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A Critical Review of Planetary Protection Strategy

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Abstract

Planetary protection policies, such as those codified and promulgated by the Committee on Space Research (COSPAR) and the Outer Space Treaty, are inherently tied to the idea of preventing “harmful” contamination and limiting the transfer of biological material from the Earth to other celestial bodies and vice versa. The interpretation of what might constitute “harmful contamination”, however, is far from self-evident and is dependent on how one defines the delineation between living/biotic and non-living/abiotic entities and on the perceived significance of preventing contamination of a particular environment.

At present, there is a limited amount of data with which to inform planetary protection policy: the only data available on biological life is from Earth-based lifeforms, and scientific understanding of biological survivability in non-Earth contexts is incomplete at best. Experiments such as those demonstrating the survivability of terrestrial microbes in microgravity and high-radiation environments, as well as recent advances in documenting extremophilic microbiota, have challenged prior assumptions on the limits of habitability and biological diversity, which would suggest that it would be beneficial for planetary protection policies to err on the side of more stringent protections.

The present planetary protection approach exemplified by COSPAR policy, however, errs on the side of minimalism, and uses the standard of whether canonical Earth-based lifeforms have been observed to survive in similar environments as its standard for determining contamination risk. Human interests and the desire to minimize the burden of planetary protection compliance are also prioritized above preserving the integrity of planetary environments: indeed, current planetary protection requirements do not mandate any sort of precautionary protections for planetary environments which are deemed not to be of direct scientific value.

This paper presents a critical evaluation of current planetary protection policy/strategy and the scientific assumptions that underpin it, and seeks to assess whether current strategy affords comprehensive protection to biological entities that would be classified as living under some of the main emerging definitions of life being discussed in the astrobiological literature. In particular, shortcomings of the current COSPAR risk classification system in accurately capturing risks to scientific interests, as well as in current measures taken to protect various planetary targets, are addressed based on the astrobiological literature. The paper also presents a recommended set of modifications to planetary protection strategy to better align with emerging perspectives on astrobiological life and biological survivability limits.

Keywords: planetary protection, contamination, space policy, habitability, definition of life, astrobiology

Acronyms/Abbreviations

A_w	:	<i>water activity</i>
°C	:	<i>degrees Celsius</i>
COSPAR:		<i>Committee on Space Research</i>
DNA	:	<i>deoxyribonucleic acid</i>
EVA	:	<i>extra-vehicular activity</i>
ISS	:	<i>International Space Station</i>
NASA:		<i>National Aeronautics and Space Administration</i>
RNA	:	<i>ribonucleic acid</i>

1. Introduction

As astrobiology becomes a priority of increasing importance to the scientific community and to space agencies [1], so too has planetary protection proven to

be a topic of mounting significance [2]. It is a well accepted fact within the space community that the limitation of biological contamination of other worlds, and the planetary protection policies that enact contamination-preventative practices on space-bound projects, are both necessary aspects of protecting the interests of future scientific missions; contamination of the biological environment of other planets with Earth-based organisms and/or organic material, after all, directly impacts the ability of missions to collect accurate data about the biological profile of outer space, habitability, and other such matters of scientific interest [3]. Issues of biological contamination control have been a part of the scientific discourse since the dawn of

the space age, with concerns regarding biological survivability in space [4] and inter-planetary contamination being discussed as early as 1956 at the 7th International Astronautical Congress [5]. The need for standardization of planetary protection measures has led to the development of international guidelines on planetary protection which are, at present, standardized and promulgated by the Committee on Space Research (COSPAR) [6] and reinforced by national space agencies [7], [8]. These policies effectively determine which missions require planetary protection measures and to what extent; consequently, they also have a direct impact on whether meaningful biological studies of the environments visited by those missions can be effectively studied afterwards. It is thus of great importance that planetary protection policies be constructed with care, and that they provide appropriate consideration and evaluation of the risks various missions pose to the integrity of planetary environments, future science, and any potential astrobiological life.

