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The COSPAR planetary protection policy for missions to Icy Worlds: A review of history, current scientific knowledge, and future directions

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A R T I C L E I N F O

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A B S T R A C T

Recent discoveries related to the habitability and astrobiological relevance of the outer Solar System have expanded our understanding of where and how life may have originated. As a result, the Icy Worlds of the outer Solar System have become among the highest priority targets for future spacecraft missions dedicated to astrobiology-focused and/or direct life detection objectives. This, in turn, has led to a renewed interest in planetary protection concerns and policies for the exploration of these worlds and has been a topic of discussion within the COSPAR (Committee on Space Research) Panel on Planetary Protection. This paper summarizes the results of those discussions, reviewing the current knowledge and the history of planetary protection considerations for Icy Worlds as well as suggesting ways forward. Based on those discussions, we therefore suggest to (1) Establish a new definition for Icy Worlds for Planetary Protection that captures the outer Solar System moons and dwarf planets like Pluto, but excludes more primitive bodies such as comets, centaurs, and asteroids: *Icy Worlds in our Solar System are defined as all bodies with an outermost layer that is believed to be greater than 50 % water ice by volume and have enough mass to assume a nearly round shape.* (2) Establish indices for the lower limits of Earth life with regards to water activity (LLAw) and temperature (LLT) and apply them into all areas of the COSPAR

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Planetary Protection Policy. These values are currently set at 0.5 and -28 °C and were originally established for defining Mars Special Regions; (3) Establish LLT as a parameter to assign categorization for Icy Worlds missions. The suggested categorization will have a 1000-year period of biological exploration, to be applied to all Icy Worlds and not just Europa and Enceladus as is currently the case. (4) Have all missions consider the possibility of impact. Transient thermal anomalies caused by impact would be acceptable so long as there is less than 10^{-4} probability of a single microbe reaching deeper environments where temperature is >LLT in the period of biological exploration. (5) Restructure or remove Category II* from the policy as it becomes largely redundant with this new approach, (6) Establish that any sample return from an Icy World should be Category V restricted Earth return.

1. Introduction

Planetary protection has as a central concern the protection of undoubtedly the most important scientific question humans can ask – is there life beyond Earth? When we explore other potentially habitable worlds in our Solar System seeking extant or extinct life, this needs to be done responsibly to avoid inadvertently introducing terrestrial microbial and organic contamination that may confound any such discoveries.

The definition of the traditional habitable zone in a planetary system focuses on surface temperature: it is located at the radial distance from a host star where incident stellar radiation permits liquid water to remain stable on a planetary surface, potentially aided by an atmospheric greenhouse (e.g., Huang, 1959; Kasting et al., 1993; Kasting, 1997). Away from Earth, subsurface habitable environments, on the other hand, are mostly independent of direct solar heating. In these environments, liquid water is made available by thermal heating provided from accretion, radioactivity, impacts, or tidal dissipation, and chemical sources of energy that can support metabolic activity. The stability of both surface and subsurface habitable environments depends on feedback between stellar, orbital, atmospheric, and geological evolution (Nimmo and Pappalardo, 2016; Lunine, 2017). In order to make the major discovery of life in these environments, responsible handling of samples returned to Earth becomes a critical concern to avoid inadvertent deleterious effects on the Earth's biosphere.

Following Lammer et al. (2009), four classes of habitats can be considered. On rocky bodies, liquid water can be stable on the surface, or hosted in regolith and, in the deeper subsurface, sometimes beneath cryospheres, thus leading to classes I and II, which are dependent on the existence of habitable conditions: in the present (Earth-like, class I) or putative in the past (Mars-like, Venus-like, class II). Extension of the concept across the outer Solar System, where water can exist in the subsurface of certain bodies and be directly in contact with a rocky core are defined as class III habitats, which we believe includes Europa and Enceladus. Based on the definition in Lammer et al. (2009), liquid water within ice shells themselves or sandwiched between two ice layers as is the case of Ganymede, Callisto, and possibly Titan is defined as class IV.

The data now support the hypothesis that the ice-covered oceans of the outer Solar System are the most likely present-day habitable environments outside of Earth. Due to intense robotic exploration of the outer Solar System over the past 40 years, in particular of Jupiter and Saturn, with missions like Voyager, Galileo, Cassini-Huygens and Juno, we have acquired extensive evidence for large amounts of liquid water existing underneath the surfaces of several of the gas giant planet's satellites (e.g. Iess et al., 2012; Kivelson et al., 2002; Nimmo et al., 2016, Hand et al., 2020 and references therein). Exploring these subsurface oceans could provide us with the revolutionary discovery of another genesis of life and extend our understanding of the emergence of life in extreme environments, further away from the Sun than considered before by the models of the traditional habitable zone.

The current definition of habitability refers to the ability of an environment to sustain the activity of life as we know it, where activity is related to its survival, maintenance, growth, or reproduction processes (e,g, Cockell et al., 2016). Thus, in addition to the presence of liquid water, other physical and chemical factors are necessary for the aqueous environments to be considered habitable. The water temperature, pressure, pH, alkalinity, and salinity inferred from current observations for these alien oceans (where possible) are all compatible with terrestrial life (Rothschild and Mancinelli, 2001), albeit one or more of them could provide stringent limitations for life. Hand et al. (2020) describes some of these factors and details current understanding of the elements, energy and astrobiological potential required to build life in these environments with the conclusion that *"Scientifically, ocean worlds are arguably the best place to search for extant life, and a second, independent origin of life."* Whether these Ocean Worlds (bodies with evidence of an ocean beneath ice) ever contained habitats that may have witnessed the emergence of life, and perhaps even harbors life today is unclear. However, missions including JUICE, Europa Clipper and Dragonfly, which are currently in flight or in development, have scientific objectives that include the search for habitable conditions in the moons of Jupiter and Saturn.

Habitable conditions in a planet or satellite, however, do not imply the emergence of life. But by extrapolation to what we have on Earth, it is worth considering this possibility. Indeed, we now have strong arguments for thinking that at the bottom of their internal liquid layers rock-water interactions and potential seafloor hydrothermal activity are ongoing in many Icy Worlds (Fig. 1). Detection of salts and silica particles in measurements performed by various space missions give clues as to such possible interactions, as Cassini's exploration of Enceladus has exemplified (Postberg et al., 2009; Hsu et al., 2015).

With large moons, such as Ganymede, Callisto, and Titan, the pressures at the base of their oceans may lead to the formation of higher phases of water ice (Lunine and Stevenson, 1987; Kirk and Stevenson, 1987; McKinnon, 1998). As a result, the seafloors of such worlds may be an interface between liquid water and water ice, not liquid water and silicates. Despite this barrier, several studies suggest that the exchange of nutrients from the core to the liquid ocean may still be possible (Lebec et al., 2023 and references therein). Furthermore, energy sources, such as H, Fe, S and other parameters favorable to life (e.g. habitable ranges of pH, temperature and salinity) have been detected on several of these bodies in various manifestations (Cockell et al., 2016; National Academies of Sciences, Engineering, and Medicine, 2023). As a result, the astrobiological potential of these worlds is considered significant.

The detection of living organisms on Icy Worlds (defined below in Section 3) of the outer Solar System would have an important impact on scientific research concerned with a possible multiple origin of life and, extant or extinct, such a discovery would provide important insights to our understanding of biological or biochemical processes. Today, we still lack a well-constrained understanding of detailed conditions that lead to, or prohibit, the origin of life. Investigations on terrestrial analog environments shift the limits of life, recommending caution with extremophile species. Therefore, it is important to review and update planetary protection policies for exploring the Icy Worlds as new information is gathered.

In this paper, we review current scientific knowledge relating to Icy Worlds in our Solar System and planetary protection considerations to date. We propose a reworking of the COSPAR Planetary Protection policy concerning Icy Worlds that centers around the low-temperature limit for life on Earth. This paper summarizes the history of planetary protection considerations for Icy Worlds and proposes potential changes to COSPAR planetary protection policy that consider our new understanding of these worlds.

