Report

COSPAR Workshop on Planetary Protection for Outer Planet Satellites and Small Solar System Bodies

European Space Policy Institute (ESPI)

Vienna, Austria

15-17 April 2009

Prepared by the COSPAR Panel on Planetary Protection

John D. Rummel
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Pascale Ehrenfreund
Nicolas Peter
Editors

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held under the auspices of the

Committee On Space Research (COSPAR)

of the

International Council for Science (ICSU)

at

European Space Policy Institute (ESPI)
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Cite this document as:

Rummel, J., Ehrenfreund, P., and Peter, N., *eds.* 2009.
COSPAR Workshop on Planetary Protection for
Outer Planet Satellites and Small Solar System Bodies.
COSPAR, Paris, 41 pp.

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1. Introduction

The prospects for continued exploration and discovery in the Outer Planets of the Solar System have never been better. Among others, the Rosetta, Dawn, and New Horizons missions are enroute, the Cassini mission continues its comprehensive exploration of the saturnian system, and the Juno mission is preparing for a 2011 launch to Jupiter. Elsewhere, NASA and ESA are focusing on a flagship-class mission opportunity to Europa and the rest of the Jovian system, followed by a mission back to Titan, and a New Frontiers announcement of opportunity has been released by NASA to solicit missions across a wide spectrum, including missions to the South Pole of the Earth's Moon, Venus, the surface of a comet (and back again), Mars, Mercury, the Trojan or Centaur asteroids in Jupiter's orbit, other asteroids (and back again), Io, or Ganymede. New missions are also under way at ESA.

Many of the science questions inherent to this set of future missions relate to the prospects for life in the Solar System—either due to the potential to find life within the Outer-Planet systems, themselves, or by improving our understanding of the potential contribution to the origin of life on Earth by Solar System material that originated (and may still be found) elsewhere. As a consequence, some of the future mission opportunities and their potential encounters with other Solar System bodies raise serious questions about biological or organic contamination that may be carried to the Outer Planet satellites or other small solar system bodies by these missions.

As a result of a resolution recommended in Montreal (Canada) during the COSPAR Planetary Protection Workshop of January 2008 (Rummel *In preparation*) and accepted by the Bureau and Council at the Committee on Space Research (COSPAR) Assembly later in July 2008 (also in Montreal), the COSPAR Panel on Planetary Protection, working with Scientific Commissions B (planetary sciences) and F (space life sciences), determined to hold a COSPAR Workshop to consider the planetary protection status of Outer Planet satellites and other small Solar System bodies, and the measures that should be taken (or not) to protect them from Earth-sourced biological and organic contamination. The starting point for the 2009 COSPAR Planetary Protection Workshop was to considered the probabilistic approach in place in the COSPAR Planetary Protection Policy (COSPAR 2008) for the protection of Europa, and discussed the application of the approach and the associated formulation and parameterization to other Outer Planet satellites and small bodies. This application, as well as other considerations brought forward by the group, resulted in a full consideration of the various Outer Planet satellites and other Small Solar system bodies, and the recommendations found in this report for the categorization of missions that may encounter or closely study them in the future.

Subsequently, the Workshop also reviewed the consequences of applying these recommendations to the Outer Planets Flagship missions that have been under consideration by ESA, NASA, and their cooperating partners, allowing the Workshop to ensure that a full understanding of their implications was available to the group.

The COSPAR Workshop on Planetary Protection for Outer Planet Satellites and Small Solar System Bodies was hosted gracefully by the European Space Policy Institute (ESPI) in Vienna (Austria), and began on the afternoon of April 15th, 2009, ending the afternoon of April 17th. The summary of the discussions and the decisions reached are given below.

2. Agenda Overview: Plan of Workshop

The agenda for the Workshop (see Appendix A) was broken into four parts. First, the Workshop participants were given the opportunity to review the pertinent data available both in the literature and from each other about the Outer Planet satellites and other small bodies of the Solar System, and how previous planetary protection considerations (regarding both forward and backward contamination) had been handled by COSPAR and various other groups. Then, the participants were broken into small groups to reconsider these bodies and their planetary protection status with respect to the COSPAR Planetary Protection Policy (COSPAR 2008) and recommendations from the U.S. Space Studies Board, and others, with a focus on protection against forward contamination. After the meeting of the small groups, a third part of the Workshop focused on a synthesis of recommendations from the small groups, and the drafting of recommendations on mission categorization and other improvements to the COSPAR policy. Finally, the Workshop considered the effects of these recommendations on ongoing missions under study by NASA and ESA, and also at the scientific research required to reduce uncertainties in the Workshop recommendations for those and other missions. The result of this examination was a proposed set of recommendations for inclusion in the COSPAR Planetary Protection Policy, after consideration by the Panel on Planetary Protection and the COSPAR Bureau and Council at Bremen (Germany) in 2010. Additionally, the recommendations for further research were passed to the ESA and NASA Planetary Protection Officers, present at the Workshop, for their consideration and possible implementation—in some cases, prior to the next Scientific Assembly.

3. Overview of Presentations

1) John Rummel: ***Overview and Agenda / Small Bodies Report***

This introductory presentation reviewed the overall concept and philosophy of the Workshop and presented the agenda for the next several days. In particular, the basic concepts of the COSPAR Planetary Protection Policy (COSPAR 2008) were reviewed, including its basic rationale, the range of requirements applied to missions to affect the policy, the categorization scheme applied to missions to different target bodies, and a review of some of the missions previously considered and categorized.

Specific attention was then drawn to the U.S. National Research Council (NRC) report (Space Studies Board 1998) that forms the basis of the COSPAR policy with respect to sample return missions from small bodies of the solar system (which include all planetary satellites, asteroids, comets, and Kuiper-Belt Objects). The framework provided in the report, and its potential for use during this Workshop were noted.

***2) Cassie Conley:* Current Requirements: Europa SSB/COSPAR & Juno Application**

The confirmation by the Galileo mission that Europa was a potential site for liquid water oceans raised significant questions about how to implement planetary protection for missions targeting Europa. In the late 1990s, the U.S. NRC's Space Studies Board (SSB) was asked to generate a report on "*Preventing the Forward Contamination of Europa,"* (Space Studies Board, 2000) addressing concerns regarding the potential for contamination of an Europan ocean in the context of current knowledge about terrestrial microbial life. The SSB recommended to NASA that (in contrast to Mars) a probabilistic approach regarding the contamination of Europa should be retained. The SSB recommended that a number of factors be considered in such a probabilistic approach, including:

- The initial number of organisms carried on a spacecraft
- Any bioburden reduction treatment
- The fraction that survives the cruise phase
- The fraction that survives the space radiation environment
- The probability of landing at an "active site" on Europa
- The fraction of surviving organisms that would be buried and transported to an ocean
- The probability that an organism might proliferate once submerged.

Regarding the last factor, the SSB recommended that the conservative approach would be to set the probability of proliferation at one, until data suggest otherwise.

Overall, the SSB recommended that a mission demonstrate a probability of less than $1x10^{-4}$ that an Earth organism could contaminate an Europan ocean over the entire spacecraft lifetime, including after the active mission ends. Four classes of microbes were identified that must be considered separately due to differing survival rates, including microbes that form spores vs. those that do not, and microbes that are resistant to radiation (due to additional physiological adaptations) vs. those that are not. This recommendation was incorporated into NASA's formal planetary protection requirements, as documented in NASA Procedural Requirements (NPR) document 8020.12C. In 2007, the Planetary Protection Subcommittee of the NASA Advisory Council considered the question of planetary protection requirements for icy satellites, and recommended that this Europa requirement be expanded to require a $1x10^{-4}$ probability of contaminating, by a single viable Earth organism, liquid water on or within any icy object in the outer solar system.

The first project to implement a Jupiter-system mission under the SSB probabilistic formulation is the Juno mission, which emphasizes studies of the Jovian magnetosphere. During the development of the Juno mission's planetary protection implementation approach, it became clear that spacecraft reliability and preferred trajectory, factors not overtly included in the SSB analysis, would have significant impact on spacecraft and mission design. These factors are of critical importance to assess early in mission development. To calculate the probability that a spacecraft might contaminate Europa either during or after a mission, it is necessary to take into account spacecraft reliability, and have a clear understanding of failure modes, both hardware/software-related and those caused by natural events, that could cause loss of control of the spacecraft. For each trajectory change maneuver and orbital encounter, the probability of failure and loss of control must be evaluated and the resulting orbit propagated forward, in order to determine the contribution of that failure mode to the total probability of contaminating Europa (or any other body of concern).

These calculations must be performed starting from the point at which an object of concern first comes into jeopardy—for the Jovian system, this should be evaluated starting at Jupiter orbit insertion—and extend until all organisms carried by a spacecraft should be dead, with a conservative margin. Analysis of the combination of spacecraft reliability and mission trajectory should be used to evaluate the extent to which the radiation environment in flight is likely to reduce viability of contaminating organisms. Other factors may also be considered, such as the recognition that DNA repair of radiation damage is not possible in extremely desiccated conditions, or lethality due to the energy of impact with a target body, that might contribute to reductions in viability. These results may be used to revise spacecraft designs and trajectories, and must be used to determine the degree to which pre-launch bioburden control will be necessary. It is almost unavoidable that active bioburden reduction will be required for shielded spacecraft components, because the accepted lethal dose for microbes is 7 Mrads, a dose that is likely to damage radiation-sensitive spacecraft components.

For the nominal active Juno mission the spacecraft will not encounter Europa, but after the nominal End-of-Mission, such encounters become increasingly likely. Accordingly, the primary implementation proposed by the project is to deorbit the spacecraft into Jupiter at End-of-Mission, thereby avoiding Europa encounters. Because the probabilistic implementation is required, it is necessary to consider spacecraft reliability and the effect of a potential inability to perform the deorbit maneuver. Failure of the deorbit maneuver is currently allotted a 5% probability of occurrence, which is sufficiently high to be of concern. To constrain the duration that organisms on the spacecraft could remain viable and potentially contaminate Europa after impact, the project evaluated the probability of survival in the Jovian radiation environment after Jupiter orbit insertion, and concluded that all organisms would be dead after 300 years.

This constrained the timing of the orbital trajectory simulations, both deterministic and Monte Carlo, that were used to establish the probability of impacting Europa, which was shown to be slightly less than 1% over 300 years.

This combination of factors gave a probability of greater than $1x10^{-4}$ that the Juno spacecraft might impact Europa with viable organisms onboard. To further refine the probabilistic analysis, the project also considered the probability that onboard organisms could survive impact on Europa, taking into account that 99% of modeled impacts occurred with in the spacecraft travelling at greater than 20 km/sec. Four percent of the possible scenarios were particularly difficult to model due to a high obliquity of impact, but for the rest modeling demonstrated that contaminating organisms would be killed by the energy of impact. Even assuming that contamination would result in this difficult 4% of impacts, the combination of factors analyzed demonstrated a probability of slightly more than 10^{-5} that viable organisms might remain on the surface of Europa should the Juno spacecraft impact. This implementation strategy was reviewed by the Planetary Protection Subcommittee of the NASA Advisory Council, and accepted as a satisfactory demonstration of compliance with NASA's planetary protection requirements.

<u>3) Gerhard Kminek & John Rummel:</u> COSPAR Mars Special Regions Colloquium Report

Preventing terrestrial biological contamination from becoming established and widespread on Mars is essential to protect high-priority science goals on Mars. The search for life, the understanding of the martian organic environment, and even the future use of martian resources, may be compromised if microbes carried by spacecraft grow and thrive on Mars. Because Mars is cold, but not always, and extremely dry, but perhaps not everywhere, the concept of a “Mars Special Region“ was developed in 2002 as a way to refer to those places where the conditions might be conducive to microbial growth. Based on data returned from the Mars Global Surveyor (MGS) and Mars Odyssey missions, showing evidence for more recent water flow and/or ice flow on the martian surface and the possibility of massive amounts of subsurface ice near the polar regions, it is thought likely that such places might exist—if not on the surface, then potentially underground.

The intention of this COSPAR Mars Special Regions Colloquium was to use the original COSPAR definition for Mars Special Regions, the NRC Study on “*Preventing the Forward Contamination of Mars”* and the MEPAG Science Analysis Group on “*Mars Special Regions”* and arrive to a consolidated definition for Mars Special Regions and report this for consideration to the COSPAR Planetary Protection Panel.