2. Current standards in planetary protection

Most space agencies use some variation of the COSPAR guidelines as the governing planetary protection policies for their missions. The current COSPAR guidelines for different mission types is summarized in Table 1 (located at the end of this paper in Appendix A).

2.1. Harmful contamination

Fundamentally, the COSPAR guidelines and policies derived thereof seek to prevent the “harmful contamination” of space, an objective which spacefaring nations have been legally bound to by the international Outer Space Treaty [9]. Absent a clear scientific or legal definition of the term “harmful contamination”, planetary protection policies since the 1950s have generally taken the stance of defining “harmful contamination” as that which might significantly jeopardize scientific interests and compromise long-term scientific returns [10]. Practically, this has translated into what might be considered a “risk-forward” approach, wherein contamination is viewed as inevitable and steps to mitigate that contamination (a la planetary protection requirements) are not deemed necessary unless there is high likelihood of a threat to current scientific priorities. In the current COSPAR requirements, for instance, no planetary protection precautions whatsoever are imposed on interplanetary missions unless there is justification for the target being of “significant” interest to the study of the evolution and origin of life (i.e., unless it is Category II or above). Similarly, nothing beyond “simple documentation”, to use the term from the COSPAR policy itself, is required for a mission unless it is the mission is targeting a body of astrobiological interest where, per the current

scientific understanding of the target environment, terrestrial organisms are likely to be able to transfer, survive, and replicate (i.e., unless it is Category III or above) [6].

2.2. Expectations of biological habitability

As alluded to above, planetary protection standards typically take a graded or scaled approach to the degree of contamination control requirements imposed on a mission, with more stringent requirements only being imposed for missions where current knowledge indicates a high risk for damaging scientific interests. For lower risk missions, contamination control is generally considered to impose “unnecessary burdens on flight projects” that should be avoided “whenever possible” [11], due to the logistical and financial burden that contamination control efforts require. Given that policies start from the underlying assumption the existence of life elsewhere in the solar system is unlikely [12] and that the environment of space is similarly hostile to the propagation of terrestrial lifeforms, planetary targets do not generally receive categorization as requiring active contamination control efforts (e.g. COSPAR Category IV) unless there is clear, affirmative evidence that the environment meets the currently understood criteria for habitability. The evidentiary standard used to determine whether the environment of a target planetary body potentially harbors life and/or is of astrobiological interest is whether the environment meets current documentation of the limits of survivability for known terrestrial organisms. The COSPAR guidelines, for instance, specifically define the conditions for biological replication as an environment with a temperature above -28°C , in conjunction with a water activity equal to or greater than $A_w = 0.5$ [6]. This evidence-based approach, while reasonable in ensuring that contamination control is not overly burdensome on mission design and execution, does nonetheless rely on the assumption that known survivability limits observed in laboratory experiments and/or natural habitats on Earth will also hold true for as-yet unexplored planetary environments, where there is still limited documentation regarding the survival characteristics and adaptability of biological entities.

2.3. Relation to exploratory objectives and human spaceflight

A key matter of concern in planetary protection, beyond simply sending uncrewed spacecraft to various planetary bodies, is the appropriate handling of human exploration of space and potential efforts to colonize space, since such efforts will undoubtedly present a substantial contamination control challenge. This is a matter of imminent concern, as space agencies have already commenced efforts towards establishing a

human presence on the Moon [13] and other planetary bodies [14], and in creating human outposts in space [15].

The formal guidance from COSPAR on the matter of human spaceflight, and specifically of human exploration of Mars, is that “planetary protection goals should not be relaxed to accommodate a human mission” [6]. However, given that – per the COSPAR guidelines themselves – “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” [6], there is an inherent trade-off to be performed between the performance human activity on other planets and the maintenance of planetary protection standards.