2. Planetary protection background

2.1. COSPAR policy on planetary protection

The international standards for planetary protection have been developed through extensive collaboration and discussions among the scientific community and national space agencies (COSPAR, 2023). The Policy on Planetary Protection was established by COSPAR in 2002 to provide a non-binding framework that could be regularly updated to incorporate new scientific knowledge. In this way the policy serves as the primary global standard for planetary protection, providing 'a reference standard for spacefaring nations and in guiding compliance with Article IX of the Outer Space Treaty' (Committee on the Peaceful Uses of Outer Space, 2017), which prohibits harmful contamination of solar system bodies and harmful effects on Earth (Coustenis et al., 2019a, b).

Under Article VI of the Outer Space Treaty, States Parties hold international responsibility for the activities of both governmental agencies and non-governmental entities in outer space, including celestial bodies like the Moon (UNOOSA, 2002). Governments have the authority to implement the rights and obligations stipulated by the Treaty and oversee the authorization and supervision of non-governmental activities within their jurisdiction.

The technical aspects of the COSPAR Policy have been developed through inclusive discussions involving the scientific community, the private sector, and national space agencies. Currently, the policy encompasses five categories of requirements tailored to specific mission targets, architecture, and scientific objectives. These categories outline recommended measures to be followed during missions (Coustenis et al., 2023; COSPAR, 2021). While the COSPAR Panel maintains the COSPAR Policy, it is the responsibility of State Parties to ensure compliance with Article IX by authorizing and overseeing missions. It should be noted that the Policy does not describe how to implement the guidelines, nor does it dictate any organizational structure for the implementation of the policy – both of these are at the discretion of the user (e.g. space agencies) (Kminek et al., 2019).

2.2. The COSPAR panel on planetary protection

The Panel on Planetary Protection (PPP) was established by COSPAR in 1999, with the responsibility of consolidating, maintaining, and updating the COSPAR Policy, as well as ensuring its dissemination to relevant stakeholders (Kminek and Rummel, 2015). Following restructuring in 2018 (Coustenis et al., 2019a), the Panel currently consists of 24 members, including an equal number of representatives from national space agencies (such as China, France, Germany, the United Kingdom, India, Italy, Japan, the Russian Federation, Canada, the United Arab Emirates, the United States, and the European Space Agency) and thematic experts from the international scientific community. Additionally, the Panel welcomes ex-officio members from the U.S. National Academies of Science, Engineering and Medicine (NASEM), the United Nations Office of Outer Space Affairs (UNOOSA), and the COSPAR Committee on Industrial Relations or COSPAR Leadership who contribute to the Panel's activities. The Panel also invites participation from other stakeholders, including the private sector and industry, fostering dialogue and collaboration for mutual benefits. More information about the Panel's members and related documents can be found on the COSPAR website (COSPAR, 2023).

To ensure the COSPAR Policy is up to date, the Panel conducts regular reviews of scientific data and community consensus through studies, community consultations, workshops, technical meetings, and discussions at scientific and engineering congresses dedicated to space exploration (Kminek and Rummel, 2015). The Panel evaluates information, formulates updates to the Policy, and provides recommendations to the COSPAR Bureau and Council for validation of potential policy and requirement modifications (Coustenis et al., 2023).

3. Icy world definition and background

Historically, the icy bodies of the outer Solar System have been referred to as Icy Worlds (Russell et al., 2014), Icy Moons (Sephton et al., 2018), or Ocean Worlds (e.g., Hendrix et al., 2019). For use in the COSPAR Policy on Planetary Protection, we propose to use exclusively the term Icy Worlds. This is because not all Icy Worlds that are of concern are moons, and a body does not need an ocean to be of concern for terrestrial forward contamination. For these reasons, we propose the following definition for an Icy World:

Icy Worlds in our Solar System are defined as all bodies with an outermost

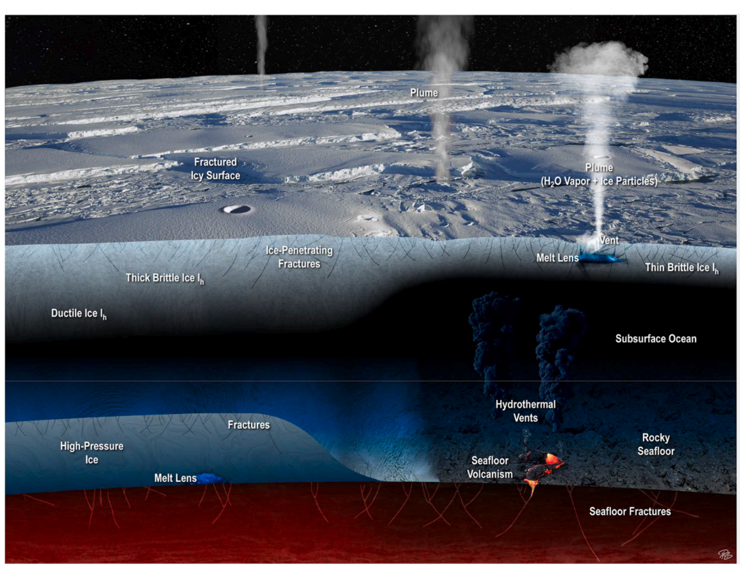

Fig. 1. Plumes and overturn of a fractured ice shell are means of exchanging matter between surface and ocean and volcanism, vents, and infiltration of fractured crust are means of exchange between ocean and core within icy satellites. From National Academies of Sciences, Engineering, and Medicine (2023). Courtesy P. Byrne.

layer that is believed to be greater than 50% water ice by volume and have enough mass to assume a nearly round shape.

We chose 50 % because bodies of the outer Solar System are half ice/rock and, if they have a round shape, differentiation is going to make the crust >50 % water ice by volume (we consider water ice in this definition to encompass both amorphous ice and clathrate). The above definition includes dwarf planets like Pluto, but rejects small bodies including comets, trojans, irregular moons, and Trans-Neptunian Objects (TNOs) including Centaurs and smaller Kuiper Belt Objects (KBOs) (Appendix A).

Some Icy Worlds are also Ocean Worlds, defined as bodies that are thought to currently support large liquid water oceans (bodies that no longer support liquid water oceans, but are believed to have supported them sometime in the past like Mars or Ceres, are known as Relic Ocean Worlds) (Lunine, 2017; Sherwood et al., 2018). In addition to Earth, there are over twenty Icy Worlds that are also suspected to have subsurface oceans (National Academies of Sciences, Engineering, and Medicine, 2023). On these bodies, tidal energy, orbital resonances, and radiogenic decay can help sustain subsurface oceans under icy crusts. These bodies include the Jovian satellites Europa, Ganymede, and Callisto, as well as the Saturnian satellites Enceladus and Titan (Table 1). Candidate Ocean Worlds, where the presence of an ocean has yet to be confirmed but evidence does point to its presence, include the Saturnian satellite Dione and the Neptunian satellite Triton. Several of Saturn's smaller satellites, including Mimas, Tethys, Rhea, and Iapetus, as well as the Uranian natural satellites Miranda, Ariel, Umbriel, Titania, and Oberon, are also credible candidates for subsurface oceans (Hendrix et al., 2019; Schenk and Moore, 2020; Ćuk et al., 2020; Beddingfield and Cartwright, 2021; Cartwright et al., 2021). Regardless of the presence of an ocean or not, however, all these worlds are considered Icy Worlds.

Table 1
The factors that govern planetary habitability, and whether those factors are present for select planetary bodies across the Solar System. Modified from National Academies of Sciences, Engineering, and Medicine (2023). Courtesy of P. Byrne.

OCEAN WORLDS

		Europa	Ganymede	Callisto	Enceladus	Titan	Mid-Size Saturnian Moons	Uranian Moons	Triton
WATER	Surface Liquid	✗	✗	✗	✗	✗	✗	✗	✗
	Subsurface Liquid	✓	✓	?	✓	✓	?	?	?
	Ground Ice	✓	✓	✓	✓	✓	✓	✓	✓
	Water Vapor	▨	▨	▨	✓	▨	▨	?	?
CHEMISTRY	CHNOPS[1]	?	▨	▨	✓	✓	?	✓?	✓
	Complex Organics	✓	▨	▨	✓	✓	▨	▨	▨
ENERGY	Solar Heating	✗	✗	✗	✗	✗	✗	✗	✗
	Interior Heating[2]	✓	✓	✓	✓	✓	✓?	✓?	▨
	Redox[3]	?	▨	▨	✓	✓	▨	▨	▨
BODY	Atmosphere[4]	✗	✗	✗	✗	✓	✗	✗	✗
	Magnetic Field[5]	✗	✓	✗	✗	?	✗	?	✗
	Present Habitability	?	?	?	✓	?	?	?	?
	Past Habitability	?	?	?	?	?	?	?	?