The agreement was that a Mars Special Region is defined as a region within which terrestrial organisms may be able to replicate, or a region which is interpreted to have a high potential for the existence of extant martian life. Based on current understanding, the temperature and the water activity are to be used as parameters to describe surface or subsurface of Special Regions on Mars on a timescale of 500 years. This timescale is chosen to constrain the geological events that will affect the environmental conditions on Mars.

Physical features were identified that indicate a significant probability of meeting the conditions for Special Regions and should be classified as Special Regions, features for which this is uncertain and should be classified as Special Regions based on the conservative nature of planetary protection, and features that clearly do not meet the conditions for Special Regions and should therefore be classified as non Special Regions. Spacecraft-induced Special Regions are to be evaluated, consistent with these limits and features, on a case-by-case basis. It was strongly recommended to continue to review the limits for reproduction of terrestrial organisms in association with potential habitable environments on Mars. The parameter definition and the list of physical features on Mars classified as Special Region should be reviewed on a 2-year cycle.

In summary, the concept of Special Regions was established because new data suggested the need for more stringent constraints. The concept of Special Regions only makes sense if:

- Observable parameters that are key to the propagation of terrestrial life ("propagation" was seen as the relevant definition for Mars!) can be selected, and
- Values with margins can be associated to the observable parameters, and
- Environments can be identified on the target body that can be classified as either special, non-special or uncertain, and
- A timescale is selected to constrain the changes in the environmental conditions.

It is imperative that the parameter definition, the associated values and margins, and the classified environments are reviewed on a regular basis.

***4) Ben Clark:* Radiation Environments & Effects on Biological Systems**

Ionizing radiation in space is extremely disruptive of cellular organization and function. For example, it breaks critical chemical bonds, generates damaging free radicals, forms cross-links, and generally creates disorder in the molecular machinery, including the storehouses of genetic information. These disruptions are generic. All biochemically-based organisms are susceptible to them.

However, smaller "simpler" organisms are often more resistant to a given level of radiation exposure. Thus, to sterilize a community of bacteria requires radiation doses measured in the hundreds of kilorads or a few megarad, whereas complex multicellular organisms can succumb at doses below one kilorad. Because it is microorganisms which are the most difficult to detect and remove from space hardware, the use of natural space radiation to sterilize a spacecraft can be problematic. In particular, although the radiation doses from rare solar particle events (SPE) are a major threat to astronauts, they are insufficient to kill a microorganism which is onboard a mission whose duration is less than one decade, especially if it is buried beneath some structure in the spacecraft, where it is also protected from the otherwise sterilizing extreme short-wavelength Ultraviolet (UV) constantly emitted by the Sun.

Small airless bodies, such as asteroids, comets, and the majority of moons in the outer Solar System are continuously exposed to highly penetrating galactic cosmic rays (GCR). Also, the cumulative doses from SPE's over millennia begin to be significant. The depth-dose profile in these bodies monotonically decreases with depth, but are still significant at depths of several meters. This is primarily due to GCR, with SPE's creating higher cumulative doses near the surface. For example, doses exceed 18 megarads to a depth of 1.5 meters in less than one million years, which is sufficient to sterilize even the most radiation-resistant organism known on Earth (and which must be actively metabolizing to repair the damage as it accumulates). For these reasons, sample return missions from these classes of small bodies are of less concern from a back contamination standpoint.

Large icy bodies with subsurface oceans or plumes may have habitable locations which are sufficiently shielded to protect against this natural sterilization by radiation, as are also planetary objects which have dense atmospheres. Some giant planets have intense trapped radiation fields around them, which also cause sterilization of the surfaces of their satellites and even the spacecraft we send to them.

5) Torrence Johnson: ***Intro to Outer Planet (and Other) Satellites***

The current observed state of Outer Planet satellites is determined primarily by their composition, particularly the fraction of rock and metals compared with water ice, their size, and their thermal, dynamical, and impact history.

Most outer Solar System bodies formed in the cold outer regions of the Solar System, well beyond the “snow line”, where temperature and pressure conditions allowed the condensation and survival of water ice as a major solid component for accretion into planetesimals and supplying the feeding zones of the giant planets[1]. As a result, their compositions are dominated by material formed from the most abundant condensable elements in the universe. The “solar” or “cosmic” abundance of the elements in the material from which the solar system formed results from multiple generations of nucleosynthesis within stars and the mixing of this material in the galactic interstellar medium through supernovae and other stellar mass-loss processes. Of the ten most abundant elements, eight (excluding the noble gases Helium (He) and Neon (Ne)) form the bulk of the solid material from which outer planet satellites and planetesimals were made: Hydrogen (H) and Oxygen (O) in the form of water ice; O, Magnesium (Mg), Silicon (Si), and Iron (Fe) in the form of silicate rocks; H, Carbon (C,) and Nitrogen (N) as hydrocarbons, organics and solid carbon; S as iron sulfide.

The mixture of materials available to make up a given outer planet solid body depends critically on the solar abundance of O and C, and on the form of C present (solid or gas as Carbon monoxide (CO) in oxidizing conditions, Methane (CH_4) in reducing conditions).

[1] With the possible exception of Io and Europa, the innermost of the Galilean satellites, which may have formed under warmer subnebula conditions close to Jupiter which limited ice formation

The best current estimates of solar abundances are given in Grevesse et al., 2007. Given these abundances, the range of potential compositions of solid condensates is illustrated in Figure 1, which shows the material density of the condensate as a function of gaseous carbon redox state, from CO dominated (top curve) to CH_4 (bottom curve) dominated conditions, and for assumed fraction of carbon tied up in solids (from 0 to 1.0, x-axis). "Solar composition" condensates may have properties lying within the area bounded by the two curves, giving a potential range of uncompressed density of about 1400 kg/m^3 to about 2200 kg/m^3. Representative proportions of rock (including metals), water ice and solid carbon at points along these boundaries are shown as pie diagrams, showing the condensates might have rock fractions ranging from about 0.37 to ~0.74 with solid carbon ranging from 0 to about 0.2.

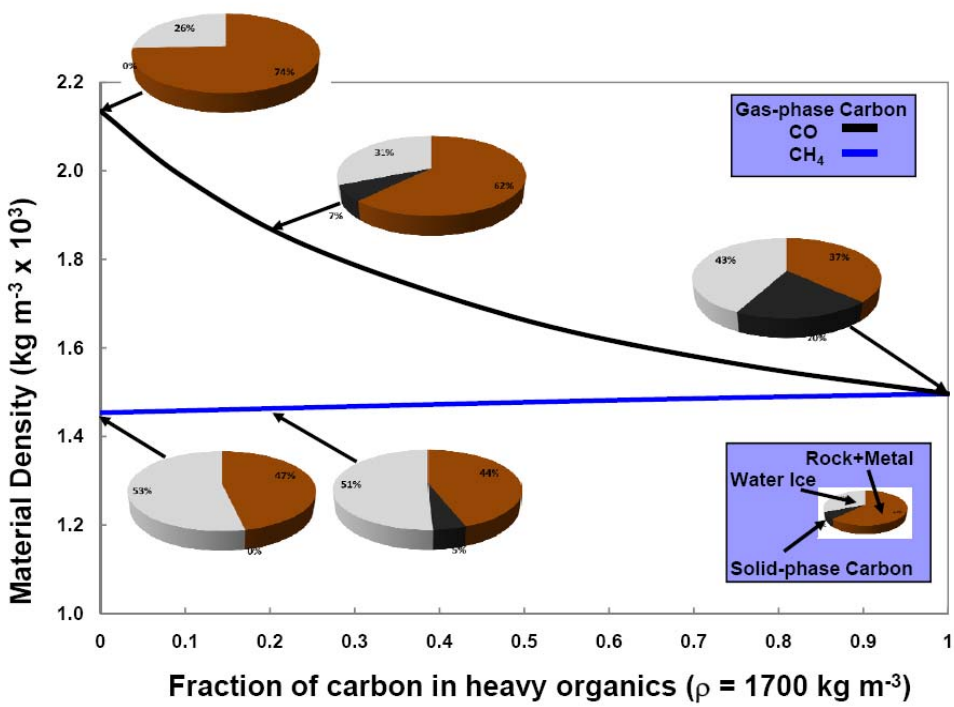


Figure 1: Solar equilibrium condensate density as a function of carbon chemistry

Measured densities (corrected for compression if required) of the icy satellites of the outer Solar System generally fall in the "solar composition" range shown in Figure 1, the major exception being small bodies with radii less than about 100 kilometers, which typically have densities significantly less than 1000 kg/m^3, indicating either a more ice-rich composition and/or extremely highly bulk porosities. Figure 2 shows densities as a function of radius for outer solar system objects[2].

[2] Europa, with a primarily rocky composition in spite of its intriguing icy/liquid shell, is not plotted in Figure 2.

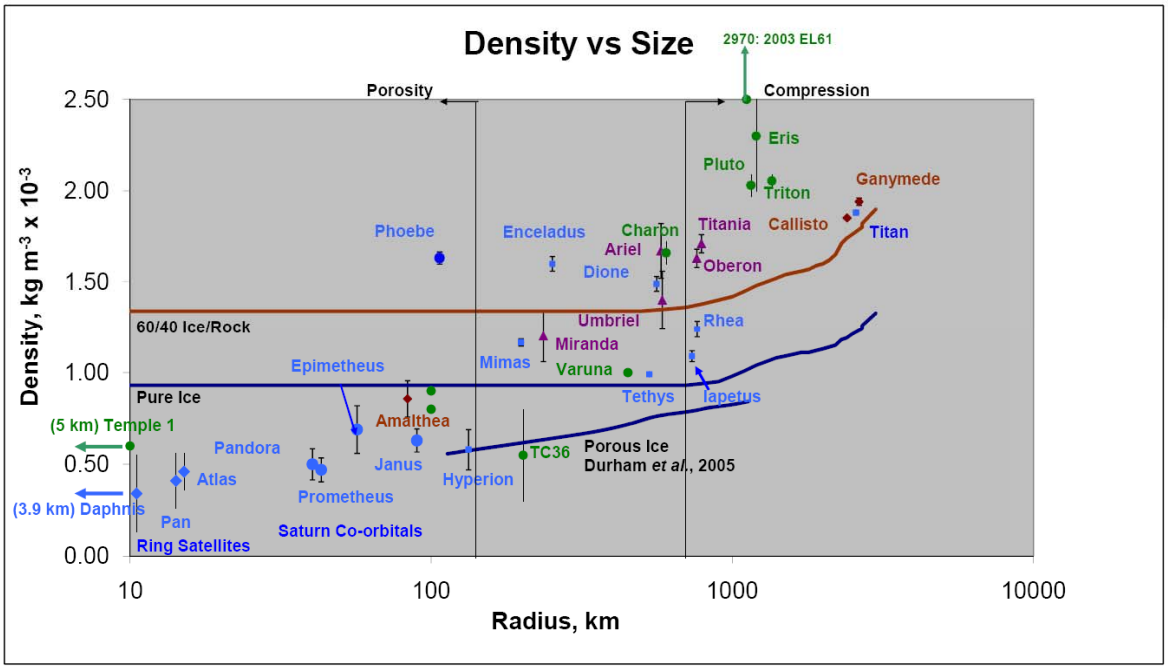


Figure 2: Densities of Outer Solar System Icy Objects

5.1 Characteristics of Icy Satellites Relevant to Planetary Protection

All of the satellites considered in detail during the workshop (Europa, Titan, Enceladus, Ganymede, and Callisto) share some key characteristics which make them objects of interest for planetary protection, but our level of knowledge and understanding of processes important to assessing planetary protection issues varies considerably. In approximate order of the ”robustness” of our current understanding these characteristics are discussed briefly below:

- Surface temperatures: From direct observations and first-order energy considerations, all the icy satellites have extremely cold, “cryogenic”, surfaces, with temperatures below about 150 K at all times, with no prospects for liquid water at the surface.
- Presence of liquid water: Both large (e.g. Ganymede) and small (e.g. Enceladus) satellites show evidence for liquid water at some depth in their interiors either at the current epoch or at some point in their history. Theoretical models for thermal evolution show that even very small planetesimals may have been heated sufficiently early in Solar System history (~ 2-3 Million years after the formation of solid material) to have melted water ice in their interiors if short-lived radioactive nuclides such as ^{26}Al were present. For larger objects, melting could have occurred from heating by long-lived radioactive nuclides (Uranium (U), Thorium (Th), and Potassium (K)) over much of their history. Finally, many Outer Planet satellites may be heated by tidal effects from resonant orbit conditions, either currently or at some point in their dynamical history.