3. Critique of current strategy

COSPAR guidelines and offshoot planetary protection policies have undoubtedly played a significant role in both establishing baseline goals for biological contamination control and establishing planetary protection discussions as a component of mission planning. Nonetheless, as space exploration efforts continue to facilitate further interaction between Earth and other celestial bodies, inclusive of efforts to place humans on other planets, it has become increasingly necessary to ensure that such planetary protection policies remain both robust and consistently enforceable in a standardized fashion. Long-term and future scientific interests are inherently dependent on the responsible use of space by current missions; as such, it is necessary for planetary protection strategy to not only reflect and support current priorities, but to also engage in ‘future-proofing’ to ensure that current exploration efforts are sufficient sustainable as to allow for the pursuit of scientific priorities which are likely to emerge in the future.

As detailed below, current planetary protection policy makes assumptions which are closely tied to an evolving segment of the astrobiological literature. New knowledge and perspectives in the astrobiology literature have consequently highlighted a number of points where such assumptions potentially require revision in order to reflect emerging knowledge. More generally, the current planetary protection approach promulgated by COSPAR takes a risk-forward stance which may not necessarily be justifiable in the face of changing long-term scientific interests.

3.1. Assumptions regarding survivability

Survivability and habitability limits are a key part of categorizing contamination risk for space exploration missions, and in turn for determining the appropriate level of contamination control which needs to be exercised on any particular mission. The COSPAR planetary protection policy makes three sets of key

assumptions regarding biological survivability and/or habitability: (1) that planetary bodies other than Earth appear to be “hostile to all known biological processes”; (2) that the minimum requirements for biological replication are an environment that is both above -28°C in temperature, and that has a water activity equal to or greater than $A_w=0.5$; and (3) that knowledge of current limits on terrestrial organism survivability mean that it is possible to conclude, with high certainty, that the environments of certain planetary bodies will not be damaged by biological and/or chemical contamination from Earth. However, all three of these assumptions have been challenged by recent studies in the scientific literature.

With regards to assumption (1), while there is a prevailing belief that microorganisms and other biological entities are incapable of surviving the vacuum, cold, and high radiation of a space environment, experimental studies have asserted that long-term survival of terrestrial organisms in space is certainly feasible [16]. This is further supported by experimental evidence; the sporulating bacteria *Bacillus subtilis* has been shown to have a survival rate of $1.4 \pm 0.8\%$ over a vacuum exposure period of 2107 days [17], and similarly rock-colonizing lichens such as *Xanthoria elegans* have been demonstrated to remain $45 \pm 2.50\%$ viable after 1.5 years in the orbit of the International Space Station (ISS) [18]. The environment of Earth’s upper atmosphere, which has been used as an analog for space [19] and was once thought to be a similarly inhospitable environment, has also been shown to permit the survival of microorganisms [20].

Similar studies have provided indication that the survivability limits specified in assumption (2) do not accurately capture the durability and adaptability of biological life. Sulfate-reducing bacterial species (most likely *Desulfovermiculus* and *Desulfobacula*) have been found to naturally inhabit and demonstrate high metabolic activity in a hypersaline anoxic basin with a water activity level of approximately $A_w = 0.4$ well below the COSPAR-specified lower limit of $A_w = 0.5$ for bacterial replication. The fact that, prior to the $A_w = 0.4$ finding, the lower limit for cell division was repeatedly cited in the literature as $A_w = 0.605$ [21], [22] suggests that planetary protection policies may not necessarily be able to rely on empirical data as a means of defining clear bounds on survivability, since doing so risks defining overly restrictive limits that might be later contradicted or proven inaccurate by new findings.

The COSPAR-specified -28°C lower limit on temperature for the replication of biological entities has also been challenged in the literature: some studies argue that some cells may be able to maintain metabolic activity at temperatures below -50°C [23] by delaying the vitrification processes which otherwise halt the progression of the cellular life cycle at about -20°C [24].