✓ Yes/Present ? Unknown/Uncertain ✗ No/Absent ▨ Insufficient Information

[1]The life-supporting elements carbon, hydrogen, nitrogen, oxygen, phosphorus, or sulfur (not all need be present)

[2]Interior heating is that energy derived from accretion, differentiation, radiogenic decay, and/or tidal dissipation

[3]The prospect for any element or molecule to be reduced or oxidized as a source of chemical energy for life

[4]Subsantial atmospheres only; exospheres (formed by, e.g., impact sputtering) are not included

[5]Intrinsically generated magnetic fields only

Dwarf Planets, which already include the requirement of a round shape in their definition (International Astronomical Union, 2006), are also considered Icy Worlds. For example, Pluto, the type-example of a Dwarf Planet, is considered an Icy World. The Dwarf Planets Haumea, Makemake, and Eris, which are similar in size to Pluto, are also Icy Worlds and, given their size, also credible Ocean World Candidates. Ceres, the largest asteroid and only inner Solar System Dwarf Planet, is considered a Relic Ocean World (De Sanctis et al., 2020) and maintains a modern subsurface brine reservoir (Castillo-Rogez et al., 2019) and surface salt deposits (Zolotov et al., 2017). While Ceres' outermost layer composition likely does not meet the >50% water ice requirement to be considered by the above definition, we include it in our policy discussions as it shares many of the characteristics and exploration objectives of the other Ocean Worlds (that are also Icy Worlds) (Castillo-Rogez et al., 2020).

Of the more than twenty Icy Worlds that are thought to have once had, or currently support, large liquid water oceans, five stand out as key targets for recent and/or upcoming planetary missions dedicated to understanding the origin and emergence of life: Ganymede, Europa, Enceladus, Titan, and Ceres, which will be discussed below.

Jupiter's moon Europa is the prototype-example for Icy Worlds in which subsurface oceans are most probably in direct contact with silicates at the seafloor. Europa's surface is characterized by a very young age as demonstrated by the extremely low density of impact craters (16 craters with diameters of 3–27 km). Europa's surface is made of bright plains (rather bluish) in which are found parallel ridges, and darker, brownish mottled terrain. The ridges originated from a variety of mechanisms, including, e.g., tectonism, cryovolcanism, or diapirism. Their existence has rapidly been considered as strong evidence either of the presence of liquid water in the shallow subsurface, or warm mobile ice underlain by an ocean at depth (see Greeley et al., 2004, and references therein). The presence of a liquid water ocean below the icy crust has been determined mostly from the Galileo Mission's detection of induced magnetic fields (Kivelson et al., 2000; 2002). This was reinforced by the study of the imaged surface characteristics (Pappalardo et al., 1999) and the thermal modeling of the moons' evolution (see for example Spohn and Schubert, 2003). However, the depth and composition of the ocean are still highly uncertain and model dependent. Furthermore, the exchange processes between the ocean and the deep interior (rocky core?) or the upper ice shell, are still unknown. Liquid water reservoirs may also exist in the shallow subsurface ice. In particular, chaotic terrains have been commonly associated with shallow lenses of liquid water (see Schmidt et al., 2011). Finally, over the last ten years and following the possible discovery of a plume of water vapor with the Hubble Space Telescope in the far-UV (Roth et al., 2014), the possibility of having direct access to a subsurface liquid reservoir (like those discussed for Enceladus and its plumes) has been debated. Indeed, the existence of such water vapor plumes, if confirmed in future observations, has far-reaching implications for the future exploration of Europa's potentially habitable environment.

Ganymede is the largest moon in our Solar System. The Galileo spacecraft discovered that Ganymede has its own magnetic field, contained within Jupiter's magnetosphere. Ganymede also has an induced magnetic field, indicating that it has a layer that acts as a conductor. The strength of the field suggests that the conductive material is a layer of liquid water containing salt, located ~150 km below the surface and sandwiched between two layers of ice of different densities. Ganymede is the only planetary moon known to have its own internally driven dipole magnetic field, with a similar strength to Mercury's dipole field – a few hundred nT at the surface. The large dipole field masks the induced field to some extent. Embedded in the rotating and variable background field of Jupiter's magnetosphere, we thus find a mini-magnetosphere within a magnetosphere – a feature that makes Ganymede unique in the solar system. Infrared spectra of Ganymede's surface indicate the presence of phyllosilicates (McCord et al., 1997, 1998), suggesting potential endogenic processes that would bring interior silicate material to the surface. As further evidence of an undersurface ocean, Ganymede displays auroral bands over northern and southern mid-latitudes that are illustrative evidence for the fact that Ganymede has a permanent magnetic field. Hubble measured slight shifts in the auroral belts due to the influence of Jupiter's own immense magnetic field, but not as big as they should have been. This activity allows for a probe of the moon's interior. The presence of a saline ocean under the moon's icy crust would reduce the shifting of the ovals. On Ganymede, old dark terrain covers one third of the surface. The other two thirds have been resurfaced to form light terrain, which has been tectonically modified by structures known as "grooves". Scientists have thus suggested that Ganymede's surface shows signs of flooding. Young parts of Ganymede may have been formed by water rising up from the interior of the moon through faults or cryo-volcanos at some point in the moon's history.

Saturn's large satellite, Titan, possesses a dense and extended nitrogen-based and organic-laden atmosphere that varies on long time scales (a year on Titan is equivalent to 29.5 Earth years) in its thermal and chemical structure with seasons. Through photochemistry and photolysis, the main components (N_2 and CH_4) produce many trace gasses and condensates in the form of complex hydrocarbons and nitriles, while some hydrogen and very little oxygen, detected in the form of H_2O, CO, and CO, also exist in the atmosphere (Horst, 2017; Coustenis, 2021a and references therein). This intense organic chemistry produces thick layers of haze surrounding the satellite. The chemical products diffuse lower in the atmosphere as aerosols and are finally deposited on the surface. Titan's atmosphere and surface thus contain abundant amounts of carbon and nitrogen in different forms. The processes operating in the atmosphere are informative of conditions on early-Earth and give hints as to the origin and evolution of our outer Solar System. Titan hosts a methane cycle like the Earth's water cycle, with surface features mimicking familiar terrestrial landforms, as well as a subsurface liquid water ocean. Indeed, although not directly detected, the Cassini density and gravity field measurements of Titan clearly indicate a rocky, silicate component in its interior (Sotin et al., 2009; Iess et al., 2010). Strong atmosphere-surface interactions have been observed, but the extent to which the surface and interior communicate remains unknown. Observations of Titan's rotational state (Lorenz et al., 2008) and its tidally deformed gravitational field (Iess et al., 2012; Durante et al., 2019) support the existence of an subsurface liquid water ocean, albeit buried under a thick ice crust of about 100 km and therefore not as close to the surface as in the case of Enceladus or Europa (e.g. Nimmo and Bills, 2010), but similar to what we find on Ganymede. Titan's organic-rich environment and ongoing prebiotic chemistry thus show important astrobiological potential (Neish et al., 2018; Barnes et al., 2021; MacKenzie et al., 2021).

