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Introduction

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Author for correspondence:
Karen Olsson-Francis
e-mail: karen.olsson-francis@open.ac.uk

Planetary Protection for Safe and Sustainable Space Exploration

Karen Olsson-Francis[1], Athena Coustenis[2], Niklas Hedman[3], Peter T. Doran[4], Petra Rettberg[5] and Jean-Claude Worms[3]

[1]AstrobiologyOU, Faculty of Science, Technology, Engineering and Mathematics, The Open University, Milton Keynes, England, UK
[2]Laboratoire d'Instrumentation et de recherche en Astrophysique (LIRA), Paris Observatory, PSL University, CNRS, Paris University, Meudon 92190, France
[3]COSPAR c/o CNES, Paris, France, Paris, Paris Cedex 01, France
[4]Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA, USA
[5]Department of Radiation Biology, DLR, Institut of Aerospace Medicine, Koeln, Germany

KO-F, 0000-0002-4684-3981; AC, 0000-0003-3414-3491;
PTD, 0000-0002-3774-2847; PR, 0000-0003-4439-2395;
J-CW, 0000-0002-0851-7341

In April 2024, the Inaugural International COSPAR (Committee on Space Research) Planetary Protection Week (ICPPW) was held at the Royal Society in London, marking a significant milestone in advancing international collaboration in planetary protection. The event was hosted by AstrobiologyOU (The Open University), funded by the UK Space Agency (UKSA) and co-sponsored by COSPAR, the European Space Agency (ESA), Cornell University, and the UK Natural History Museum (NHM). The event aimed to foster cooperation among various stakeholders, including space agencies, the scientific community, policymakers and industry. It served as a platform for experts to share their expertise, address pressing challenges and identify key knowledge gaps in our understanding of planetary protection measures for space exploration. Furthermore, it highlighted the need for collaborative efforts to address key scientific knowledge gaps to establish protocols to guide future exploration, such as crewed missions and sample return. This paper provides a comprehensive background and rationale for the

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event, detailing the historical context and recent advancements in planetary protection that informed the discussions and set the scene for the more focused papers in this thematic issue.

This article is part of the theme issue 'Planetary Protection for sustainable space exploration'.

1. Introduction

Planetary protection forms a set of guidelines and policies designed to prevent the biological contamination of celestial bodies during space exploration and to protect Earth from potential hazards associated with the return of extraterrestrial samples [1–3]. It enables space exploration by protecting scientific investigations of pristine environments that could be habitable or that offer opportunities to understand the origin and evolution of life. The field of planetary protection is driven by our current understanding of extraterrestrial environments and the physical and chemical limits for the survival and propagation of microbial life on Earth [4].

The presence of liquid water is central to when, where and under what conditions past or present life may have existed elsewhere in the Solar System. Hence, Mars and the icy moons that harbour under-surface liquid oceans, such as Europa, Ganymede, Titan and Enceladus, are prime targets for habitability/life detection missions [5–8]. However, life is not solely dependent on water; the chemical elements carbon, nitrogen, hydrogen, oxygen, phosphorus and sulfur, and an energy source, are also essential [7,9]. Environmental conditions, such as temperature, pressure, water activity and pH, must also be conducive to life, and these conditions have implications for planetary protection (as discussed in detail by [10,11] for Mars and [12,13] for the Icy Worlds). Furthermore [12,13] outline an index for the lower limits of terrestrial life based on water activity and temperature for planetary protection. This is beneficial when we assign planetary protection categories to missions, particularly to the Icy Worlds (currently set at 0.5 and −28°C based on the definition of Mars Special Regions [11]).

Planetary protection has been recognized as an international concern for over 60 years, since the International Council of Scientific Unions (ICSU) established the Committee on Space Research (COSPAR) in 1961, which introduced planetary protection measures [2]. However, recently, it has received more attention owing to increased activity by national space agencies, the emergence of new spacefaring countries and the growing involvement of commercial actors [2,3,14–16].

The legal basis for planetary protection is provided by Article IX of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (the Outer Space Treaty), which was adopted by the United Nations in 1967 (https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html). It states that '*States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose*'. States Parties bear international responsibility for their national activities and for assuring that they are carried out in conformity with the provisions of the Treaty (Article VI of the Outer Space Treaty).