The terminal result of the manner in which current planetary protection measures handle the issue of biological survivability is the underestimation of risk posed by biological contaminants on Earth to other planetary bodies. With respect to assumption (3), the inconsistencies between the latest in the scientific literature and current planetary protection standards clearly indicate that planetary protection policy is erring on the side of underestimating survivability, rather than overestimating it. However, since further discoveries are certain to only further expand the limits of survivability rather than to reduce them, it is difficult to assert with reasonable confidence that some planetary bodies are sufficiently resistant to biological contamination as to not require planetary protection (Category I). For instance, the Jovian moon Io is one of the planetary bodies explicitly categorized as a Category I target in the current COSPAR requirements, but has been posited as being potentially of substantial astrobiological interest based on its suitability for harboring sulfur and sulfate-reducing bacteria [25]. Under the current policy, missions to Io, inclusive of any landed missions, do not need to perform any sort of contamination control measures, and as such there is a risk that future study of potential life on Io could be jeopardized.

COSPAR guidelines furthermore place emphasis on organisms being able to both survive and replicate in a given environment, in determining risk. Though the monitoring of bacterial spores is explicitly referenced in COSPAR policy, such references are in the context of calculating post-sterilization bioburden limits rather than in assessing whether contamination poses a “significant” risk to future science. The policy is clear that contamination risk should be evaluated based on the likelihood of organisms surviving and subsequently multiplying; simple survival of organisms in an inert or vegetative state (e.g. as spores) on its own is not treated as a significant planetary protection risk. The underlying assumption is presumably that such organisms are unable to cause damage to the environment and are likely to be rendered inviable over time. Microorganisms such as *B. subtilis*, though, notably are able to survive ionizing radiation under space-like conditions in spore form, and have been further shown to frequently acquire nonlethal mutations in the process [26]. *B. subtilis* in particular has been shown to develop resistance to temperature changes and other fitness-improving phenotypes during mutagenesis induced by space radiation [27]. This thus opens the possibility of “inert” contaminating organisms adapting to extraterrestrial conditions, a matter which – while undoubtedly scientifically fascinating – would likely be damaging to a planetary environment were it to occur. Planetary protection efforts in the past have generally omitted acknowledging such a possibility as a contamination risk modality. Incidents such as the

discarding of astronaut feces on the Moon by astronauts and the more recent Beresheet hard landing (where live tardigrades were spilled on the lunar surface) [28] have been considered opportunities for experimentation rather than matters of concern, even though contamination of the Moon has been previously stipulated in the literature to be an “irreparable scientific disaster” [10].

Current policy is also limited in terms of acknowledging the full extent of the contamination risk that spacecraft pose, not only as potential carriers of biological contamination but as reservoirs in which biological entities might reside. Deep-space missions often utilize thermal generators to heat spacecraft components [29], resulting in the internal environment of the spacecraft being well within the optimal growth temperature for terrestrial bacteria. Radiothermal generators also may generate water in certain environments in the event of a spacecraft impact [30]. The New Horizons spacecraft, for example, was designed to maintain an average internal temperature of 20-40°C [31]. Radiation shielding used on spacecraft [32] also can mitigate one of the main threats to biological survivability in space, as can radiation-absorbing materials and adhesives which might be inadvertently applied over microbial colonies during assembly [33]. This makes the interior of a spacecraft a potential home for hitchhiking microorganisms, and consequently means that exempting spacecraft interior surfaces from bioburden accounting (as was done on the Mars Science Laboratory [34]) might pose a notable risk to planetary protection interests. Presently, COSPAR planetary protection policy does not identify the parameters of the interior spacecraft environment as being an integral part of evaluating mission contamination risk, though impact risk assessments are required for Category II missions and above. Nonetheless, since various components used in spacecraft assembly, such as polyimide film (Kapton) are susceptible to microbial degradation [35], the potential for microbial activity inside a spacecraft should still be a matter for operational concern even if it is deemed improbable that the microbes would survive the environment outside the spacecraft.