Enceladus, only ~500 km in diameter, was revealed by the Cassini mission to be a puzzling moon with dramatic jets of organic-laden water vapor and dust-sized icy particles emanating from subsurface liquid water reservoirs in the south polar region, where 200 kg/s of water vapor is ejected at speeds of 500–1000 m/s (Postberg et al., 2018; Hansen et al., 2020). This ejected material is the main source for Saturn's E-ring. Enceladus ejects plumes of sodium-salt-rich ice grains that are laced with grains of silica-rich sand, nitrogen (in ammonia), nutrients and organic molecules, including trace amounts of simple hydrocarbons such as methane (CH_4), propane (C_3H_8), acetylene (C_2H_2) and formaldehyde (CH_2O). This indicates that high temperature water-rock interactions (i.e., hydrothermal activity) may be at work as an energy source in Enceladus's subsurface ocean (Hsu et al., 2015). In addition, some models indicate the large rocky core is porous, allowing water to flow through it to pick up heat (Rovira-Navarro et al., 2022). So far, there has been no evidence of the presence of microbial life in the ocean of Enceladus, but the discovery of hydrogen gas (Waite et al., 2017) and the evidence for ongoing hydrothermal activity offer a tantalizing suggestion that habitable conditions could exist beneath the moon's icy crust (Glein and Waite, 2020). Gravitational field measurements suggest a regional south polar subsurface ocean of about 10 km thick located beneath an ice crust 30–40 km thick. Enceladus, like Europa, presents a compelling case for habitable conditions.

Unlike Europa, Ganymede, Titan and Enceladus, the presence of modern global subsurface ocean within the Dwarf Planet Ceres is doubtful, although aqueous alteration in a past epoch may have led to a subsurface endowed with the elements and perhaps also the energy needed for life (e.g., De Sanctis et al., 2020 and references therein). In addition, observations with the Herschel Space Telescope of water vapor vents indicate the possibility of residual activity at present (Küppers et al., 2014). Ceres constitutes therefore another body of potential astrobiological interest that needs to be protected from contamination in future exploration.

4. History of planetary protection related to Icy Worlds

Icy Worlds present exciting opportunities to explore environments that may host liquid water, organic chemistry, and potential energy sources. These environments could potentially harbor habitable conditions, offering a new perspective on the concept of habitability.

Prior to 1979, the outer planets and their moons were largely not considered as places of biological interest – except for Titan. A 1974 NRC report (Quarantine Considerations for Jupiter and Saturn Missions, NAS-NRC, Washington, D.C., 1971, revised 1974, cited in National Research Council, 1978 but currently unavailable) suggested that pending further information, Titan should be assigned a probability of contamination (the probability that a terrestrial organism could be deposited on the planet and grow) of 0.1. For comparison, at the time, this was 6-orders of magnitude higher than any environment on Mars. Then, a follow-on committee dropped the probability of contamination on Titan to 10^{-10}, finding *"…that a model not totally excluding the possibility of the growth of terrestrial microorganisms is barely conceivable"* (National Research Council, 1978).

NASA's Voyager Mission provided the first direct imagery suggesting that there may be liquid water beneath Europa's icy shell on its closest approach on July 9, 1979 (Fig. 2), which was later supported by Galileo Mission data in 1999. Thus began the view of distant Icy Worlds as potential places where life could take hold and be discovered, and the concern that we needed to protect that potential discovery. In response to this concern, a U.S. National Research Council task group was established to deal with the important question of how to protect Europa from inadvertent contamination from future space probes (National Research Council, 2000). The report of the task group recommended that spacecraft missions to Europa must reduce their bioload by an amount such that the probability of contaminating a putative European ocean with a single viable terrestrial organism at any time in the future should not exceed 10^{-4} per mission. The value 10^{-4} was chosen by the task group because it had a history in COSPAR planetary protection statements and resolutions. A follow-on report by the Committee on Planetary Protection Standards for Icy Bodies in the Outer Solar System (National Research Council, 2012) includes a long and interesting discussion about the origin of the 10^{-4} standard. They state *"Before its revision in 1982, COSPAR's planetary protection policies were based on a quantitative assessment of the likelihood of contaminating planetary bodies of interest. The 10^{-4} contamination criterion can be traced back to a COSPAR resolution promulgated in 1964 concerning "any spacecraft intended for planetary landing or atmospheric penetration" and still earlier. Unfortunately, the historical literature does not record the rationale for COSPAR's adoption of the 10^{-4} standard."* The 2012 study also concludes that 10^{-4} was appropriate to apply to Europa, even though it was first adopted for Mars and that the standard is appropriately conservative and implementable (National Research Council, 2012). The 10^{-4} probability standard remains unchallenged in the literature and remains in the policy today.

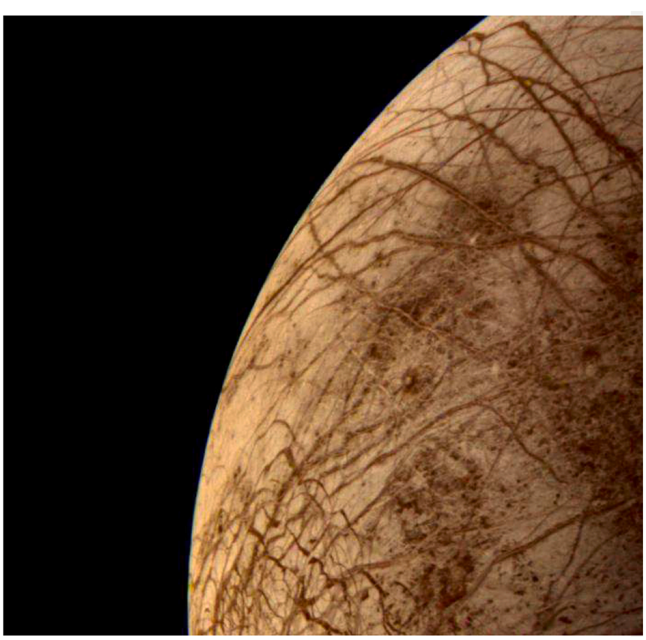

Fig. 2. Color image of Europa acquired by Voyager 2 during its closest approach on July 9, 1979. Image credit NASA/JPL https://www.jpl.nasa.gov/images/pia00459-europa-during-voyager-2-closest-approach.

Following the discovery by the Cassini Mission in 2008 that plumes of H_2O were emanating from Enceladus, COSPAR organized two colloquia (Rummel et al., 2009, 2010) to discuss, among other things, how this observation should be addressed in planetary protection considerations. This resulted in the COSPAR policy being updated to specifically add Enceladus (Europa already appeared in the policy at this time) missions to Categories III and IV (flyby and landers). A third colloquium was held in Bern, Switzerland in September 2015 (Kminek et al., 2015) to arrive at consensus around icy moon sample return requirements. This was required due to the growing interest in the scientific community to plan flyby missions that return materials from the Icy World plumes. The focus at this time was on Enceladus, but potential plumes had also been possibly detected on Europa as well (Roth et al., 2014). Among other things, the Bern colloquium recommended that a) plumes be considered for both Europa and Enceladus in the COSPAR policy, and b) that "Europa, Enceladus or their plumes" be added in the Category V sample return policy language.

A COSPAR Workshop was held in Vienna in 2009 to consider the planetary protection status of Outer Planet satellites and other small Solar System bodies, and the measures that may or may not need to be taken to protect them from Earth-sourced biological and organic contamination (Rummel et al., 2009). It was during this workshop that the concept of Category II+ was developed. Category II+ (now II* in the policy) denotes bodies where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried by a spacecraft could compromise future investigations. This includes Titan, Ganymede, Triton, and the Pluto-Charon system and Kuiper-belt objects > ½ the size of Pluto. As stated in the current policy: "The mission-specific assignment of these bodies to Category II must be supported by an analysis of the "remote" potential for contamination of the liquid-water environments that may exist beneath their surfaces (a probability of introducing a single viable terrestrial organism of $<1 \times 10^{-4}$), addressing both the existence of such environments and the prospects of accessing them." (COSPAR, 2021)

In mid-2019, NASA established the Planetary Protection Independent Review Board (PPIRB) with the purpose of evaluating and enhancing its Planetary Protection (PP) policies. The primary objectives were to identify opportunities for improvement and streamlining, as well as to determine the necessary adaptations to accommodate emerging planetary mission opportunities and the involvement of new players, including private sector entities. With regards to ocean worlds, the NASA Planetary Protection Independent Review Board (2019) found that: "The fraction of terrestrial microorganisms in spacecraft bioburdens that has potential to survive and amplify in ocean worlds is likely to be extremely small. Further, any putative indigenous life in subsurface oceans on Europa, Enceladus, or Titan is highly unlikely to have a common origin with terrestrial life." The report had one major recommendation: "The PP requirements for ocean worlds exploration should be reassessed in light of this finding."