- Exchange of material between surface and liquid regions: This is a major point of discussion in terms of the potential for any spacecraft biological contamination of zones of interest for life-related studies. Most satellites show evidence of geological activity, including tectonic features such as global fracture patterns, surface disruptions resembling ice ”rafts”, varying relative surface ages from cratering records, active plume venting, and features interpreted as “cryovolcanic” flows. In principle, these geological processes could bring material from deeper, liquid rich regions to the surface and vice versa. There is a consensus in the planetary community that the more geologically “active” and “young” a satellite appears, the more likely is communication between the surface and putative deeper liquid zones. Unfortunately, the details of these mechanisms, and, critically, the time scales over which they operate are highly uncertain, very model dependent, and hotly debated.

***6) Bob Pappalardo:* Outer Planet Satellites and Oceans Within**

The outer planet satellites are a rich and diverse set of planetary bodies, with great relevance to astrobiological studies (see Figure 3). Several of the largest satellites are believed to hide global-scale oceans within as shown in Figure 4. Titan is organic-rich with precipitation and surface lakes of ethane and methane. Many of the satellites including the smallest are rich in organic materials. Several of the icy moons show evidence for geological activity and internal heating today.

Consideration of the “ingredients” necessary for development of life (water, chemical energy and biogenic elements) point to several of the icy satellites of the outer solar system as key targets in the search for life in our solar system. A combination of radiogenic and tidal heating could allow oceans to persist over long time scales, especially if low melting-point “antifreeze” (such as salts or ammonia) is present. It is now understood that oceans can be maintained above a convecting ice shell, with a complex interplay among ice rheology, ice shell thickness, tidal heating, and heat transport mechanisms.

Data on the small satellites of the outer planets is limited, but indicates that they represent a mix of ancient circumjovian planetesimals and captured objects. In the Jovian system, their compositions may be a combination of ice and D-type asteroidal materials. These objects provide an indication of the compositions of the building blocks of the icy moons.

Observations by the Galileo spacecraft suggest oceans within all three large icy satellites of Jupiter. The probable oceans of Callisto and Ganymede are sandwiched between ~150 km thick Ice labove, and denser polymorphs of ice below. Callisto shows a generally dark surface of ancient cratered terrain, punctuated by a few very large impact structures and associated tectonic rings from impact so large that may have punched through the icy shell. The degree of internal differentiation of Callisto’s interior is uncertain. Ganymede's ancient dark terrain contains tectonic furrows probably related to ancient large impacts, and has been tectonized to various degrees.

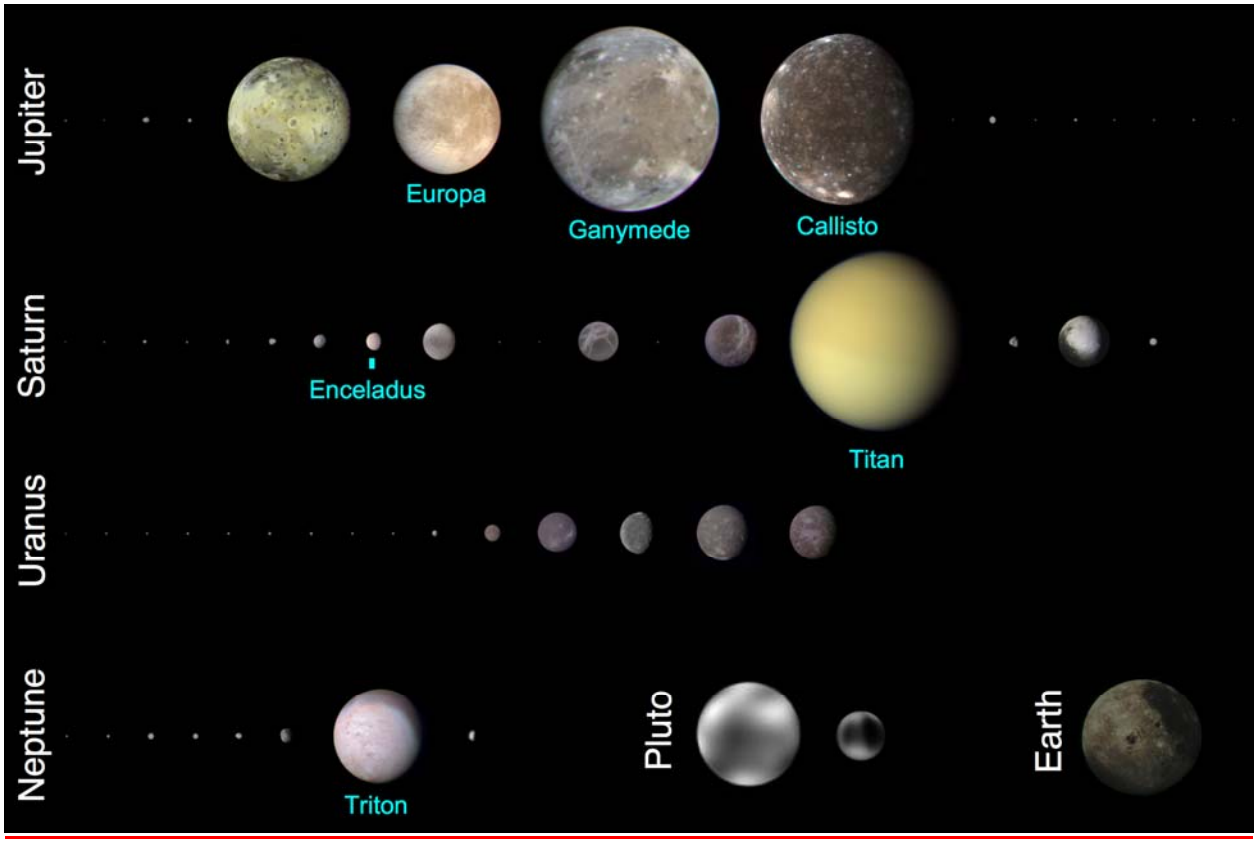


Figure 3: Family portrait of the outer planet satellites, arranged by planetary system, and shown to scale. Those major satellites which may have oceans within are shown in blue. Pluto-Charon and Earth's Moon are shown for comparison.

Ganymede's bright grooved terrain is pervasively tectonized at multiple scales and is locally highly strained, consistent with normal faulting of an ice-rich lithosphere above a ductile asthenosphere, with minor horizontal shear. The relative roles of tectonism and cryovolcanism in creating bright grooved terrain remain an outstanding issue. The absolute age of bright terrain activity is uncertain: craters suggest it may be ~200 Myr to ~2 Gyr old. Ganymede is the only moon with an internal magnetic field, indicative of an active dynamo and present-day convective cooling of a hot metallic core.

Magnetometry and unique geology point to an ocean within Europa, a few to tens of kilometers below the icy surface (see Figure 5). Europa's relatively thin and tidally heated ice shell may convect at least in part, and compositional measurements suggest the presence of salts. Sparse cratering suggests that Europa's average surface age is only ~40 – 90 Myr, pointing toward active resurfacing processes. Geological evidence affirms recent surface-ocean exchange at Europa, though the processes which might drive exchange (including cracking, melting, and/or convection) are active areas of research. Moreover, Europa's ocean is probably in direct contact with an underlying rocky mantle, facilitating direct deposition of any hydrothermal chemical energy.

The severe surface radiation environment and low surface temperatures (average ~110 K) preclude metabolism at Europa's surface, though Europa's deep (warm) ice shell and ocean may have the ingredients for life, if chemical energy is derived from above (radiation-produced surface oxidants) and/or below (from activity in the rocky mantle). Cyclical activity of Europa on a ~100 Myr time scale is plausible, based on geological observations and modeling of the evolution of the Laplace resonance, and would be driven chiefly by cyclical heat deposition within Io. In contrast to its icy brethren, Io is a relatively dry and rocky moon, dominated by volcanism due to the tidal heating processes that are so important to the geology and internal heating of icy satellites.

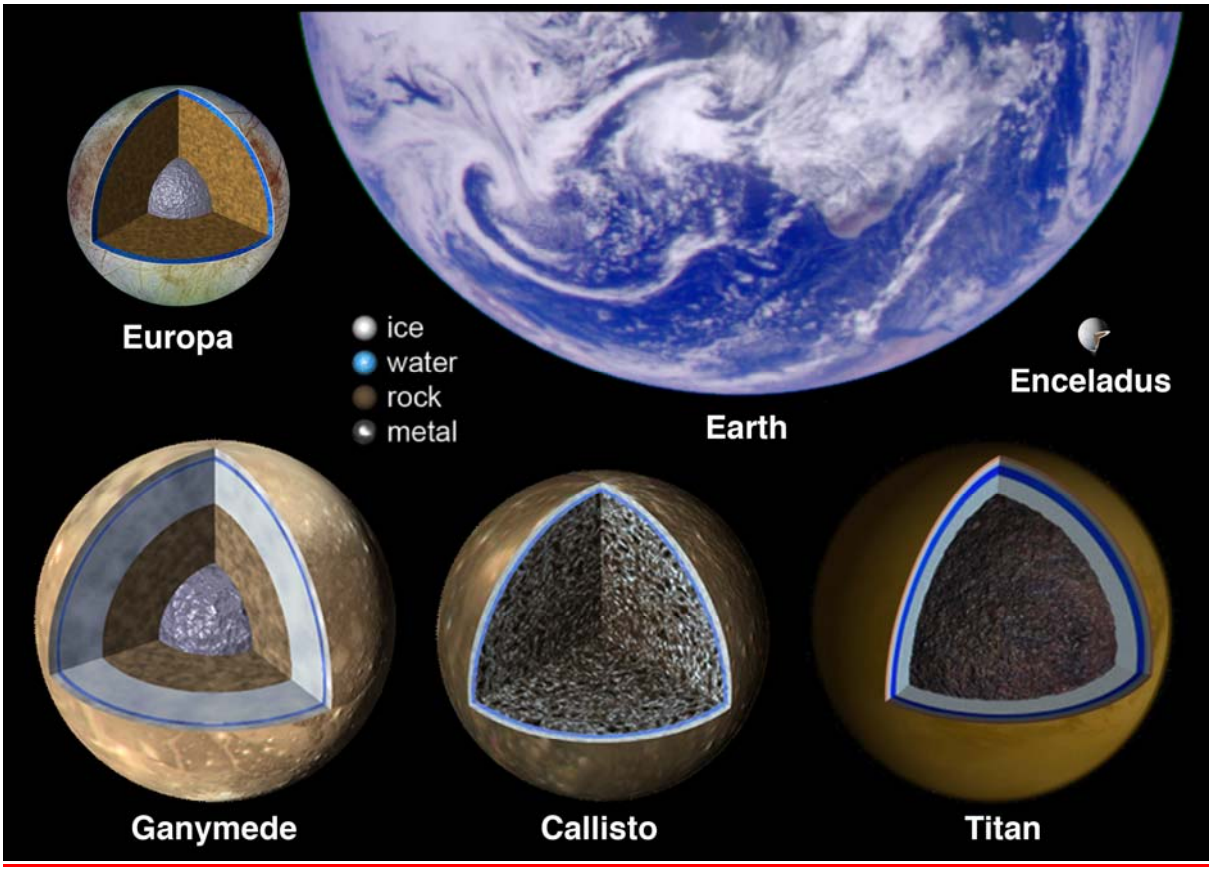


Figure 4: Schematic representations of the solar system's 6 known and most probable ocean worlds, shown to scale.

Data from the Cassini spacecraft, currently exploring the Saturn system, shows that Saturn's moon Titan is an organic wonderland where hydrocarbon rain precipitates through the thick N_2-CH_4 atmosphere. Radar imaging indicates the presence of diverse surface features, including dunes that may be made of organic sands, and shallow lakes of liquid hydrocarbons.