COSPAR is part of the International Council for Science (ICS), and its main goals are '*to promote scientific research in space at an international level, with emphasis on the exchange of results, information and opinions*' (https://cosparhq.cnes.fr/about/). The COSPAR Planetary Protection Policy is the primary international reference standard for compliance with Article IX of the Outer Space Treaty. The policy has been developed by the COSPAR Panel on Planetary Protection (PPP) through consultation with the scientific community and space agencies [2,14].

The Panel (https://cosparhq.cnes.fr/scientific-structure/panels/panel-on-planetary-protection) has international recognition and has representatives from 12 space agencies from various countries (Canada, China, France, Germany, India, Italy, Japan, the United Kingdom, the Russian Federation, the United Arab Emirates, the United States and Europe (ESA)). The primary objective of the COSPAR PPP is to develop, maintain and promote the policy, ensuring that stakeholders understand its requirements so that they can be effectively applied to space missions. The Inaugural International COSPAR Planetary Protection Week (ICPPW), hosted by AstrobiologyOU (The Open University), was an example of community engagement that facilitated discussions on various aspects of planetary protection.

The COSPAR Planetary Protection Policy has a voluntary, non-legally binding status, allowing it to be updated as scientific understanding develops [1,14,17,18]. The policy aims to: (i) ensure that scientific investigations of possible extraterrestrial life forms, precursors and remnants are not jeopardized and (ii) Earth is protected from the potential hazard posed by extraterrestrial matter carried by spacecraft returning from an interplanetary mission [1]. To date, there are five categories of requirements, which are defined based on the mission's target, type and scientific rationale, as listed in table 1 [1]. It is the prerogative of governments to determine how to implement the obligations under the treaty and how to authorize and supervise activities of non-governmental entities under their jurisdiction.

Planetary protection requirements have often been viewed as a financial burden for space missions over the years, owing to the systematic use of cleanrooms for assembly, integration, testing and potentially, control and reduction of biological contamination, as shown in figure 1. This perception is somewhat misleading and merits a more nuanced understanding. The cost associated with implementing planetary protection measures for forward missions represents less than 1% of the total mission budget [19]. This number is minor compared to the costs of developing and deploying scientific instruments. By ensuring that we minimize the risk of contaminating other celestial bodies, we protect the reliability of our scientific findings, particularly the most important question of whether life has originated elsewhere in the Solar System. Without proper measures, there is the potential for false-positive results, which could lead to misinterpretations of data and undermine scientific integrity.

2. New challenges

Planetary protection has recently gained attention from the broader scientific community. This is due mainly to the emergence of new spacefaring countries and the growing involvement of private/commercial actors, which has led to an increasing number of missions currently in operation or being planned [2,3,18,20]. The two-horse race that characterized the early exploration of space has transformed into a highly dynamic industry with approximately 70 nations operating national space programmes and an ever-growing number of commercial actors (UNOOSA, 2019). This growth is reflected in the complexity of missions planned in the next 20 years, including the first return of samples from Mars and crewed missions to the Moon and Mars [16,21]. Many countries also host non-governmental or private-sector entities within their respective jurisdictions that have ongoing or upcoming activities planned in space, including to the Moon and nearby planets [2]. The study by Hedman *et al.* [14] highlights how the role of the COSPAR PPP and the landscape of space exploration have evolved.

To support the next generation of missions, the COSPAR Planetary Protection Policy is adapting to support more complex endeavours [1,17,22]. Recent changes to the policy have addressed the need to update categorization for some celestial bodies (the Moon, Venus and small bodies) based on new knowledge acquired. It also introduced a more objective-driven and case-adapted (versus prescriptive) approach to the formulation and implementation of planetary protection controls [1]. This methodology may involve using an end-to-end probabilistic risk assessment to demonstrate compliance with requirements and inform design decisions. This was used for a series of missions, including the JAXA MMX mission [23],

Figure 1. NASA's Mars 2020 Rover in the NASA Jet Propulsion Laboratory in Pasadena, USA. Credit: NASA/JPL-Caltech.