The National Academies of Sciences, Engineering, and Medicine (2020) committee report responds to the points of the 2019 PPIRB report regarding ocean worlds. This includes a recommendation for future research on the ability of introduced Earth microorganisms to survive and propagate in an ocean world environment (with temperatures and pressures comparable to those found in Earth's deep ocean) and whether such life forms would be readily distinguishable from indigenous life. The panel disagreed that any potential ability to distinguish terrestrial contaminants from indigenous life negates concerns over potential contamination of ocean worlds with replicating terrestrial microorganisms.

The 2020 update of the COSPAR policy (COSPAR, 2020) was informed by a project funded by the European Commission and led by the European Science Foundation in collaboration with DLR/Germany, INAF/Italy, Eurospace, Space Technology/Ireland, Imperial College London (UK), China Academy of Space Technology, and NASEM-SSB (as an observer). This project, known as the Planetary Protection of the Outer Solar System (PPOSS) study, aimed to reassess the planetary protection requirements for missions targeting Europa and Enceladus (Rettberg et al., 2019). The study also considered the recommendations outlined in the National Research Council (2012) report on icy bodies. The study resulted in recommendations provided to COSPAR (Planetary Protection of Outer Solar System, 2019) in an effort to further enhance our understanding and approach to planetary protection (see Section 6).

4.1. Period of biological exploration (PBE) of Icy Worlds

The Period of Biological Exploration (PBE) refers to the time necessary for robotic missions to determine whether biological systems occur on a potentially habitable planetary body (National Research Council, 2012). This period has long been in the COSPAR policy but was referred to as the period of exploration and used in guidance that this period can be no less than 50 years after a Category III or IV mission arrives at its protected target (COSPAR, 2021). The 2000 NRC Task Group formed for Preventing Forward Contamination of Europa concluded that for Europa, the period of exploration should be essentially infinite – *"for every mission to Europa, the probability of contaminating a europan ocean with a viable terrestrial organism at any time in the future should be less than 10^{-4} per mission"* (National Research Council, 2000). A 2012 NRC Panel redefined this period further to be 1000 years (National Research Council, 2012). They argued that clearly since the first planetary space probes are now around 50 years old and space exploration is still in its infancy, that 50 years or even 100 years is too little time. They further argued that the speed at which technology evolves and the duration of human civilizations do not offer a solid rationale for implementing a period of planetary protection lasting 10,000 years or beyond. So, a PBE of 1000 years was proposed by the National Research Council (2012) panel. It should be noted that this PBE was suggested for icy bodies in general, not just Europa and Enceladus, which is how it appears in the current policy.

5. Planetary protection of past and current missions to Icy Worlds

The following section briefly describes the planetary protection plans and concerns for previous and current missions dedicated to Icy World exploration. Note that we are excluding survey missions, such as the Pioneer and Voyager, from this description. We also exclude all mission concepts not currently in formulation and/or implementation for further development such as future landers or sample return concepts.

5.1. Galileo

Galileo was launched in 1989 and entered orbit around Jupiter in December 1995 for its initial 2-year mission. The mission was extended for an additional year in 1997 to, among other things, enable more studies of Io and Europa (National Academies of Sciences, Engineering, and Medicine, 2000). The mission was classified as a Category II, requiring only documentation on probabilities of impact, contamination control procedures used during assembly, and disposition of all launched hardware at completion of the mission. Microbiological assays were not required. (National Academies of Sciences, Engineering, and Medicine, 2018). However, the Galileo mission's planetary protection plan incorporated a provision stipulating the need to furnish data regarding the biological significance of the Jovian satellites before the mission's culmination. This information was to be relayed to the mission planetary protection officer while the spacecraft was still maneuverable, enabling a judgment to be made regarding the intentional and secure disposal of the craft (National Academies of Sciences, Engineering, and Medicine, 2018). Indeed, NASA, supported by the Space Studies Board's (SSB's) Committee on Planetary and Lunar Exploration (COMPLEX), decided to terminate the Galileo mission with a direct impact into Jupiter (National Academies of Sciences, Engineering, and Medicine, 2000). On September 21, 2003, Galileo plowed into and disintegrated in Jupiter's atmosphere becoming the first mission to purposefully crash into a planet to protect another solar system body (Meltzer, 2012). This example was followed by others, including Cassini in 2017.

5.2. Cassini and Huygens probe

The Cassini spacecraft launched on October 15, 1997. The Cassini–Huygens (C–H) mission was a joint venture between NASA, ESA, and the Italian Space Agency (ASI). The mission aimed to study the planet Saturn, its rings, and its moons, with the Huygens probe specifically designed to explore Saturn's largest moon, Titan. In August 1995, the mission received a categorization of II (Cassini Planetary Protection Plan JPL D-7689 – Rev. A). Subsequently, it was realized that the planned magnitude of the Doppler shift in the radio link between the Huygens Probe and the Cassini spacecraft during probe entry into Titan would exceed the capabilities of the Cassini data system. After careful study, it was decided to change the original Saturn tour to one that would eliminate the trouble with Doppler shift. As part of that change, the new tour was documented in a second planetary protection plan (also Category II) in June 2004 - (Cassini Planetary Protection Plan JPL D-7689 – Rev. B) – 7 months before the Huygens' descent to Titan. The Huygens probe detached from the Cassini orbiter on December 25, 2004, and entered the atmosphere of Titan on January 14, 2005, becoming the first spacecraft to successfully land on a moon other than our own. The probe carried 6 instruments: Aerosol Collector and Pyrolyser, Descent Imager/Spectral Radiometer, Doppler Wind Experiment, Gas Chromatograph and Mass Spectrometer, Huygens Atmospheric Structure Instrument, and a Surface Science Package that measured temperature, pressure, and the electrical properties of the soil (Lebreton and Matson, 2002). The probe with all these instruments was assembled under class 100,000 clean room conditions (Cassini Planetary Protection Plan JPL D-7689 – Rev. B).

The change In the deployment of the Huygens probe also included new language requiring that the results of the C—H mission be reported to the NASA Planetary Protection Officer and be taken into account before an End-of-Mission scenario was agreed to by the project. This language (similar to language in the Galileo Planetary Protection Plan), led to the decision to dispose of the Cassini spacecraft into the atmosphere of Saturn to prevent it from inadvertently ever impacting Saturnian satellites potentially habitable – particularly Enceladus and Titan, which had become sites of even higher biological interest during the mission (Spilker, 2019)

5.3. New horizons

Launched on January 19, 2006, New Horizons was the first mission to provide a close-up investigation of Pluto and its system. On July 14, 2015, after traveling for nearly a decade, New Horizons made its closest approach to Pluto, coming within approximately 7800 miles (12,500 km) of the dwarf planet's surface. After this flyby reconnaissance of the Pluto-Charon system, the mission is continuing its exploration of KBOs and other bodies during an extended mission until 2025. The characterization of the organic materials from the surfaces of Pluto, Charon, and other KBOs was a main objective of this mission because of their potential to provide insights of prebiotic compounds (National Research Council, 2007; Cruikshank et al., 2019). These planetary targets were not expected to have any other significant planetary protection concerns for a flyby mission, so it was categorized as a type II mission (National Research Council, 2012).

The use of General Purpose Heat Source-Radioisotope Thermoelectric Generators (GPHS-RTG) in the New Horizons mission was discussed in terms of planetary protection in the NRC 2012 report, which resulted in recommending their substitution for a different type of heat generator in missions to other Icy Worlds, such as Enceladus or Europa because they could initiate local melting after an impact with an Icy World.

The geological and compositional information provided by New Horizons indicate that other types of future missions to Pluto-Charon or to large KBOs will require specific studies before being assigned as Category II.