It has been suggested that Titan may have cryovolcanic features and perhaps active cryovolcanism. Titan may contain an interior water-ammonia ocean deep within, sandwiched between ice Iabove and higher density ice polymorphs below. Areas of active research include the age of Titan's surface as implied by its craters, the degree of internal activity including convection, the degree of differentiation of the satellite, and any means of material transport between the surface and interior.

Saturn's tiny moon Enceladus (radius 252 km) shows jets of water vapor and ice grains that rise from prominent fractures in its measurably warm and tectonically deformed south polar region. Simple organics including benzene have been observed in the plume, and detected salts imply expulsion of liquid water that has been in communication with rock. Jet activity at Enceladus might result from tidally driven shear heating along sliding fractures causing sublimation and near-surface redeposition of water vapor, or fractures might be directly connected to subsurface reservoirs.

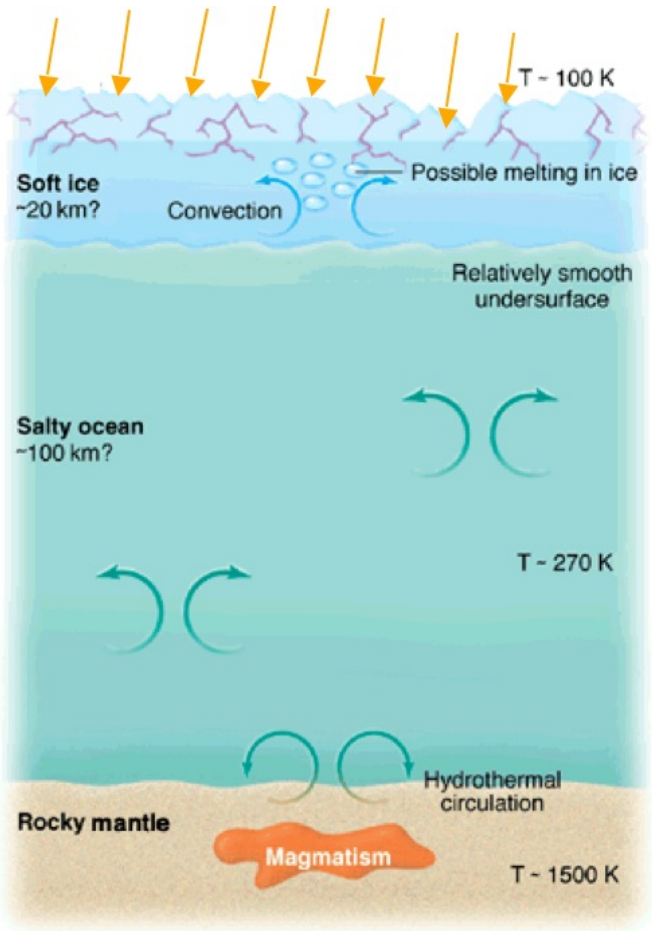


Figure 5: Schematic cross section through Europa's icy shell (from Stevenson, 2000). Radiation at the surface (arrows) produces surface oxidants (including O_2, H_2O_2, and perhaps CH_2O). If hydrothermal activity occurs at the rock-water boundary, then reductants will enter the ocean (potentially including H_2S, H_2, CH_4, and Fe).

The internal structure of Enceladus probably consists of an ice shell approaching 100 km thick overlying a silicate core. The tectonic deformation and current activity observed at the surface suggests decoupling of the ice shell from the silicate interior by a subsurface ocean or localized south polar sea. Processes of material exchange and the time scale of Enceladus's activity are active areas of research.

Neptune's large icy moon Triton is probably a captured Kuiper Belt Object. Its surface age is only ~100 Myr, implying that Triton may be still active today. Past tidal activity and current radiogenic heating may combine to an interior ocean today. Triton shows strong evidence for past icy volcanism and present plume activity. If low melting temperature ammonia exists within Triton and the larger mid-sized icy satellites and Kuiper Belt Objects (including Pluto), then these bodies may have internal oceans maintained by radiogenic heating alone. The interior oceans of icy bodies may be the most common potentially habitable environments for life that exist in our solar system and throughout the universe.

7) Dennis Matson: Satellites of Saturn: Results from Cassini

The Cassini-Huygens mission is returning new geophysical data for the midsize, icy satellites of Saturn. These data have enabled a new generation of geophysical model studies for Phoebe, Iapetus, Rhea, Mimas, Tethys, Dione, and Enceladus. We consider the new model studies that have reported significant results elucidating the evolutionary histories and internal structures of these satellites. Those results have included their age, the development of their internal structures and mineralogies, which for greatest fidelity must be done concomitantly with coupled dynamical evolutions Heat is required to power the satellites' evolution, but is not overly abundant for the midsized satellites. All sources of heat must be evaluated and taken into account. Phoebe has an oblate shape that may be in equilibrium with its spin period of about 9.3 hours. Its orbital properties suggest that it is not one of the regular satellites, but is a captured body. Its density is higher than that of the other satellites, consistent with formation in the solar nebula rather than from material around Saturn. Oblate shape and high density are unusual for objects in this size range, and may indicate that Phoebe was heated by ^{26}Al decay soon after its formation, which is consistent with models of the origin of Kuiper-Belt objects. Iapetus has the shape of a hydrostatic body with a rotation period of 16 hours. It subsequently despun to its current synchronous rotation state, about a 79 day period. These observations are sufficient to constrain the required heating in Iapetus' early history, suggesting that it formed in 3.4 to 5.4 Million years after CAI (Calcium Aluminium Inclusions) condensation. Since Saturn had to be present for Iapetus to form, this date also constrain the age of Saturn and how long it took to form.

The combined observations of Saturn's moon Enceladus by the Cassini CAPS, INMS and UVIS instruments detected water vapor geysers in which were present molecular nitrogen (N_2), carbon dioxide (CO_2), CH_4, propane (C_3H_8), acetylene (C_2H_2), and several other species, together with all of the decomposition products of water.

The presence of N_2 in the plume indicates thermal decomposition of ammonia, and hence high temperatures in the interior (e.g., 500 to 800 K). Such an environment also appears to be suitable for the production of CH_4 from CO, or CO_2. The presence of C_2H_2 and C_3H_8 strongly suggests that catalytic reactions took place within a very hot environment. The internal environment of Enceladus is inferred to be or has been favorable for aqueous, catalytic chemistry. This permits the synthesis of many complex organic compounds that could be detected in future *Cassini* observations.

***8) Toby Owen:* Titan as a Special Case**

It is essential to distinguish between evolution of an established species and the origin of life. On Titan both forms of biological activity are prohibited by the extremely low surface temperature of 94 K and recent findings that a water ocean, if it exists, must be at a depth of 10 to 40 kilometers or more. If Titan once was warm enough that it had a surface ocean, that ocean would have been global. According to our current models for the origin of life, some dry land is essential for life to begin. It is needed to provide templates for polymers and to allow peptide bonds that require the release of water. Even if life began, it would be annihilated by the low temperatures that now exist.

Could some type of life on Earth survive in this environment? The rule of thumb is that life on Earth requires liquid water at some period of its existence in order to reproduce. A useful experiment would be to take the toughest low temperature extremophile bacteria we know, immerse colonies of this organism in liquid nitrogen and keep them there for times of 1, 3, and if still viable 10 and 30 years. Did any reproduce? Are any capable of reproduction after being exposed to liquid water? Now think about 4.6 billion years!

How about oceans under the crust? They are 10 to 40 kilometers under the crust. Do we care what is going on down there in the dark?

1. Our “black smokers” are a poor model as early ideas that archaeobacteria had Deoxyribonucleic acid (DNA) that indicated an early, warm environment for their ancestors’ origins have been disproved. Furthermore, the lifetimes of these hot chimneys are typically less than 100 years, hopelessly short for either origin or evolution.

2. But cryovolcanism could bring some of this slush up to the surface. Maybe! Our model on Earth is magma, which does not stay liquid very long.

3. So what about the components of life; the organic molecules that are products of the chemical evolution that must precede biopoesis.

Here the situation is far more favorable. Organic chemistry is going on even today on Titan. Organic aerosols are raining from the sky. Endogenous products could not be mixed up with exogenous compounds brought by spacecraft because both nitrogen and hydrogen on Titan are isotopically “tagged”.

Deuterium (D)/H on Titan has the value 1.32 x 10^{-4}, whereas on Earth, the ratio D/H has the value of 1.56 X 10^{-4}, and the ratio $^{15}N/^{14}N$ on Titan is 6.7 x 10^{-3} whereas on Earth the ratio $^{15}N/^{14}N$ is equal to 3.7 x 10^{-3}. Consequently, there is no danger of contaminating Titan down to the lowest values you are considering!!

<u>9) Helmut Lammer:</u> What Makes a Planet Habitable?

A classification of four habitat types has been recently proposed by Lammer et al. (2009). Class I habitats represent bodies on which stellar and geophysical conditions allow Earth-analog planets to evolve so that complex multi-cellular life forms may originate. Class II habitats include bodies on which life may evolve but due to stellar and geophysical conditions that are different from the class I habitats, the planets rather evolve toward Venus- or Mars-type worlds where complex life-forms may not develop. Class III habitats are planetary bodies where subsurface water oceans exist such as on Europa, which interact directly with a silicate-rich core, while class IV habitats have liquid water layers between two ice layers, or liquids above ice.

Class I habitable planets where complex multi-cellular surface life forms may evolve need to orbit around the right star. G-type stars and K and F-types starts with masses close to G stars should fall in this category. In such a case, the activity of the host star decreases fast enough so that an evolving atmosphere and life may not be in danger of losing the atmosphere or the planet's water inventory. Furthermore, the large distance of the corresponding "Habitable Zone" (HZ) of such star systems lessens the efficiency of the non-thermal loss processes. The possibility that various atmosphere compositions and the water inventory can remain stable on such planets over geological time spans exists as long as the environment can keep plate tectonics with all its related consequences active over billions of years.

Class II habitat environments where life may originate but a planet evolves differently from Earth could be expected within HZs of low mass M and K-type stars which are located very close to these stars, so that their atmosphere-magnetosphere environments experience extreme stellar radiation and plasma exposures over very long time periods or even during most of their life-time. In such cases, thermal and non-thermal atmospheric escape processes could modify the atmospheres and water inventories of the planets in such a way that they may end up after some hundreds of million years as geophysically inactive, dry Venus-like or cold Martian-like planets, although they originated and orbit within the classically defined HZ. It seems possible that life has started early in the history of class II habitable planets and if favorable conditions prevailed long enough to allow evolution it may have persisted even after the loss of (almost) all water. The production of complex and diverse ecosystems, however, depends on the carrying capacity of the planet and on how fast life may develop.

Class III habitats have subsurface oceans that are in contact with silicates on the sea-floor and open the question of where the building blocks for life could come from. Organic material necessary to start life may be supplied by impact of meteorites and comets and their fragments.

However, material impacting on the surface has to remain intact and has to find its way into the subsurface oceans. Also this material has to reach meaningful concentrations in some (small) compartment of the ocean, which is hard to imagine in a connected body of water as large as a planet-wide subsurface ocean. However, one should keep in mind that synthesis of organic material by either Fischer–Tropsch reactions or catalytic cycles are possible under the high pressure/high temperature conditions occurring at deep-sea vents. In such environments on Earth, reduced radicals such as H_2 are contained in the hot fluid and can provide energy for a variety of organisms. However, the source of energy necessary to power an organism could be another problem.

Class IV habitats and exoplanets where a water ocean is in contact with a thick ice layer represent a much better case for the influx of organic material from outside compared to bodies like the Jovian satellites Ganymede or Callisto. The main problem encountered in class IV habitats is, however, much more severe: that of sufficient concentration of the necessary ingredients for life. A planet whose surface is completely covered in water several kilometers deep with nothing to act as a concentrating "sponge" for organic chemistry is probably too vast for any two or more interesting molecules to meet. While a sea/ice system could in theory provide an environment to concentrate life's ingredients, most likely the starting concentrations needed for a system like that are crucial in addition to quite specific temperature conditions.

