‘Astrobiology Priority Exploration” regions (APEX regions), need to be systematically explored in search for life before the arrival of manned missions, or else the astrobiological exploration of the planet will soon become compromised. New exploration strategies in biosignature detection and new mission architectures are needed to help complete this endeavor within the next 1–2 decades.

Acknowledgments

The research leading to these results is a contribution from the Project ‘icyMARS”, funded by the European Research Council, Starting Grant no. 307496. A.G.F. and V.P. acknowledge funding support from grant no. ESP2015-69540-R (MINECO/FEDER). D.S.M. acknowledges support from ERC Advanced Grant no. 339231. Reviews by Gary Ruvkun, Chris McKay and an anonymous reviewer greatly contributed to refine this work.

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