5.4. Dawn

The Dawn spacecraft was launched in September 2007 to study protoplanets Vesta and Ceres. It entered orbit around Ceres in 2015 and completed its mission there in 2018. Dawn remains in a stable orbit around Ceres today (https://www.jpl.nasa.gov/missions/dawn). Even though current COSPAR planetary protection policy assigns missions to Ceres to Category II, Dawn was assigned a Category III because of the risk posed by a flyby of Mars en route to Vesta (Rayman et al., 2006). Dawn provides some lessons for categorizing future missions to Ceres which are discussed in Castillo-Rogez et al. (2020)

5.5. Jupiter Icy Moons explorer (JUICE)

JUICE was launched in April 2023 and is expected to reach Jupiter in July 2031. The objectives of the mission will be the exploration of Jupiter, its magnetosphere and the Icy Worlds Europa, Ganymede, and Callisto (Coustenis et al., 2021). The planetary protection approach is to limit the probability of impact on Europa to a level below 1×10^{-4} and by default covering the risk of contamination of a sub-surface ocean to levels below that (i.e., there is no need to perform a contamination transfer analysis). The risk of collision with Europa is limited to the period up to the Europa flybys. For the period after Jupiter Orbit insertion and prior to the Europa flybys, a dedicated study was performed analyzing the likelihood of impact, in case of spacecraft failures up to the Europa flybys. Accordingly, JUICE has been designed to reliably maintain control of itself, so the likelihood of accidentally colliding with Europa and potentially contaminating it with cells from Earth is below the requirement for planetary protection. After the Europa flybys, the orbit of the spacecraft in all its mission phases will be such that collisions are sufficiently unlikely within the timeframe of concern (several 100 years) (Boutonnet and Martens, 2020).

Following the Jupiter tour, JUICE will orbit Ganymede in its final phases. Within the current Planetary protection categorization, missions addressing Ganymede science receive provisional mission categorizations of "Cat II*". Thus, the possible exchange processes between the surface and any putative habitats were investigated by Grasset et al. (2013) who discussed the "remote'' versus "significant'' chance of contamination of Ganymede. Conservative estimates of the time duration for each possible mechanism of downward migration through the icy layer were quantified to place constraints on the planetary protection measures for Ganymede. Based on the different estimates they performed, the authors found it extremely unlikely that introduced material could be migrate downward through the upper icy layer of Ganymede and, thus, bring material into the ocean over timescales consistent with the survival of Terran microorganisms. Accordingly, JUICE was then assigned as Category II.

5.6. Europa Clipper

The Europa Clipper mission is currently scheduled to launch in October 2024 (https://europa.nasa.gov/mission/faq/) and will conduct dozens of flybys of Europa, enabling detailed observations (from 25–2700 km altitude) of its surface, subsurface, and exosphere environment. The spacecraft will study different regions of the moon to characterize its activity, habitability, and its potential for supporting life. The NASA Planetary Protection Officer designated the flyby mission as Category III in 2018, adopting the standard requirement to warrant the exploration that includes reducing the probability of inadvertent contamination of an ocean or other liquid water body to less than 1×10^{-4} per mission in accordance with COSPAR policy (McCoy et al., 2021; Hendrickson et al., 2021; Smith and Hendrickson, 2022).

At the end of 2018, JPL-NASA in consultation with the science community elaborated on the planetary protection Probabilistic Risk Assessment (PRA) for Europa Clipper to demonstrate the planetary protection requirements compliance and for being used in mission design decisions. The study considered the combined analysis of three models, which were fed by the best available data of the moment: i.e., impact, resurfacing, and biological (McCoy et al., 2021; DiNicola et al., 2022; Smith and Hendrickson, 2022). While modeling was conservative in some assumptions of the three aspects, it benefited from specific investigations of Europa such as those to constrain the surface age for the resurfacing model that was revealed as the most sensitive in reducing the magnitude of contamination probability. Updating various planetary protection parameters also produced refinements in the models.

The synergic approach applied in the PRA manifested that the probability of the Europa Clipper mission to contaminate the icy moon is fulfilled by one order of magnitude better than the stated requirement (McCoy et al., 2021), thus it was accepted by the Project. On the other hand, the study showed that the factor of bioburden at launch does not contribute decisively to the probabilistic contamination for this flyby mission. This finding would lead to the prelaunch bioburden reduction being less stringent with respect to cleaning protocols for sensitive hardware, not only for Europa Clipper but for other future space missions. Earlier investigations of planetary protection for the JUNO mission to avoid contamination on Europa proposed 7 Mrad as the radiation dose for the total spacecraft sterility. This value was declared also independent of initial bioburden but overestimated because of survival of problematic species (Bernard et al., 2013).

5.7. Dragonfly

Within the current Planetary protection categorization, Titan missions receive provisional mission categorizations of “Cat II*”. This was assigned in 2017–2019 to the Dragonfly mission proposal during its initial Step-1 proposal and Phase A by the NASA Planetary Protection Officer. In presenting the details of the Dragonfly rotorcraft lander mission and considering the nature of Titan’s organically laden and habitable but harsh environment, the Dragonfly Proposal concludes that the inoculation of the moon’s potentially habitable subsurface liquid water ocean with viable terrestrial biota represents a remote, very low probability event ($<< 1 \times 10^{-4}$), justifying a Category II determination for the planned mission, consistent with previous missions to Titan.

6. New planetary protection considerations for Icy Worlds

In 2020 the COSPAR PPP updated the policy with a revision of the planetary protection requirements for missions to Europa and Enceladus, following the PPOSS study funded by the European Commission and led by the European Science Foundation with several other institutions and agencies involved. The PPOSS study had as a main goal to provide an international platform to review the specificities of Planetary Protection regulations as concerns outer Solar System bodies and to provide related recommendations to COSPAR (Planetary Protection of Outer Solar System, 2019). The PPOSS recommendations were presented to the ESA Planetary Protection Working Group (PPWG) and to COSPAR in 2019. They include:

- *Policy should include a generic definition of the environmental conditions potentially allowing Earth organisms to replicate*
- *Implementation guidelines should be more specific on relevant organisms*
- *Implementation guidelines should be updated to reflect the period of biological exploration of Europa and Enceladus*
- *Implementation guidelines should acknowledge the potential existence of Enhanced Downward Transport Zones at the surface of Europa and Enceladus.*

The ESA PPWG provided a written assessment of the PPOSS recommendation to COSPAR. Following this multi-year-long process, COSPAR’s policy and requirements for missions to Europa and Enceladus were updated in COSPAR (2020). Updates included adding the definition of environmental conditions. The definition reads as follows:

> “*Given current understanding, the physical environmental parameters in terms of water activity and temperature thresholds that must be satisfied at the same time to allow the replication of terrestrial microorganisms are:*
>
> – *Lower limit for water activity: 0.5*
> – *Lower limit for temperature: -28 °C*”

These values come from a robust review of literature and community consensus discussions over the last two decades, mostly in efforts to establish parameters for special regions on Mars (regions where terrestrial organisms are likely to propagate, or a region interpreted to have a high potential for the existence of extant martian life). Beaty et al. (2006) reported on the outcome of a MEPAG effort that found that experiments and field observations had failed to show microbial reproduction at temperatures below -15 °C. They further found that the lower limit of life with regards to water activity (A_w) was 0.62. For this reason, this committee proposed adding buffer to these values and establishing the temperature and A_w limits for identifying Mars Special Regions to be -20 °C and 0.5. A COSPAR colloquium (Kminek et al., 2010) agreed with the A_w limit, but added more buffer to the temperature limit making it -25 °C. Since then, there have been recurring studies and workshops critically evaluating these numbers based on the peer-reviewed literature. The most recent was that of Rummel et al. (2014) which left the lower limits untouched, and this conclusion was affirmed by a later study jointly sponsored by the National Academy of Sciences Space Studies Board and European Science Foundation (National Academies of Sciences, Engineering, and Medicine, 2015). Finally, a COSPAR colloquium in Bern in 2015 (Kminek et al., 2015–47) decided that the temperature limit should be extended to -28 °C to maintain a 10 °C buffer between the limit and the data the lowest temperature is based on. Throughout the development of these limits, it has been understood that many environmental parameters can limit life (e.g., pressure, radiation, acidity, etc.), but among these factors, temperature and A_w emerged as the two crucial parameters that must be simultaneously satisfied for the replication of life on Earth. Notably, the relative ease of remotely measuring and modeling both these parameters made them particularly desirable for planetary protection.