***10) Karla Clark and Jens Romstedt:* Europa Flagship/ L-class Mission**

In 2008, the Europa Jupiter System Mission (EJSM) concept was developed in order to carry out a systematic and in-depth study of the Jupiter system aiming at a common overarching theme: "*The emergence of habitable worlds around gas giants".*

The baseline architecture for EJSM consists of two primary elements operating in the Jovian system at or near the same time: the NASA-led Jupiter Europa Orbiter (JEO), and the ESA-led Jupiter Ganymede Orbiter (JGO). The expansive Jovian system is scientifically rich and is best studied using multiple elements. To explore the system in detail, two flight systems are envisioned performing an intricately choreographed dance to explore the system from multiple perspectives. Though both would examine the whole system, one would focus on the inner two Galilean satellites and one would focus on the outer two Galilean satellites. Both flight elements would perform multi-year studies of the Jovian system, including the giant planet's magnetosphere, rings and atmosphere, and the rocky Galilean moons. JGO would focus on Ganymede and Callisto while JEO would focus on Io and Europa. This architecture allows JGO to stay outside of the most intense radiation belts and thus, be designed for a lower radiation environment. Each baseline spacecraft carries 11 instruments. Similar instrumentation allows for each flight system to study the whole system from different perspectives and provide data for synergistic science.

Launched independently in early 2020, the systems would use chemical propulsion, with Venus and Earth gravity assists, to arrive at Jupiter approximately six years later.

After insertion into Jovian orbit, both flight systems will perform tours of the Jovian system using gravity assists of the major moons to shape the trajectory for optimum science measurements. JGO uses Ganymede to shape the initial highly elliptical Jupiter orbit, thereby avoiding the main radiation belts of Jupiter. After a nearly 10 months tour through the Jovian system, performing measurements in the magnetosphere and observing Jupiter and a series of Ganymede swing-bys, the spacecraft JGO transfers to a Callisto resonance orbit. It then performs remote sensing observations during the 19 swing-by opportunities with closest approach at 200 kilometers. After more than a year in this resonance orbit with Callisto, JGO transfers to Ganymede into an elliptical polar orbit, performing, among other observations, measurements in the magnetosphere of Ganymede. Thereafter, JGO enters into a 200 kilometers near polar circular orbit for close-by observations of Ganymede. The mission will end when the flight system impacts Ganymede's surface.

JEO enters the Jovian system by using Io for gravity assist. This lowers the required propellant load but increases the radiation exposure of the flight system. JEO has a 30 month Jovian system tour which includes four Io flybys, nine Callisto flybys, six Ganymede flybys, and six Europa flybys. JEO enters orbit at Europa and spends the first month in a 200 kilometers circular orbit and then descends to a 100 km circular orbit for another eight months. The mission will end when the flight system impacts Europa's surface.

The joint ESA/NASA Jupiter Saturn Planetary Protection Working Group (JSPPWG) has met, and JEO plans for meeting currently envisioned requirements have been reviewed by and have been agreed to by this working group but not reviewed or endorsed by the respective agency planetary protection officers. The final fate of both the JEO and JGO spacecraft will be surface impact at Europa and Ganymede, respectively. The overarching requirement is to not contaminate the underlying ocean. The JEO approach to meeting the Planetary Protection requirements has been conceptualized and documented in the Jupiter Europa Orbiter Final Report, JPL dated November 3, 2008.

Planetary protection requirements for Europa are a significant challenge. The JEO mission will be classified as Category III under current COSPAR and NASA policy [COSPAR, 2008]. In specifying requirements for Europa missions, in general, under Category III, current NASA planetary protection policy (NPR8020.12C, 2005) specifies requirements for Europa flyby, orbiter, or lander missions as follows: "Methods…including microbial reduction, shall be applied in order to reduce the probability of contamination of an Europan ocean to less than 1×10^{-4} per mission."

[Note: The planetary protection approach outlined below is subject to further clarification/approvals between the flight mission project and the NASA and ESA Planetary Protection Officers]

A proposed approach to planetary protection compliance for the JEO flight system is summarized as follows:

- Pre-launch sterilization to control bioburden for those areas not sterilized in-flight. DHMR is the baseline sterilizing technology.
- The mission will request credit for in-flight sterilization, via radiation, prior to Europa orbit insertion (EOI). The additional requirement to avoid contamination of (impact with) other Jovian satellites will be met through trajectory analysis, based on the approaches of Cassini and Juno. This includes the 10^{-4} requirement to avoid impact on Europa prior to EOI.

The probability of contamination (P_c), for a Europan mission, is dependent on the following terms [Space Studies Board, 2000]:

- Microbial bioburden at launch (N, measurable by classical bioassay),
- Probability of cruise survival (P_{cs}, estimable, but typically a small reduction factor),
- Probability of Jovian tour survival (P_{rad}, estimable based on flight system design and radiation dose effects),
- Probability of landing on Europa (P_e, = 1 for JEO),
- Probability of transport to the Europan sub-surface (P_t, an item difficult to estimate),
- Probability of organisms' survival, dispersion and proliferation (P_g, an item difficult to estimate).

This will be interpreted for JEO as:

$$P_c = N \times P_{cs} \times P_{rad} \times P_e \times P_t \times P_g \leq 1 \times 10^{-4}$$

Early formalization of the mission categorization and technical approach will be sought through the NASA PPO, so that the project can switch to an alternative (e.g., system sterilization) methods early in the project at low cost penalty. This is facilitated through the inclusion of the mid-Phase-B Planetary Protection review so that costs of developing mitigation strategies can be factored into the mission early.

At the current stage of maturity, no planetary protection show-stoppers have been identified with this approach. In the current approach, it is assumed that the option exists to maintain post-sterilization recontaminant spore density on the surface at a nominal value of $300/m^2$ (which was the pre-sterilization value for the Viking landers) as was done for the two Mars Exploration Rover (MER) spacecraft. It is assumed that Radioisotope Power Supplies self sterilize (e.g., per Mars Science Laboratory [MSL]), propellant can be filtered or otherwise made sterile, and that other marginal-cost approaches beneficial to planetary protection mitigation are followed (for example, modification of contamination control bake-out parameters to allow bioburden reduction credit to be taken).

No specialized planetary protection facility costs or launch vehicle costs have been assumed in this approach. It is considered that Assembly, Test & Launch Operations (ATLO) will be in standard class 100K cleanroom conditions. Requirement to work cleaner than this to manage initial bioburden (e.g., in tented 10K conditions, or better) will be carried as a technical risk. The detailed integration of the ATLO/planetary protection flow will be an output from Phase A. However, it is already anticipated that aseptic joining of flight hardware may be required during ATLO, particularly in the context of rework activities. Validation of these aseptic joining approaches will be a Phase A activity.

It is necessary that areas of the flight system not experiencing adequate levels of Jovian radiation to achieve sterility will be sterilized before or during ATLO and cleanliness maintained by protecting from recontamination prior to launch with HEPA filters (per MER/MSL) and/or biobarriers (per Phoenix).

Data from the operational phase of the mission, particularly during the Jovian tour, will inform the true irradiation environment experienced by the hardware. This is accomplished by the on-board dosimeter to record the level of radiation in real-time during the JEO mission.

This will give confidence that the required level of sterilization is achieved prior to EOI. Extending the pre-EOI tour to achieve a given irradiation dose for planetary protection purposes remains a possible option. JGO is ESA's contribution to the joint NASA/ESA EJSM.The mission design and the JGO spacecraft will be developed and launched by ESA. Its element focuses on the two outer Galilean satellites Callisto and Ganymede. Multiple flybys of Callisto and in-orbit operations around Ganymede build the platform for a thorough in-depth characterisation of both bodies. In addition, the science objectives address interactivity and evolution of all bodies in the Jovian system as a whole, as well as studies on the thermal structure, dynamics and composition of Jupiter's atmosphere.

In the studied baseline, the spacecraft carries a 73 kg of scientific sensing payload. The potential inclusion of up to two penetrators as part of the suite of payload instruments is currently under study. The current mission profile foresees a launch in March 2020. After a cruise phase of almost six years, the spacecraft reaches the Jupiter system in 2026. After 19 fly-bys at Callisto the final destination Ganymede will be reached in 2028. A nominal duration of 180 days in a circular orbit concludes the mission. At its end of life it is planned that JGO will crash on Ganymede's surface.

This mission is provisionally assigned Planetary Protection Category II, with additional requirements. Extra caution for Ganymede beyond the standard Category II requirements was recommended by a COSPAR working group on Outer Planet Satellites (this paper) because of insufficient knowledge on the potential to transfer contamination to the subsurface. As a result the probability of inadvertent contamination of an ocean on Ganymede shall be less than 10^{-4}.

<u>11) Dennis Matson, Kim Reh and Jens Romsted:</u> Titan Flagship/ L-class Mission

Titan Saturn System Mission (TSSM) consists of a Titan Orbiter provided by NASA that would carry to Titan two *in situ* elements provided by ESA: a montgolfière and a lake lander. The mission would be launched in 2020 and arrive nine years later for a 4-year duration in the Saturn system. Following delivery of the ESA *in situ* elements to Titan, the Titan Orbiter would explore the Saturn system via a 2-year tour that includes Enceladus and Titan flybys. The montgolfière would last at least 6-12 months at Titan and the lake lander 8-10 hours. Following the Saturn system tour, the Titan Orbiter would culminate in a 2-year orbit around Titan. Synergistic and coordinated observations would be planned between the orbiter and *in situ* elements.

TSSM has three scientific goals:

(1) Explore Titan as an Earth-Like System—How does Titan function as a system? How are the similarities and differences with Earth, and other Solar System bodies, a result of the interplay of the geology, hydrology, meteorology, and aeronomy present in the Titan system?

(2) Examine Titan's Organic Inventory—A Path to Prebiological Molecules--- What is the complexity of Titan's organic chemistry in the atmosphere, within its lakes, on its surface, and in its putative subsurface water ocean and how does this inventory differ from known abiotic organic material in meteorites and therefore contribute to our understanding of the origin of life in the Solar System?

(3) Explore Enceladus and Saturn's magnetosphere—clues to Titan's origin and evolution—What is the exchange of energy and material with the Saturn magnetosphere and solar wind? What is the source of geysers on Enceladus? Does complex chemistry occur in the geyser source?

After a cruise phase of almost ten years the mission enters into the Saturn orbit. During the first and second fly-by at Titan the probes are released. Neither probe has a flight path control system, and both follow a ballistic entry into Titan's atmosphere.

The first released element is a hot air balloon (montgolfière). After braking the entry velocity by a series of parachutes (similar to Huygens), a balloon will be inflated with ambient gas, which will be heated by a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). The Gondola hanging underneath the balloon carries a payload complement of 25 kg for atmospheric measurements, imaging, spectrometry, subsurface radar profiling and electric field measurements. The nominal lifetime is six months with a possible extension up to 12 months. At the End of Mission, the montgolfière is expected to land on Titan's surface.

The second released element is a lake lander. This probe will carry out scientific measurements throughout the descent to and on the surface. The landing target is a liquid ocean in the northern atmosphere, Kraken Mare. The lander is designed to float for up to four hours on the surface. It carries 32 kg of payload for imaging, spectroscopic analysis, atmospheric and in-situ sampling measurements. The main instrument package is a suite of chemical analysers to measure chemical and isotopic composition of the ocean and atmosphere. New scientific results on the nature of Titan imply a reinforcement of the currently assigned Planetary Protection Category II. Extra caution should be taken in order to avoid a possible contamination of a potential sub surface ocean and survival of organisms collocated with a perennial heat source. Future mission studies will specifically address the issue of preventing a transfer of heat from the MMRTGs directly to the surface, e.g., by caging of the MMRTG.

4. Discussion Group Summaries

For ease of discussions and to take full advantage of the different expertise and perspectives of the Workshop attendees, three splinter groups were formed to facilitate independent discussions, as listed below.

Overall instructions were given for each group to 1) initially focus on a specific assigned body or group of bodies, and 2) then consider the overall assemblage of Outer Planet satellites and small Solar System bodies to the level of detail practicable in the time available. For each Outer Planets satellite, or class of satellites, and for each group of asteroids, comets, and Kuiper Belt Objects (KBOs), the groups were asked to evaluate:

- Whether the satellite/group is of interest to organic chemical evolution and/or life in the universe.