Table 1. Planetary protection categories [1].

category	mission type	target body
I	flyby, orbiter, lander	undifferentiated, metamorphosed asteroids; Io
II	flyby, orbiter, lander	Venus; Moon (Cat. II, IIa & IIb); comets; carbonaceous chondrite asteroids; Jupiter; Saturn; Uranus; Neptune; Icy Worlds[a]; Kuiper-belt objects that are not classified as Icy Worlds
III	flyby, orbiters	Mars; Icy Worlds[a]
IV	landers	Mars (Cat. IVa, IVb, & IVc); Icy Worlds[a]
V 'restricted Earth return'	return	Mars; Small Solar System Bodies and Icy Worlds[a] [b]
V 'unrestricted Earth return'	return	Venus; Moon; Small Solar System Bodies and Icy Worlds[a] [c]

[a] By default, missions to Icy Worlds are considered either Cat. III (Orbiter) or Cat. IV (Lander). Assignment of these missions to category II must be supported by an analysis that determines the probability of introducing any component of the spacecraft into greater than lower limit of temperature (-28°C) environments that may exist beneath their surfaces within the period of biological exploration of 1000 years [1]

[b] With an answer of 'no' or 'uncertain' to all six questions in section 6.5.2 [1]

[c] Without an answer of 'no' or 'uncertain' to all six questions in section 6.5.2 [1]

NASA's Europa Clipper mission [24], ESA's Juice mission [25] and NASA's Dragonfly mission [26].

Tobie *et al*. [25] demonstrated that in the current JUICE trajectory, the probability of impact alone is sufficient to ensure that the mission addresses the planetary protection requirements for Europa [27]. In the case of Ganymede, there is no identified risk of biological contamination of subsurface liquid reservoirs, as such reservoirs are expected to be rather deep and exchange processes through the thick lithosphere are inhibited. Furthermore, in [26] they demonstrated that the Dragonfly mission to Titan would have a probability of less than 1×10^{-4} of a biological inoculation event into a potentially habitable extraterrestrial environment. The paper includes state-of-the-art analyses that determine the probability of various end states of the mission hardware elements, including the thermodynamic conditions, putative terrestrial biota contamination and the movement of material from hardware sites to elsewhere on Titan.

A crucial aspect of a planetary protection probabilistic risk assessment approach is understanding the types of terrestrial contamination present before a launch. It is important to determine whether these contaminants can survive the harsh environmental conditions of spaceflight and subsequently proliferate on the target celestial body. Innovative molecular biology techniques are being applied in cleanroom environments and on space hardware to gain deeper insights into the function and survivability of microbial contamination [28–30]. In [31], researchers utilize multiple distinct binning programmes to construct metagenomic-assembled genomes. Using this approach, they identified the potential physiological tolerances, replication and metabolic potential of microbial cleanroom contamination, which is critical to informing the risk to potential mission planning and informing potential revised cleanroom treatment strategies.

By combining this methodology with environmental simulation studies that investigate microbial survivability under extraterrestrial conditions, for example, on the surface of Mars, or by simulating the environmental parameters during a mission to Europa or Enceladus, we can identify specific microorganisms and their key genetic traits that may be problematic for planetary protection for future missions (e.g. [32–36]). Zaccaria *et al*. [36] used state-of-the-art environmental simulation experiments to determine the effect of long-term desiccation, freezing–thawing and ionizing and non-ionizing radiation on microbial survival (simulating space transport and replication in the oceans of Europa or Enceladus). Combining these results with metagenomic data is imperative as we plan for a tailored, targeted risk assessment approach.