These generic limits of terrestrial life have not yet been applied to Icy Worlds planetary protection. We suggest in this paper to do this, by establishing the indices LLT (Lower Limit Temperature, currently -28 °C) and LLAw (Lower Limit water activity, currently 0.5) that can be applied across the solar system for use in planetary protection. Further, we suggest simply using LLT on Icy Worlds. The reason is the following. In a liquid reservoir trapped in an icy mantle, or in a liquid ocean, we are dealing with a solution mostly composed of supercooled water which is in equilibrium with ice. Sippola & Taskinen (2018) demonstrated that the activity of supercooled water in equilibrium with ice at standard pressure is independent of the electrolytes in the solution and is always above 0.6 to well below the LLT (Fig. 3). On the other hand, the effect of the pressure is still unknown. To our knowledge there has been no research done on the effects of extreme pressure (and related ice type changes) on the tolerance limit of extremophiles to water activity. For these reasons we choose to be conservative and assume that A_w is always above LLAw on Icy Worlds. This allows us to simplify and just focus on temperature as the environmental parameter that indicates risk of harmful contamination. In other words, on Icy Worlds we only need to be concerned with forward contamination being able to replicate in ice or liquid that is above LLT. This approach moves away from the presence of liquid water as a trigger for concern on Icy Worlds and focuses on the more diagnostic low temperature limit for propagation of terrestrial life. Extreme brines (e.g. CaCl-rich solutions) found on Earth can cool to below -50 °C without freezing (Toner et al., 2017), and so liquid water does not always equate to habitability for Earth life. Other examples of brines that can remain liquid below the LLT include, LiCl and $MgCl_2$ (Lamas et al., 2022). Furthermore, as we are approaching sub-ice oceans (if present) from above, this approach raises concern when we get near the warmer temperatures (>LLT) in the lower ice. Ice crystal boundaries of ice have been shown to be habitable environments on Earth. For example, excesses of CH_4, N_2O, CO_2 in terrestrial ice cores have been identified as indicators of metabolism in ancient basal ice (Rhodes et al., 2013; Mitchell et al., 2013; Li et al., 2010; Souchez et al., 1998; Montross et al., 2014).

Focusing on just the LLT, mission teams would model and report the depth to which spacecraft, or their components would have to penetrate to pose a risk of harmful contamination of Icy World environments >LLT. The mission teams would need to demonstrate that the probability of introducing a single viable terrestrial organism to a region >LLT within the 1000-year Period of Biological Exploration (PBE) is less than 10^{-4}. For mission teams that can meet this requirement, their mission would receive PP categorization II. For orbiters that cannot meet this requirement, PP categorization III would be assigned. Landers that cannot meet this requirement would be assigned categorization IV. Both orbiting and landed missions should consider the possibility of impact. Transient thermal anomalies caused by impact would be acceptable so long as there is less than 10^{-4} probability of reaching deeper native regions >LLT in the PBE. A decision tree depicting this categorization strategy is provided in Fig. 4.

Fig. 5 shows examples from a simple model calculation that predicts

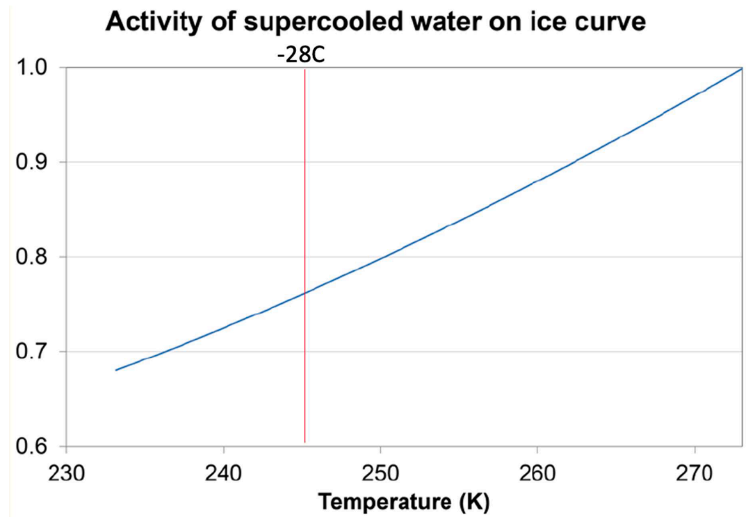

Fig. 3. Modeled temperature vs water activity in pure ice (blue line). Red vertical line shows the water activity at the current established lower temperature limit for Earth life in COSPAR policy. Modified from Sippola & Taskinen (2018).

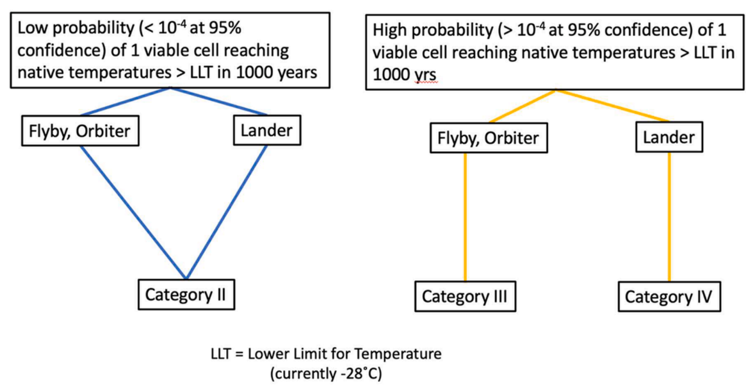

Fig. 4. Decision tree for categorization of orbiters and landers with regards to the lower limit for replication of Earth life.

the depth required to reach -28 °C on Europa and Enceladus under various assumptions for ice shell thickness and near-surface interior heat transport (fully conductive shell vs. stagnant lid scenario,[2] see for instance Schubert et al., 2001). Note that this model is just an example of what could be used. The model assumes that conductive regions of ice shells (1) are in thermal equilibrium, (2) do not generate heat through tidal dissipation, and (3) possess constant thermodynamic material properties (e.g., thermal diffusivity). The result is thermal profiles that vary linearly with depth from warm ice-ocean interface or brittle-ductile transition temperatures of 270 K (conductive shell) and 260 K (stagnant lid), respectively, to colder surface temperatures. Such assumptions are supported by contemporary modeling efforts, which suggest brittle non-convecting regions of planetary ice shells should exhibit conductive thermal gradients (akin to Earth's lithospheric geotherm) (McKinnon, 1999), should behave elastically under tidal stresses (thus generating significantly less tidal heat than convective regions) (Han and Showman, 2010), and should possess temperature profiles that are minimally affected by temperature/chemistry dependent material properties (e.g., specific heat, thermal conductivity) (Buffo et al., 2020; 2021). These results provide a first order estimate for planetary protection relevant depths in outer conductive planetary ice layers. It should be noted that there will likely exist 'special regions' associated with active ice shell geological processes (e.g., young chaos, plume vents) that will not possess such simple thermal structure and will require additional characterization through the lens of planetary protection.

Note that a unified Icy World mission categorization, based on the LLT, might make Category II* largely redundant in the COSPAR planetary protection policy, since the protection that II* provides is largely covered by this new approach. This is because under this new Icy Worlds categorization, all Icy Worlds, not just those listed under II*, would undergo the scrutiny required by II* in the current policy (COSPAR, 2021). This means that all the named Icy Worlds listed as Category II* (Ganymede, Titan, Triton, and Pluto/ Charon) would no longer require this designation as they will be covered by the new Icy Worlds categorization. That would leave the only object designated with a * in Category II being "Kuiper-belt objects > ½ the size of Pluto". It is possible that these objects are also captured by our Icy World definition, but not certain. To address this, possible options could be: (1) Leave the KBOs > ½ the size of Pluto as the only II* bodies remaining in the Policy, (2) Add KBOs > ½ the size of Pluto to our definition of an Icy World, or (3) Assume the larger KBOs will be sufficiently captured by our Icy World definition and leave KBOs in Category II only as "KBO's that cannot be classified as Icy Worlds". The first option leaves II* in the policy; the

[2] "Solid-state convection operates within the solid portion of the ice shell, but on most bodies convection is confined beneath a so-called stagnant lid that is several kilometers thick. The stagnant lid is composed of cold material that is so viscous that it cannot participate in convection. If there is no overlap between top-down and bottom-up vertical transport processes, a "no-man's land" exists in the middle of the ice shell that interrupts exchange of material between the surface and a subsurface ocean" (National Research Council, 2012).