- If the satellite/group is of interest, to rate missions to these bodies as “Category II” (or III or IV), depending on whether 1) by the criteria from the Europa mission study, 2) by the considerations of the small body sample return study, or 3) in view of the Mars Special Regions (MSR) Report, they may have habitats where Earth organisms could grow and thrive. If Earth organisms could grow and thrive the groups were told to rate missions to those bodies as Category III / IV.

The splinter groups were fully engaged in the task, and each group approached the goals in a different manner, as can be ascertained from their reports, below. As a result, the examination was both thorough and instructive, and allowed a final result on categorizations and other suggestions for improving the COSPAR policy to be made in the ensuing plenary discussions. Some of the groups found it useful to frame their discussions using the original definitions of “Planet Priorities” in DeVincenzi et al. (1983) and DeVincenzi & Stabekis (1984).

These definitions are roughly defined by the following equivalents, where a particular "Planet Priority" suggests that a particular mission categorization should be applied:

- Planet Priority A ≈ Category I
- Planet Priority B ≈ Category II
- Planet Priority C ≈ Categories III and IV

4.1 Group 1: Triage with a Europa, Ganymede, Callisto focus

Greeley, Ronald (Chair),
Bolton, Scott
Buxbaum, Karen
Clark, Karla
Conley, Catharine
Pappalardo, Robert
Senske, David
Voytek, Mary

Because the group's focus was mainly on scientific attributes of the satellites relevant to planetary protection rather than mission categorization, each target body was discussed and identified as fitting the A, B, or C priorities defined in NASA policy documents. This was not entirely consistent with the instructions to make mission category I, II, or III/IV assignments, but helped to keep the focus on science knowledge rather than mission-related considerations. It was noted that any mission to a particular satellite would need to be assessed as a Category I, II, II/IV based on its mission design characteristics including Io, Callisto, Ganymede and Europa considerations.

Group 1 also discussed MSR parameters—temperature and water activity—and their potential applicability to outer Solar System bodies. The group agreed that while limits on microbial reproduction would be equally applicable to Outer Planet satellites, specific requirements adequate for the Mars analysis (temperature and water activity for a 500 year time frame) would be insufficient for the case of Europa.

Io—Is it of direct interest for understanding the process of chemical evolution? Is it even comparable to Venus in this regard? The consensus was "no" to both questions. This would be consistent with a planet priority A, leading to Category I for a mission to Io only, with no further requirements beyond the mission categorization letter. It is not necessarily defensible to say that there is no water at Io. It is a priority A object because Io would not be studied for organic "chemical evolution and/or the origin of life" in the universe.

Callisto—Is there a significant chance of harmful contamination? There is evidence of organic molecules in the dark material and there is the possibility of a deep subsurface body of water. But, according to the planet priority definitions, Callisto would be a priority B object. Scientific data clearly led to a conclusion that there would be no communication of a potential habitat with the surface where contamination might occur.

Any contamination at the surface would not jeopardize future exploration.

Ganymede - Is it the same as Callisto? Assessment of Ganymede is similar to Callisto, but Ganymede shows evidence of surface activity from endogenic processes, such as tectonic deformation of the ice. Timing and access to the putative subsurface ocean need to be considered. The youngest ages for grooved terrains are hundreds of millions of years old. The magnetic field data suggest that the interior is sufficiently warm to sustain an ocean. There is consensus concerning Ganymede for processes of surface change, but is there any mechanism or speculation concerning processes that could move surface material into the subsurface? The input to the group was that no such model exists. The conclusion was that the chance of contamination (which would compromise future exploration) is remote and there is not a risk of global contamination. A concern was raised about whether there could be mechanisms for near-surface water that could receive and transport biological contamination, but there is no known transport process. The Galileo mission showed no (or little) evidence for cryovolcanic processes. Initial discussion in the group suggested that a conservative approach would make Ganymede a priority B-minus object, with missions required to address the probabilistic risk of contamination. However, it was decided in subsequent discussion of the groups that Ganymede does not merit a priority C designation. It was grouped with a subset of priority B objects (not a significant chance of contamination by spacecraft that would jeopardize future exploration) that might warrant greater mission planetary protection requirements than the rest of the priority B objects, but should not be elevated to category C.

Europa. Europa is a priority C object based on current knowledge, including uncertainly of the ice thickness and possible surface turnover rates. Europa merits significant protection from harmful contamination. There are no values that the NRC used with which anyone took strong exception. The group's Europa scientists were comfortable with numbers in the NRC report (2002) on forward contamination. Even though there was general agreement concerning the need to protect Europa from harmful contamination, there was a recommendation to revise the equation (the SSB's report example calculation of probability of contamination) so that it is mathematically correct and consistently communicated. The expression as written requires clarification of terms and use. Also, based on the Juno approach, a term for impact survival fraction may need to be added. There was brief discussion of adding spacecraft reliability into the equation; this may warrant further consideration. However, this application is not directly analogous to Mars orbiter probabilistic requirements, which incorporate spacecraft reliability.

Titan and Enceladus: along with Europa, both of these objects were ranked at priority C.

Other Outer Planet satellites and small bodies—Size isn't the issue. Even though Io is a Galilean moon and ranked as a priority A object, some of the smaller satellites could be priority B because of organics, water, or scientific uncertainty. The conclusion was that other objects in the Jovian system should be viewed as priority B, either because of our knowledge of their status or our uncertainty about them.

In light of the possible relevance of cryovolcanism to any discussions of planetary protection and the icy moons, the group spent time to define what is meant by cryovolcanism, making sure that there was a common understanding of the terminology. The working definition of cryovolcanism: "*Eruption of solid, liquid, or vapor phases (with or without entrained solids) of water or other volatiles that would be frozen solid at the normal temperature on the surface of a planetary body*."

The group agreed to recommend in the plenary session that a single definition of cryovolcanism be provided and used in the final report. In the absence of a single consensus definition, the group recommended that the final Workshop report and any ensuing policy language use non-controversial terms to be clear and consistent in describing the intended physical processes.

4.2 Group 2: Triage with a Titan focus

Hipkin, Victoria (Chair)
Clark, Ben
Ehrenfreund, Pascale
Kminek, Gerhard
Magner, Thomas J.
Matson, Dennis
Owen, Tobias
Romstedt, Jens
Spry, J. Andrew

Task 1: *Consider first whether the satellite/group is of interest to organic chemical evolution and/or life in the universe*

Group 2 formulated their recommendations within a slightly restricted framework: a table of satellites was drawn up for consideration to include Europa, Callisto, Ganymede, Triton, Enceladus, Io, comets/small moons of Saturnian/Jovian system. Small bodies such as asteroids and KBO's were not explicitly considered.

Of the bodies considered, only Io was determined not to be of interest to organic chemical evolution, and/or life in the universe. The rationale for this categorization was that nothing of biological interest has been detected and high surface temperatures and very active resurfacing do not provide an environment suitable for the preservation of a history of organic evolution. Contamination is not possible. All other bodies considered were classed as of interest due to expectation of organics or habitable environments.

Task 2: *If the satellite/group IS of interest then rate it "Category II" (or III or IV), depending on whether, by the criteria from the Europa mission study, the considerations of the small body sample return study, or in view of the Mars Special Regions Report, they may have habitats where life could grow and thrive. If so, rate them Category III / IV, which will depend on future missions.*

Group 2 then established a leading presumption to apply in the recommendation of categorizations for the remaining satellites: black body temperatures for bodies at distances from the sun equivalent to the Jupiter system or beyond would be <180K based on solar radiation in the absence of endogenic/tidal forcing activity. At these temperatures, any contamination would be quickly frozen in place and contained. The paradigm of containment was very influential in the classification process and did not have full consensus within the team, as it generated similar categorizations for satellites of interest as habitable environments as for much lower interest targets. The issue of a spacecraft induced lens was flagged as something to be evaluated case-by-case. In the case of a nuclear powered spacecraft on an icy planet, such a micro-environment where terrestrial life may grow could be created, but an evaluation may still determine no possibility for transport beyond a contained zone.

In determining evidence for endogenic/tidal forcing activity, group 2 adopted recent surface geological features as the indicator to consider.

Europa: Group 2 agreed with the existing classification due to high scientific interest in its sub-surface ocean as a potentially habitable environment, and evidence of endogenic activity visible at the surface that suggests a means of propagation of contamination from the surface to the ocean below. It was, however, suggested that recent papers could be taken into account that relate to advances in our knowledge of the radiation environment which may prove that the surface environment of Europa is fundamentally too hostile for the survival of terrestrial bacteria.

Initially, Group 2 recommended both Ganymede and Callisto as Category II, on the basis of interest in organics but evidence of ancient surfaces: no evidence at the surface of recent activity that could propagate contamination beyond a spacecraft zone. However, it was noted that Ganymede was slightly more "special" than Callisto, due to the evidence of endogenic activity presented by its intrinsic magnetic field. It was recommended that should any geological evidence appear of activity at the surface through higher resolution mapping, the classification should be revised.

For Triton, the group recommended Category II but acknowledged that the only information that exists is from Voyager and quite limited. While there is some evidence of surface activity, surface temperatures are exceptionally cold and contamination is expected to be contained.

Enceladus is of very high scientific interest due to presence of both water and organics. Furthermore, Argon (Ar) and Sodium (Na) isotopes suggest rock is in contact with water providing an expectation that the water may be nutrient-rich. Surface activity suggests a current transport pathway between surface and sub-surface ocean. For these reasons, Group 2 recommended Category III.

For all other small bodies aside from Titan, it was recommended that the question to be answered is whether the surface that formed during accretion is intact, or been resurfaced at a later time.

If there has been no activity for 3 billion years, there will be very low possibility of contamination – it will not be possible to destroy the surface by terrestrial contamination. Spacecraft induced contamination will be frozen in place.

Task 3: *Examine "special body(s)" assigned to group and make an estimate of the factors appropriate to its treatment (using the Europa report factors, as available).*

A very lively discussion ensued related to Titan. Group 2 agreed that this was a target of high scientific interest due to extensive evidence of organics, the methane/ethane hydrological cycle, and some evidence for a sub-surface ocean.

Titan's surface temperatures of 90K are too low for terrestrial propagation, so this group initially recommended Category II due to the inability to envision a credible mechanism on a reasonable timescale that could provide a conduit to a watery ocean. Tidal activity appears too low to create heat sources or drive deep transport processes. This inability to identify an active site and potential location for forward contamination renders the probability approach applied to Europa excessively conservative, leaving a zero or near zero value (if a remote likelihood is retained) as a multiplicative term. Argument for this approach centres on evidence for cryovolcanism and thermal models of a liquid ocean.

Crater density indicates active surface alteration over the last 100 million years, of similar level to Earth, but this could be due to the methane hydrological cycle. If there were evidence of Enceladus-like transport mechanisms, (plumes, thermal anomalies) there would be great difficulty seeing this with the same instrumentation due to interference with Titan's atmosphere. Observations of brightening on Titan suggests current activity but if this is evidence of cryovolcanism, it is very limited in areal extent (10 km^2). If a sub-surface ocean exists, water would be at greater depth than Enceladus as Enceladus has additional heat sources. The question for forward contamination on Titan is whether there is a conduit to a subsurface liquid zone. Models for cryovolcanism which suggest shallow oceans are based on 30% water-ammonia mixtures where the eutectic temperature is 176 K (lowest temperature). Outflow would be at lower temperatures (90-176 K) than relevant for propagation of terrestrial organisms. Models for cryovolcanism based on pure water suggest deep oceans and we cannot envision a credible mechanism to reach a deep ocean for Titan on a reasonable timescale. The group considered that measurements of Love number and asynchronous rotation could provide new evidence for the depth of a water ocean, and heat flow measurements could indicate convection, but the lack of a source of heat for strong convection and a mechanism to transport water to depth appear at this time to be fundamental limitations to propagation of contamination.

The group was instructed to map the Category I, II, III classification scale to the A,B,C classification scale in order to highlight bodies which may be in need of future reclassification and ensure a conservative risk approach. Group 2 recognized that the current categorization logic model for class B includes two statements: one which refers to the importance of the scientific target, and another that refers to the probability of forward contamination.

Group 2 defined the new B- class as applying to targets that may be relevant to life (implicitly that there may be evidence for habitable zones or environments) and with inadequate data to assess risk of contamination.