3.2. Assumptions regarding the definition of life

Another key facet of current planetary protection strategy is its focus on defining life based on characteristics observed in terrestrial organisms. Emerging trends in astrobiology [36], [37] suggest that Earth-centric definitions may be too restrictive to properly enable the study of the biological profile of other planets [38], since extraterrestrial environments have vastly different chemical profiles and evolutionary pressures than those which have shaped life on Earth. The astrobiology community is currently moving

towards identifying an environment-agnostic means of defining life [39], which is not necessarily restricted by previously observed phenotypes optimized for the Earth environment [40].

Approaches to defining life, and delineating between abiotic and biotic entities, can be broadly thought of as falling into one of the following categories, as proposed by the author of this paper:

- (1) *observation-based canonical*: defining the boundaries of life based on biochemical characteristics of observed entities considered to be lifeforms on Earth (e.g., the presence of DNA/RNA and proteins);
- (2) *observation-based non-canonical*: a broadened variant of definition type (1), which expands the definition of life to include known, observed terrestrial entities such as viruses and prions (infectious proteins) which resemble life but are not canonically considered lifeforms;
- (3) *theoretical canonical*: expanding definition (1) to include as-yet unobserved lifeforms with similar general characteristics as canonical lifeforms, but which are theorized to rely on alternate biochemical processes (e.g. replication in non-aqueous solvents [1]); and
- (4) *theoretical non-canonical*: the widest possible approach to defining life, where any entity which demonstrates generic manifestations of the attributes or requirements of life (e.g. self-containment, Darwinian evolution, responsiveness to its environment) may be considered a lifeform.

Current planetary protection measures almost exclusively rely on definition (1). As such, the COSPAR regulations and those like it contain no provisions to protect any sort of non-canonical lifeforms (and their metabolic byproducts) from needless exposure to terrestrial organisms, since there is no knowledge as to how such lifeforms might be harmed by interaction with terrestrial organisms. Viruses, for example, would meet the criteria for the second-most restrictive definition of life, definition (2), but would still not impact planetary protection considerations since they are not known to demonstrate long-term viability outside a definition (1) lifeform [41]. The possibility that viruses and similar entities might interact differently than expected with an extraterrestrial environment – e.g. that an Earth virus might be able to infect an astrobiological lifeform, if one was found – is not typically incorporated into risk calculations, even on missions explicitly dedicated to searching for astrobiological life. This approach risks jeopardizing emerging scientific interests in studying as-yet uncharacterized forms biological entities, such as those which would fall under life definitions (2) or (3).

3.3. Risk stance

Current planetary protection guidelines are arguably contingent on the scientific community having a near-

complete understanding of the limits of biological survivability and on the criteria for a planetary target being of astrobiological interest. If one is able to assume that current knowledge regarding those topics is complete (or effectively so), taking a risk-forward approach and not imposing biological contamination control measures for targets known to be of non-interest from an astrobiological perspective is justifiable, as it permits a reduction in mission costs without introducing much uncertainty regarding the integrity of future scientific missions. However, given that the scientific community's current understanding of limits of habitability, etc. is actively and rapidly broadening to include environments previously considered unlikely to harbour life, taking a risk-forward approach is not necessarily worth the financial gains. An incomplete and actively evolving understanding of the limits of habitability means that there is a non-negligible risk of mis-categorization of planetary targets, and that the COSPAR guidelines may permit targets initially assigned low-priority category ratings under the COSPAR guidelines (Category I and II) to receive exposure to scientifically harmful levels of contamination before their category status is re-evaluated and adjusted.

An example that has been highlighted in the literature [30] regarding the issues of the risk-forward approach is of the Mars Polar Lander, which crashed into the ice-rich south pole of Mars due to a system failure and may have consequently introduced contamination into the area. Since it was not an astrobiology mission, it was not sanitized to the same standard as components on the subsequent Phoenix Scout mission to the same approximate region. As such, there have been concerns about whether the Mars Polar Lander crash might have impacted the viability of the science data from the Phoenix Scout mission. Such questions are unavoidable in instances where the implementation of planetary protection on prior missions engenders uncertainty later on about the biological integrity of a given environment.