A primary goal of the COSPAR Planetary Protection Policy is also to protect Earth from the potential hazard posed by extraterrestrial matter carried by spacecraft returning from an interplanetary mission (backward contamination) [22]. Fifteen samples have successfully been returned to Earth: 10 from the Moon, three from asteroids, one from the coma of a comet and one that collected solar wind at Earth–Sun Lagrange point one [37–39]. The missions to date have focused on celestial bodies or parent bodies that have, so far, not been considered habitable, which means that there was limited concern for potential extraterrestrial life [40]. However, bringing samples from Mars is more challenging for planetary protection owing to the potential habitability of the planet, making it a Class V Restricted Earth-return [1]. The mission will depend on ‘a break the chain’ approach to isolate and contain samples delivered to the Earth-Moon system [21]. On return to Earth, the samples will be transported to a sample receiving facility. This is a specialized facility where the samples will be initially curated and assessed for safety, and/or sterilized while maintaining the sample integrity by protecting the samples from terrestrial contamination [41]. One containment solution that is often discussed to address this challenge is the double wall isolator.

Holt *et al*. [42] discuss the technological development of the double wall isolator, and how it enables the safe handling/movement, analysis and curation of the precious samples in a pristine environment. The paper discusses the double wall concept as a primary containment solution, its relationship to class III containment within a bio-safety level 4 laboratory, and how the space between the walls is configured to provide a tertiary pressure barrier, therefore addressing the curation and containment requirements.

3. International collaboration

An integral part of planetary protection is international collaboration and consultation. For example, the COSPAR Planetary Protection Policy requirements for the icy moons have been scrutinized as part of the Planetary Protection of the Outer Solar System (PPOSS) project, which was commissioned by the European Commission's H2020 Programme [43] and also as part of a report: *Assessment of Planetary Protection Requirements for Spacecraft Missions to Icy Solar System Bodies* [44]. Both reports made recommendations to the panel, and the changes were incorporated in the COSPAR Planetary Protection Policy published in 2020 [22]. Following on from that work, Doran and coworkers [12,13] proposed further changes to the policy, which are currently being evaluated through ongoing international community engagement studies.

To promote an inclusive environment for international discussion regarding planetary protection, in 2024, the ICPPW was held at the Royal Society in London. The meeting marked a substantial milestone in advancing international collaboration in planetary protection and served as a platform for promoting international collaboration and knowledge exchange on best practices in planetary protection. The total number of in-person attendees was capped at 100, and an additional 171 people attended online. This included academics, policy-makers and representatives from the commercial sector from 24 countries.

The meeting focused on five key topics:

- The evolving landscape of planetary protection and the future direction of the requirements.
- The Icy Worlds and changes to the COSPAR Planetary Protection Policy to reflect our current understanding.
- Limits of life on Earth and implementations on planetary protection requirements.
- Scientific knowledge gaps must be addressed to facilitate future Mars activities, including both robotic and crewed missions.
- The planetary protection requirements for Mars sample return.
- A discussion led by industry experts about the implementation of planetary protection requirements.

The meeting reflected the significant milestones achieved over the past 60 years, from both a governmental and a scientific viewpoint, tracing the evolution of this vital field from its beginnings to the present day.

A further outcome of the meeting was the formation of two additional subcommittees of the COSPAR PPP to assess the following:

- The Moon: focusing on lunar crewed mission/ human mission policy;
- Metagenomics: use of metagenomics to meet planetary protection requirements.

They will contribute to the panel's activities similarly to the Mars [15] and Icy Worlds [12] subcommittees.

4. Conclusion

The papers presented at the ICPPW highlight the challenges and opportunities that lie ahead for planetary protection in the context of space exploration. It is imperative to recognize and address the delicate balance between fulfilling planetary protection requirements and enabling the ambitious goals of space exploration. This will require a transparent approach, where international collaboration is actively pursued, including the sharing of best practices and fostering collaboration among stakeholders to help ensure that space exploration benefits future generations. The panel seeks to ensure that our endeavours beyond Earth yield valuable scientific knowledge and safeguard the integrity of other celestial environments for scientific investigation. As such, ensuring that the benefits of space exploration extend to future generations will depend on our commitment to planetary protection practices and continuous dialogue among all stakeholders involved in this international endeavour.

Data accessibility. This article has no additional data.

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Authors' contributions. K.O.-F.: conceptualization, funding acquisition, project administration; A.C.: validation, writing—review and editing; N.H.: validation, writing—review and editing; P.D.: validation, writing—review and editing; P.R.: validation, writing—review and editing; J.-C.W.: validation, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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