4.3 Group 3: Triage with an Enceladus, KBO, comets, asteroid, subUranus/ Neptune focus

Viso, Michel (Chair)
Abe, Masanao
Brucato, John
de Vera. Jean-Pierre
Grasset, Olivier
Lammer, Helmut
Peter, Nicolas
Schwehm, Gerhard
Stabekis, Pericles

Group 3 revisited the various objects of interest in view of the current COSPAR planetary protection policy. The considered objects are the moons of the giant planets, the comets, the asteroids and the KBOs.

Considering the current COSPAR definitions, the group reworded two particular expressions used in the definitions of Category II and Category III. For Category II, it is stated, inter alia, "… *where there is only a* ***remote chance*** *that contamination carried by a spacecraft could jeopardize future exploration"*. In this case we define *"remote chance"* as *"the absence of niches (places where terrestrial micro-organisms could proliferate) and/or a very low likelihood of transfer to those places."*

For Category III, it is stated, inter alia, *"…where there is a* ***significant chance*** *that contamination carried by a spacecraft could jeopardize future exploration."* We define *"significant chance"* as *"the presence of niches (places where terrestrial micro-organisms could proliferate) and the likelihood of transfer to those places."*

With these more precise definitions we reviewed the status of the various objects to be considered in light of the most recent knowledge acquired by the scientists. The group agreed that each object is to be considered as a single body. If the object is not homogenous, then the categorisation will be based on the highest chance to find a favourable environment for terrestrial micro-organisms. Group 3 considered also that "adaptation" means that the organisms can proliferate as they are in the considered environment. For planetary protection purposes, Enceladus deserves special consideration because it cannot be ruled out that terrestrial microorganisms might be able to reach a subsurface water reservoir. And if they were able to reach those reservoirs, there is no evidence that proliferation would not be possible for some terrestrial species.

Except the asteroids of type S, all the considered objects are of interest, in various degrees, to study the organic chemical evolution and the origin of life. Nevertheless, moons of Uranus and Neptune, mid size moons of Saturn and the KBOs are considered as members of category II provided further evidence that objects larger than half the size of Pluto could contain some liquid water reservoir. Double objects covered by water ice (like Pluto & Caron) deserve special attention because the interaction could maintain some water reservoir underneath. In the same way, the moon of Neptune, Triton, is a member of category II providing new evidence of material exchange between the surface and a possible subsurface liquid water reservoir. Comets as asteroids of category P, D and C are also considered as members of category II.

The group did not identify the exact meaning of the "prioritisation" and focused on the need to give to the objects of the Solar System, which are not yet categorized, a preliminary status in light of the current planetary protection policy.

5. Overview of Results of Group Discussions

Each of the splinter groups provided an interesting and partially non-overlapping perspective on the questions posed by the Workshop. While there were some disagreements on the particulars of the categorizations that were assigned by each of the groups, there were none that were not resolved in the subsequent plenary, as reported below. In addition, Group 3 provided a thoughtful critique of the current wording of the COSPAR Planetary Protection Policy with respect to the differences between Category II and Categories III and IV. Accordingly, the Workshop participants were able to resolve that critique in plenary, too, and generated a recommendation to update the wording, originally proposed in the early 1980s, to reflect the current realities of its usage in assessing mission requirements.

6. Translations into Categorizans

After the three splinters groups had reported on their results, the subsequent plenary discussions considered their findings and the Workshop came to a consensus on the proposed categorizations for each body or group of bodies, as given in Appendix C. For most of the Outer Planet satellites and small Solar System bodies the proposed categorization is new—those bodies not having been considered before. For some bodies, however (notably Ganymede, Titan, Triton, the Pluto-Charon system, and other large KBOs), the Workshop accepted an initial Category II assignment for missions to those bodies ("only a remote chance that contamination by spacecraft could jeopardize future exploration"), but acknowledged that additional data are required to ensure that this mission categorization is a correct one. On one hand, additional data may show that these bodies contain liquid-water environments that could be inhabited by Earth organisms, and that such environments are accessible under the nominal circumstances of certain missions. On the other hand, such environments may not exist, or may be completely inaccessible to our best efforts in exploration.

7. Overview of Proposed Category Wording Changes

The Workshop discussions of the categorizations of the missions that may go to this wide variety of Solar System objects highlighted certain aspects of the COSPAR definitions of mission categories that have matured significantly since the COSPAR policy was first proposed in the early 1980s (DeVincenzi et al. 1983, DeVincenzi & Stabekis 1984).

The Workshop attendees discussed the nature of the categories, as originally applied and as currently being applied in 2009, and proposed the following wording changes relative to the "interest" definitions relating to Category II, and to Category III and IV.

<u>Current COSPAR Wording:</u>
Category II: "Of significant interest relative to the process of chemical evolution and the origin of life, but only a remote chance that contamination by spacecraft could jeopardize future exploration."

Category III/IV: "Of significant interest relative to the process of chemical evolution and the origin of life *or* for which scientific opinion provides a significant chance of contamination which could jeopardize a future biological experiment."

<u>Recommended Revision</u>
Category II: "Of significant interest relative to the process of chemical evolution and the origin of life, but only a remote chance that contamination by spacecraft could *compromise future investigations.*"

Category III/IV: "Of significant interest relative to the process of chemical evolution and the origin of life *and* for which scientific opinion provides a significant chance that contamination by spacecraft could *compromise future investigations.*"

Where "Remote" is defined as "the absence of niches (places where terrestrial micro-organisms could proliferate) or a very low likelihood of transfer to those places."

and

"Significant" is defined as "the presence of niches (places where terrestrial micro-organisms could proliferate) and the likelihood of transfer to those places."

8. Proposed Future Scientific Studies

8.1 Key Uncertainties in Current Knowledge

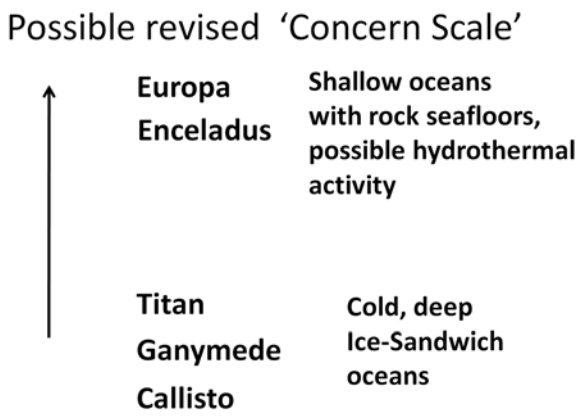
Based on current understanding, there seems to be consensus on the *relative* ranking of the satellites in the Jupiter and Saturn systems with respect to the degree of concern for planetary protection. This ranking, illustrated below, results primarily from a combination of: 1. Evidence for liquid water in their interiors, 2. Probable depth to liquid layer (shallow or deep), and 3. Geologic 'youthfulness' and activity.

Consensus on 'Concern Scale'

↑

Europa
Enceladus
Titan
Ganymede
Callisto

As discussed in the Introduction to Outer Planet Satellites section, a major difficulty in assessing the degree of concern more quantitatively is a lack of agreement in the planetary community regarding the mechanisms and time scales of the geological processes which might result in the exchange of material between the surface and the liquid layers. Consideration of models for the interior structures of these objects suggests a rationale for further sub-division of the ranked list above, based on the probable nature and location of liquid water layers. Titan, Ganymede, and Callisto are close siblings in their bulk properties (radius and density), and models of their interiors based on the complex nature of the water phase diagram suggest that all three may possess deep liquid oceans (more than 150 km below the surface), "perched" or "sandwiched" between a thick crust of low density Ice I and a icy mantle of high density Ice III, with completely or partially differentiated silicate or silicate plus ice below. Models for Europa and Enceladus on the other hand suggest liquid layers at shallow (tens of kms) depths below an Ice I crust, the liquid being in contact with a primarily silicate mantle or core. There are uncertainties in all of the current interior and thermal models and this research area is currently very active, with a rapid influx of both new models and new constraints from spacecraft and laboratory studies. Despite these uncertainties, however, the basic nature of the probable liquid oceans in the larger satellites render them intrinsically less likely to result in easy or rapid exchange of material between liquid and surface regions. Additionally, the lack of contact between liquid and silicates in recent geological times (i.e. post differentiation, if it occurred) in these satellites limits the role of hydrothermal alteration in possible pre-biotic chemical processes compared with Europa and Enceladus. Thus a possible refinement of the 'Concern Scale' above might reflect two groupings of satellites with a distinct qualitative, if not yet quantitative, gap between the groups:



In order to make progress in improving our understanding of the processes important to assessing planetary protection needs, new data and research in several different areas are needed, including spacecraft and telescopic observations, theoretical modeling, laboratory measurements, and related astrobiologic studies. Although not exhaustive, the following sections briefly describe some important areas of future studies.

8.2 Spacecraft and Telescopic Studies

In the Saturn system, the Cassini mission is continuing to acquire important data on the icy satellites, with Titan and Enceladus being high priority targets for in-depth study. For the Jupiter system, NASA and ESA are studying a mission to explore both Europa and Ganymede with orbiters, in addition to adding significantly to our knowledge of the rest of the satellites, Jupiter, and the magnetosphere. Telescopic studies, both from large ground-based facilities and space-based systems, continue to provide key information about the satellites, and are particularly important in providing information about the long term temporal behavior of these systems (e.g. seasonal variations in the clouds on Titan, E-ring characteristics, Sodium emissions, and Io volcanic activity). Some specific prospects for new information are noted below.

Titan

- Evidence for ocean layer - Cassini
  - Crustal decoupling versus axial precession from radar and tracking
  - Dynamical determination of moment of inertia from tracking
  - Love number, k_2 from tracking
- Atmospheric evolution and time scales – remote sensing and radio occultation data from Cassini expected to cover about one half of the Saturn seasonal cycle, supplemented with long time baseline telescopic observations
- "Cryovolcanism" rates – searches for temporal variations, radar and VIMS imaging of new terrains
- Level of endogenic activity – tectonics, convection, erosion – radar and VIMS imaging

Enceladus

- Plume gas, particulate composition: Cassini *in situ* data from plume fly-through
- Temporal variations – Cassini remote and *in situ* observations supplemented by telescopic studies of long term evolution of E-ring
- Gravity anomalies – from Cassini tracking and radio science
- Thermal mapping of active South Polar Region – Cassini CIRS observations with S. pole in darkness

8.3 Modeling and Laboratory Studies

Addressing the many issues related to time scales and mechanisms of exchange process between surface and interior requires improvement in computer thermal and convection modeling techniques, including full 3D, dynamically coupled capabilities. Additionally, the physical and rheological behavior of the ice and ice mixtures present in the satellites is still poorly understood over the range of conditions found in satellite interiors. Among the areas needing further work are: studies of rheology at low temperatures, stress conditions, and rates appropriate for satellite interiors and ice dissipation, and studies of ice clathrate and ammonia mixtures which may play a role in satellite interiors and evolution.

Another important laboratory discipline the requires further work is spectral studies from the ultraviolet to the infrared of ices and ice mixtures with potentially important materials such as ammonia, salts and organic compounds, again under conditions appropriate for the satellites (e.g. Zhou et al. 2009).

As discussed in previous sections, space data indicate that Titan's surface is covered with hydrocarbon lakes. Spectroscopic data and optical constants of liquid hydrocarbons measured in simulated space conditions are therefore crucial for the interpretation of space data. The heteropolymer "tholin", likely formed from simple organic molecules (such as CH_4) by radiation processing, seems common in the outer solar system and has been investigated with many laboratory techniques (see Quirico et al. 2008 for a review). Cassini-Huygens data of Titan's atmosphere provide the basis for new laboratory experiments on tholins to characterize more precisely their composition, evolution and diversity.

During the Cassini/Huygens flyby mission, aromatic compounds (e.g., benzene, C_6H_6) were detected in situ in the ionosphere at concentrations higher than expected. Benzene is a required precursor in the pathway of larger aromatic species such as polycyclic aromatic hydrocarbons (PAHs). PAHs may be involved in Titan's aerosol production. Future experiments will use combined cavity ring down spectroscopy and time-of-flight mass spectrometry studies to investigate the formation and destruction processes of Titan aerosol particles (Ricketts & Salama 2008).