As has been noted in the literature [3], [10], damage to planetary environments via biological contamination can be catastrophic and irreversible, and as such should be consistently mitigated and prevented to the greatest extent possible. Clear trends towards pursuing an understanding of astrobiology as encompassing non-canonical biological entities also militate in favor of a more risk-conservative strategy, so as to better balance the trade-off between current scientific priorities and the chance of harmful contamination of future scientific interests.

3.4. Prioritization of interests

Despite increasing interest in astrobiology research prevailing views of the trade-off between planetary

protection and human exploration tend to heavily favor the prioritization of exploratory objectives, even at the cost of planetary protection objectives. This viewpoint has undoubtedly been augmented by the value that the human exploration of space offers to humanity, both from a strategic and scientific perspective. offers to In 2019, for instance, the administrator of the United States' National Aeronautics and Space Administration (NASA) stated at a press conference that:

“...when we go to Mars with humans, by definition, there will be contamination. We, as humans, will leave our microbes behind. Some would say that is harmful contamination, and what we need to figure out, ultimately, is what contamination is harmful and what contamination is not harmful? That is the definition we are going to have to work through as each of our agencies put together plans to go to Mars, because ultimately we all want to go to Mars.” [16]

As highlighted in that statement, current COSPAR policy does not provide a clear view on what limitations the “harmful contamination” standard might impose on crewed space exploration efforts, which may provide grounds for a future shift in contamination control recommendations based on how the “harmful” standard is interpreted in the future. Pre-existing assumptions about the general inhospitable nature of space with respect to biological entities, as well as perspectives on contamination being the inevitable cost of exploration, have generally contributed to the view that “harmful contamination” should only refer to threats to human interests. However, recommendations made as part of recent decadal surveys suggest the possibility of shifting perspectives [30] in order to encompass ethical obligations towards the safeguarding of other planets, not just human interests on those planets.

4. Recommendations and discussion

In light of the critiques made above, the following changes to the COSPAR planetary protection policy are recommended:

4.1. Establish maximum contamination control (Category IVb) as the baseline for interplanetary missions

Biological contamination is known to be largely irreversible in susceptible environments, as has been readily seen through the introduction and spread of various invasive species between different biomes on Earth. Therefore, a risk-conservative, or at minimum risk-neutral, posture towards planetary protection should be taken since harmful contamination events, even if unlikely, can be expected to have significant repercussions. In reflection of this stance, missions should be assigned to the highest planetary protection

risk category and have the expectation of taking appropriate measures unless a waiver (i.e. elimination or reduction) of such procedures is appropriately justified. This represents a reversal of the current approach to planetary protection, wherein missions are generally expected to justify requiring planetary protection measures.

While this approach places a larger logistical and financial burden on missions, such a cost is reasonable compared to the cost of scientific losses that might result from irreversible disruption/damage of planetary biomes. Designing missions on the assumption that they pose a low risk results in them being ill-prepared to handle the repercussions of inadvertent contamination events, such as containment failures, spacecraft impact, operational issues, etc. Erring on the side of caution in cases of planetary protection mitigates the risk of harmful contamination events, and – from a more practical perspective – means that missions are required to comply with the more detailed planning requirements of COSPAR Category IV by default.

It has been noted in the literature that missions tend to suffer from neglecting planetary protection considerations until late in mission development [42]; having stringent planetary protection measures be the norm, rather than the exception, thus places an incentive for mission designers to make concerted efforts to reduce contamination risk (so as to justify allocation to a lower risk category and thus reduce mission cost) and develop innovative means of maximizing scientific value without causing significant environmental damage to planetary bodies. Autonomous experimental instruments, in lieu of crewed missions, present a notable means of curbing contamination risk in mission planning.