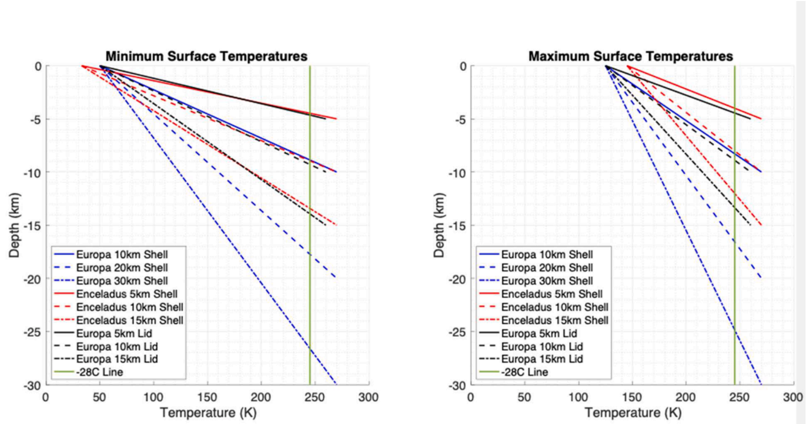

Fig. 5. Model results of ice shell thermal profiles and their intersection with the -28 °C limit of life (green line) for a) minimum and b) maximum surface ice temperatures. Variations in ice shell/brittle lid thickness are represented by line types (solid, dashed, dot-dashed) for both Europa (blue/black) and Enceladus (red).

second and third removes II* entirely. How we deal with Category II* needs further discussion and community input.

Another area that needs more discussion and consensus is sample return from Icy Worlds. A conservative approach demands that any sample return from an Icy World should be categorized as restricted Earth return. The limits of extant life survivability that may exist on an Icy World is unknowable prior to the discovery of such life. It is also unknown how long Icy World biota can remain dormant but viable preserved in ice. Furthermore, all Icy Worlds would almost certainly be classified as restricted Earth return using the 6 questions in Section 11.2 Sample Return Missions from Small Solar System Bodies of the current policy. A prudent way forward would be to generalize the 6 questions to be applicable to Icy Worlds as well as small bodies, but we will need to have this discussion with the community in the near future.

7. Discussion and future directions

Considering the findings of the current exploration of the inner Solar System and in particular of Mars (Olsson-Francis et al., 2023), Icy Worlds likely represent the most promising targets in our Solar System for uncovering extant life, representing a quest of unparalleled significance in human history. The potential revelation of life existing beyond Earth would profoundly redefine our perspective, reshaping our understanding of our place in the cosmos. Hence, ensuring the preservation of this extraordinary opportunity stands as an utmost priority. Responsible exploration of Icy Worlds demands a meticulous approach, where stringent policies and practices must be established to avert any inadvertent contamination of these pristine environments with terrestrial microbes. Preserving the authenticity of any potential discoveries is essential, as it enables us to discern between native life and unintended introductions from Earth. Nonetheless, as always, striking a balance between protection and facilitating discovery is vital. Implementing these protective measures should not impede our scientific endeavors or render mission achievements impossible. Instead, a mindful approach is necessary, one that permits exploration while upholding the integrity of the unparalleled scientific question - are we alone?

Towards this goal, in this manuscript we have articulated a few key elements concerning Icy Worlds that we suggest should be considered for inclusion in the COSPAR planetary protection policy:

1. Provide a definition for Icy Worlds for Planetary Protection that captures the outer Solar System moons and dwarf planets like Pluto, but excludes more primitive bodies such as comets, centaurs, and asteroids.
2. Establish new indices for the Lower Limit for Water Activity (LLAw - currently 0.5) and Lower Limit for Temperature (LLT - currently -28 °C) to be used in all areas of planetary protection policy.
3. Establish an Icy World (not just Europa and Enceladus) categorization that is based on the modeled depth to the LLT and the likelihood of a connection from the surface to that depth. For an orbiting mission, if the probability of accessing the depth to the LLT inadvertently is less than 10^{-4} in 1000 years, that mission would be classified as Category II. Other examples of how this categorization would work are shown in Fig. 4. This would essentially treat regions where there is a possibility within 1000 years of a single microbe accessing temperatures higher than the LLT as "special regions" and would require making that language more general to include Icy Worlds in Category IVc. Note that we also propose to use a PBE of 1000 years for all Icy Worlds as was intended by the National Research Council (2012).
4. All missions should consider the possibility of impact. Transient thermal anomalies caused by impact would be acceptable so long as there is less than 10^{-4} probability of a single microbe reaching deeper permanent regions >LLT in the PBE.
5. Restructure or remove Category II* from the Policy as it becomes largely redundant with this general Icy Worlds approach.
6. Due to the unknowable limits of extant Icy World life before its discovery, all sample return missions from Icy Worlds should be assigned "Category V restricted Earth return".

These are recommendations/findings only and not specific policy changes at this time. In the next steps, these findings will be discussed and promoted at relevant planetary meetings and at the COSPAR Panel on Planetary Protection next open meetings. Specific policy changes can be developed after that for validation by the COSPAR Bureau. The Panel will continue to work on developing sensible and scientifically rigorous guidelines for the exploration of the Solar System objects in consultation with the scientific community and engineers, encouraging exchanges with different national and international space agencies, the private sector and industry and other stakeholders. When new information becomes available either from missions and/or from the peer-reviewed literature, the COSPAR Panel will carefully review the new input and find consensus in the planetary community using workshops, meetings, studies, etc. in order to keep the policy in line with the most recent scientific findings.

Declaration of AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT to improve readability and conciseness of some minor sections of the manuscript. No research was done with AI. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

List of known or suspected Icy Worlds and their current categorization (established categorizations listed in NASA Procedural Requirements (NPR) 8715.24 Appendix C)[a]

Body	Category	Current classification
2002 MS_4	Dwarf Planet[b], Cubewano[c] (TNO)[d]	II
Ariel	Moon of Uranus	II
Callisto	Moon of Jupiter	II
Charon	Moon of Pluto	II*
Dione	Moon of Saturn	II
Enceladus	Moon of Saturn	III/IV
Eris	Dwarf Planet, Scattered Disk Object (TNO)	II
Europa	Moon of Jupiter	III/IV
Ganymede	Moon of Jupiter	II*
Gonggong	Dwarf Planet, Scattered Disk Object (TNO)	II
Haumea	Dwarf Planet, Haumeid (TNO)	II
Iapetus	Moon of Saturn	II
Makemake	Dwarf Planet, Cubewano (TNO)	II
Mimas	Moon of Saturn	II
Miranda	Moon of Uranus	II
Oberon	Moon of Uranus	II
Orcus	Dwarf Planet, Plutino (TNO)	II
Pluto	Dwarf Planet, Plutino (TNO)	II*
Quaoar	Dwarf Planet, Cubewano (TNO)	II
Rhea	Moon of Saturn	II
Salacia	Dwarf Planet, Cubewano (TNO)	II
Sedna	Dwarf Planet, Sednoid (TNO)	II
Tethys	Moon of Saturn	II
Titan	Moon of Saturn	II*
Titania	Moon of Uranus	II
Triton	Moon of Neptune	II*

[a] https://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_8715_0024_&page_name=AppendixC

[b] Dwarf Planets are based on the list of 10 bodies designated as being Dwarf Planet with "near certainty" at https://web.gps.caltech.edu/~mbrown/dps.html as of January 24, 2024.

[c] Classical Kuiper Belt Object

[d] Trans-Neptunian Object

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