4.2. Elimination of COSPAR Category I

The existence of COSPAR Category I is fundamentally predicated on the premise that contamination control measures are not necessary unless a planetary environment is deemed to be of interest to “understanding the process of chemical evolution or the origin of life” [6]. This premise inherently ignores any ethical obligations to preserve the integrity of planetary environments for their own sake, as the need to enact protective measures is being defined relative to human interests alone. Even from the perspective of protecting humanity’s scientific interests, though, a minimal level of contamination control is warranted. The literature has made it clear that both ambiguities regarding the limits of biological survivability, and uncertainties regarding the potential for contamination-based harm to indigenous biological populations on other planetary bodies (should they exist) [30], are too substantial to permit conclusive determinations regarding the presence or absence of biomes on planetary bodies. Neglecting

contamination control entirely on certain missions thus presents a substantial risk of irreparable harm to future scientific interests, which cannot be justified given the ready availability of methods for contamination mitigation on missions. Therefore, until such time as astrobiological knowledge and associated measurements can permit the scientific community to distinguish confidently between high- and low-risk targets, all interplanetary missions should warrant a certain baseline level of contamination control.

4.3. Elimination of COSPAR Category II

Per the logic set forth above in support of eliminating Category I, it is recommended that Category II – which only imposes documentation requirements on missions, rather than any specific planetary protection actions – also be eliminated.

The evaluative standard for differentiating missions with “remote” chances of harmful contamination (Category II) from those that pose “significant” contamination risks (Category III/IV) is presently based whether canonical lifeforms observed on Earth are expected to be able to withstand the planetary environment of interest. Given that it is unclear how reliable the current understanding of terrestrial survivability limits is in accurately assessing extraterrestrial contamination risk, separating Category II from Category III needlessly jeopardizes future scientific endeavors conducted on Category II planets.

4.4. Standardization of risk calculations

While the matter of how best to calculate contamination risk is one that has not yet been resolved in the literature, it is recommended that the COSPAR guidelines standardize a specific quantitative approach to estimating the probability of harmful contamination. The COSPAR guidelines do not specify any format for probability of contamination calculations at the present time; however, absent such a format, it is impractical to meaningfully apply the numerical risk threshold specified by COSPAR (a probability of $<1 \times 10^{-3}$ that a planetary body will be contaminated during the period of exploration) [6]. At present, it is unclear how COSPAR recommends that its risk threshold be evaluated relative to factors specified in its policy (e.g. the timescale of environmental transfer processes on a planetary body, proliferation after transfer), or indeed how those quantitative factors should be evaluated in the first place. Even if the recommended risk estimation method is not expected to provide a particularly precise measurement of contamination risk, there needs to be some sort of standardization in the risk calculation methodology to enable comparison of an individual mission’s risk against the COSPAR threshold and against similar missions.

4.5. Requirement for contamination mitigation measures as part of operations for direct-contact astrobiology missions

All missions should exercise planetary protection procedures prior to launch and (if applicable) upon return to Earth. However, on missions seeking to collect astrobiological data via direct contact with a planetary target, there is an additional need for contamination control measures during the mission operational phase. These measures may include thermal, radiative, or chemical cleansing of sampling instrumentation, as well as regular monitoring of estimated contamination levels within said instrument(s). The rationale for doing so is to minimize the risk of cross-contamination from a portion of the spacecraft which is expected to regularly interface with the exterior environment. As contamination also affects data quality, self-cleaning operations already tend to receive consideration during mission design; this requirement merely codifies the necessity for such measures in support of planetary protection objectives.

4.6. Utilization of sterilization techniques which inactivate viruses and prions

In addition to requiring the minimization of bacterial and fungal counts on spacecraft, it is recommended that missions also actively seek to reduce the quantity of viruses and proteinaceous material transferred into the space environment. Methods which are already used to facilitate the removal of bacteria, such as irradiation with ultraviolet light, have been shown to also be effective in inactivating viruses and destroying prions [43]. It is recommended that planetary protection efforts make use of such methods over those which may be ineffective in reducing viral/protein load.

4.7. Post-sterilization instead of pre-sterilization bioburden monitoring

Verification of the bioburden level on spacecraft is presently evaluated based on pre-sterilization bioburden levels and the reduction factor the sterilization method(s). However, since sterilization methods can vary in efficacy based on the material being sterilized and the contaminating organisms present, it is recommended that bioburden be evaluated post-sterilization.

4.8. Evaluation of pre-flight bioburden

Current bioburden requirements are based on spore counts, determined on the basis of the number of aerobic microorganisms that are able to survive a 15-minute 80°C heat shock and which are culturable in 72 hours on Tryptic Soy Agar at 32°C [6]. While these counts provide a starting point for bioburden estimation, they do not accurately capture the number or distribution of microorganisms which are actually

present. It is documented in the literature that only approximately 1% of bacteria on Earth can be readily cultivated *in vitro* [44]; 31 of the 61 distinct bacterial phyla recognized on Earth have no culturable representatives at all [45]. Based bioburden estimates on the number of aerobic organisms which are able to survive at a specific growth temperature and in a particular medium also promotes the growth of microorganisms optimized to those conditions, rather than the growth of organisms which are likely to prove problematic in an extraterrestrial environment. The focus on aerobes in particular, though convenient for procedural purposes, also makes the current spore count methodology particularly ineffective for space missions, since the microbes most likely to thrive in the vacuum of space and/or in extraterrestrial atmosphere are those that are anaerobic.

A more accurate means of evaluating bioburden, which is a recommended requirement for the planetary protection of *in-situ* astrobiology missions (and is a suggested procedure for all missions, if feasible) is to utilize a combination of modern microbial quantification methods, such as fluorescence microscopy [46], oligonucleotide arrays [47], and/or spectroscopy-based proteomics [48], [49], to document the biodiversity and quantity of contaminating organisms. Proteomics in particular is a particularly promising technique as it enables the tracking of viral and proteinaceous particles in addition to more canonical lifeforms.

5. Conclusion

Planetary protection is a matter of increasing relevance for modern missions, particularly given the space community's dual – if at times opposing – interests in astrobiology and the human exploration of space. The COSPAR guidelines have laid the foundation for making planetary protection a topic of discussion on missions, but current planetary protection policy still falls short of adequately protecting future scientific interests in extremophilic and non-canonical lifeforms. A more risk-conservative approach to planetary protection, along with more rigorous bioburden monitoring efforts, is recommended.

Appendix A (Current guidelines)

Table 1. COSPAR guidelines for planetary protection. *Source:* Generated by the author based on COSPAR policy.

* = *Implemented on an “as necessary” basis*

	Category I	Category II	Category III	Category IV	Category V
Astrobiological value of target body	None	Significant	Significant	Significant	Varies
Expected probability of harmful cross-contamination	None	Remote	Significant	Significant	<i>Unrestricted:</i> varies; <i>Restricted:</i> significant
Mission type	Non-Earth return	Non-Earth return	Flyby, non-contact orbiter	Lander, probe, some orbiters	Earth return
Expected contact with target planetary surface	Varies	Varies	No direct contact	Direct contact	Varies
Expected contact with Earth post-launch	None	None	None	None	Direct
Documentation required	None	Brief reports	Category II + contamination control measures; <i>organics inventory*</i>	Category III + Pc analysis plan; microbial reduction & assay plans; organics inventory	Category II + Pc analysis plan; microbial reduction & assay plans
Actions required	None	None	Trajectory biasing; cleanroom use; <i>bioburden reduction*</i>	Category III + Bioburden reduction & monitoring; <i>partial sterilization of contacting hardware*</i> ; bioshield	<i>Unrestricted return:</i> based on category of target; <i>Restricted return:</i> Trajectory biasing; sterile/contained returned hardware
Impact requirements	None	None (record of impact probability)	Limit on impact probability	Limit on non-nominal impact probability	<i>Unrestricted return:</i> based on category of target; <i>Restricted return:</i> no impact on Earth or Moon
Bioburden requirements	None	None (record of contamination control measures)	Passive control	Active control	<i>Unrestricted return:</i> based on category of target; <i>Restricted return:</i> sterile

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