8.4 Astrobiology

Several issues raised by recent studies and models of icy satellites prompt astrobiological questions which may be addressed by future biological research. These include:

- Limits of life/biological potential of ammonia/water environments over a range of ammonia concentrations and low temperatures.
- "Perched ocean" habitability for a range of possible scenarios, including nearly complete lack of contact between liquid and silicate in the interior in the current epoch, contact with cold silicate/high pressure ice mixtures, mixing of silicate and organic material from the surface on a variety of time scales by convective or diapiric activity.

Our evaluation of the potential for biological contamination by missions to the Outer Planets satellites or other small solar system bodies was based primarily on the assessment of survivability and reproduction limits established by ambient temperature, water activity and solute composition. In general, investigations of the biological limits to life, with respect to low temperatures and water activities have been limited and most of the work has been done on laboratory isolates. A significant limitation of the existing datasets is that only a small proportion of microbes, representing a narrow phylogenetic diversity, have been checked. Further work is needed on defining the lower temperature limit and water activity for growth and reproduction in both laboratory and field environments e.g., deep anoxic basins, Don Juan Pond (Antarctica), and other similar environments, where reproduction under water activities lower than 0.6 is equivocal. Solute water activity studies have been limited to a narrow group of chemicals and needs to be expanded to include compounds relevant to the target body.

Our current understanding of environmental conditions and potential habitats specific to the icy satellites raises astrobiological questions that should be addressed by future research.These include two areas, basic research on the limits of life, and a better understanding of potential habitats and the conditions necessary to support life. Specific examples include:

<u>Biological limits to life and tolerance to planetary conditions</u>

- Low temperatures and water activities. Studies should not be limited to isolates and should include both laboratory and analogue environments on earth.
- Metabolism and growth in ice or permafrost with focus on permanently cold locations such as equatorial high alpine environments.
- Limits of life/biological potential under high pressure.
- Limits of life/biological potential of ammonia/water environments over a range of ammonia concentrations and low temperatures.
- Improved understanding of the reproduction of communities, rather than merely isolates.

- The synergistic effects of physical and chemical stressors, including those of impact survival on the planet (cf., Moeller, et al., 2008; Stöffler, et al., 2007; Horneck et al., 2008).

Potential habitats on target bodies

- Identification of potential habitats either at the surface or subsurface (including within ice veins of the ice cover and the oceans below).
- 'Perched ocean' habitability for a range of possible scenarios, including:
  - nearly complete lack of contact between liquid and silicate in the interior in the current epoch,
  - contact with cold silicate/high pressure ice mixtures,
  - mixing of silicate and organic material from the surface on a variety of time scales by convective or diapiric activity.
- Characterization of solutes present in subsurface oceans and ice cover contributing to water activity.
- Characterization of potential metabolites present in subsurface oceans and ice cover providing carbon, other nutrients, and energy sources.
- Habitability of solvents other than water (e.g. methane).

9. Planned Future Study Activities

During the deliberations of the Workshop, a number of bodies in the outer Solar System were identified as being potentially the II+ category (denoting a body that is of interest to chemical evolution and the origin of life, but whose potential to support living organisms is undecided), including at least Titan, Ganymede, Triton, and the Pluto-Charon system. Of these objects, Titan is the highest priority target for a near-term robotic flagship mission. To address concerns raised by the current Workshop, another dedicated Workshop on Titan is planned to be held jointly by NASA, ESA, and COSPAR during the winter of 2009-2010, to include additional experts on Titan and to inspect detailed information about the most recent Cassini-Huygens results. The goal of this future workshop will be to resolve the mission category for Titan and develop a consensus on the II versus II* dichotomy, taking into account both the conservative nature of planetary protection policy and the physical constraints on the Titan system. Organizers for this Titan workshop have been identified, and the participant list is in preparation, with specific attention to ensuring appropriate representation of experts in data and modeling. The planetary protection advisory bodies of both NASA and ESA will be briefed on the results of this future Workshop, and comments will be invited. In addition to the results documented in this Workshop Report, the outcome of the Titan workshop will be distributed to the COSPAR Planetary Protection panel for consideration prior to the next General Assembly meeting in Bremen (Germany) of 2010. Results from the Titan study will also be coordinated with inputs from this Workshop in a larger evaluation of outer planet icy satellites that may be requested from the U.S. NRC's SSB.

In the late 1990s, the SSB was requested to prepare a report on *"Preventing the Forward Contamination of Europa"*, considering factors such as the type and level of terrestrial contamination as well as the methods that might suitably remove them from spacecraft. In the 2009-2010 timeframe, NASA will request the SSB to expand this report to address the range of icy bodies found in the outer solar system, taking as input this Workshop report and the results of the Titan workshop described above. Topics that may be included for consideration in the request to the SSB include:

- Assess the potential for habitable environments to be present in icy bodies of the outer Solar System,
- Assess the potential to introduce terrestrial organisms carried by spacecraft into an habitable environment that could jeopardize future biological investigations, given the constraints on these environments and our current understanding of terrestrial organisms,
- Identify scientific investigations that should be accomplished to reduce the uncertainty in the above assessments.

10. COSPAR Policy Update: Next Steps

The COSPAR Workshop on Planetary Protection for Outer Planet Satellites and Small Solar System Bodies was successful in achieving its stated goals: reviewing existing categorization and establishing new categorization; addressing the categorizations of future missions to the Outer Planet satellites and making recommendations both to improve the COSPAR Planetary Protection Policy and to resolve scientific uncertainties associated with the Workshop's conclusions. These conclusions and the context provided by this Report will be reported to the Panel on Planetary Protection at the next Scientific Assembly of COSPAR in 2010. Additionally, formal resolutions to incorporate these recommendations into the COSPAR policy will be made at the Business Meeting of the Panel at the Assembly, and then (if they are approved by the Panel) will be forwarded to the COSPAR Bureau and Council for their consideration, and if judged appropriate, will be incorporated into the COSPAR policy at that time.

References

COSPAR. 2008. Planetary Protection Policy (revised 20 July 2008). COSPAR, Paris, France.

DeVincenzi, D. L., P. D. Stabekis, and J. B. Barengoltz. 1983. A proposed new policy for planetary protection. *Advances in Space Research* 3:13-21.

DeVincenzi, D. L. and P. D. Stabekis. 1984. Revised planetary protection policy for Solar System exploration, *Advances in Space Research* 4:291-295.

Grevesse, N., et al. 2007. The solar chemical composition. *Space Science Reviews* 130, 105-114.

Horneck, G., D. Stöffler, S. Ott, U. Hornemann, C. S. Cockell, R. Moeller, C.Meyer, J. P. de Vera, J. Fritz, S. Schade, and N. A. Artemieva. 2008. Microbial rock inhabitants survive hypervelocity impacts on Mars-like host planets: first phase of lithopanspermia experimentally tested. *Astrobiology* 8:17-44.

Jovian and Saturnian Planetary Protection Working Group 2008. Report in Support of the TSSM and EJSM Mission Studies (2009) JPL D-49066/ESA SRE-PAP/2008.073.

Jupiter Europa Orbiter Final Report, JPL dated November 3, 2008.

Kminek, G., and Rummel, J.D. (eds). *In preparation.* COSPAR Mars Special Regions Colloquium Report Rome, 18-20 September 2007. COSPAR, Paris, France.

MEPAG Special Regions-Science Analysis Group (SR-SAG). 2006. Findings of the Mars special regions science analysis group. *Astrobiology* 6:677-732.

Moeller, R., Horneck, G., Rabbow, E., Reitz, G., Meyer, C., Hornemann, U. and Stöffler. D. 2008. Role of DNA Protection and Repair in Resistance of Bacillus subtilis Spores to Ultrahigh Shock Pressures Simulating Hypervelocity Impacts. *Applied and Environmental Microbiology* 7:6682-6689.

Lammer, H., Bredehöft, J. H. , Coustenis, A., Khodachenko, M. L., Kaltenegger, L., Grasset, O. Prieur, D., Raulin, F., Ehrenfreund, P., Yamauchi, M., Wahlund, J.-E., Grießmeier, J.-M., Stangl, G., Cockell, C. S., Kulikov, Yu. N., Grenfell, J. L. and Rauer, H. 2009. What makes a planet habitable? *Astronomy and Astrophysics Review* 17:181-249.

Quirico, E. et al. 2008. New experimental constraints on the composition and structure of tholins, *Icarus* 198:218-231.

Rummel, J. D. (ed). *In preparation.* Report on the COSPAR Workshop on Planetary Protection, Montréal, Quebec, Canada, 16-18 January 2008. COSPAR, Paris, France.

Space Studies Board. 1998. *Evaluating the Biological Potential in Samples Returned from Planetary Satellites and Small Solar System Bodies: Framework for Decision Making*. Task Group on Sample Return from Small Solar System Bodies, National Research Council. National Academy Press, Washington, 116 pp.

Space Studies Board. 2000. *Preventing the Forward Contamination of Europa*. Task Group on the Forward Contamination of Europa, National Research Council. National Academy Press, Washington, 54 pp.

Stevenson, D. J. 2000. Europa's Ocean – The Case Strengthens. *Science* 289, 1305–1307.

Stöffler, D., G. Horneck, S. Ott, U. Hornemann, C. S. Cockell, R. Moeller, C.Meyer, J. P. de Vera, J. Fritz, and N. A. Artemieva. 2007. Experimental evidence for the potential impact ejection of viable microorganisms from Mars and Mars-like planets. *Icarus* 186:585-588.

Zhou, L, Kaiser, R. I., Tokunaga, A. T. 2009. Infrared spectroscopy of crystalline and amorphous diacetylene (C_4H_2) and implications for Titan's atmospheric composition, *Planetary and Space Science* 57:830-835.

Appendix A: Agenda

COSPAR WORKSHOP ON PLANETARY PROTECTION FOR OUTER PLANET SATELLITES AND SMALL SOLAR SYSTEM BODIES

European Space Policy Institute
Schwarzenbergplatz 6 – Entrance: Zaunergasse 1-3
1030 Vienna, Austria

COMPLETED AGENDA

Day 1 – Wednesday, 15 April 2009

2:00pm	Welcome and Introduction	John Rummel
2:05pm	ESPI Welcome	Kai-Uwe Schrogl
2:15pm	Introduction of Participants	All
2:25pm	Meeting Overview and Agenda / Small Bodies Report	J. Rummel
2:50pm	Current Requirements: Europa SSB/COSPAR & Juno Application	Cassie Conley
3:15pm	COSPAR Mars Special Regions Colloquium Report	Gerhard Kminek
3:45pm	Break	
4:00pm	Radiation Environments & Effects on Biological Systems	Ben Clark
4:30pm	Intro to Outer Planet (and other) Satellites	Torrence Johnson
4:35pm	Satellites of Jupiter: From the Galileans on Down	Bob Pappalardo
5:05pm	Satellites of Saturn: Results from Cassini, etc.	Dennis Matson
5:35pm	Oceans in Icy Worlds: A Synthesis	Bob Pappalardo
6:00pm	Adjourn	All
6:15pm	Reception (at ESPI)	

Day 2 – Thursday, 16 April 2009

9:00am	Convene at ESPI: Introduction to Day 2	J. Rummel
9:05am	Titan as a Special Case	Toby Owen
9:30am	Beyond the Planets of the Gods: Asteroids, Kuiper Belt Objects, etc.	Toby Owen
9:55am	What Makes a Planet Habitable?	Helmut Lammer
10:35am	Applying the Europa Formulation	J. Rummel
11:00am	Break	

11:15am	Group Meetings	All
12:30pm	Lunch (at ESPI)	
1:30pm	Finalize Group Discussions	All
2:30pm	Reports from Groups	Chairs
3:15pm	Break	
3:30pm	Discussion of Europa Formulation in Practice	All
4:15pm	Initial Triage for Forward Contamination Control: Yes, No, Maybe So	All
5:15pm	Plan for COSPAR Policy for Outer Planet Satellites	All
6:00pm	Adjourn	

Day 3 – Friday, 17 April 2009

9:00am	Convene at ESPI: Introduction to Day 3	J. Rummel
9:05am	Review of Results from Day 2 and Discussion	J. Rummel
10:00am	Europa, etc., Flagship/ L-class Mission	Karla Clark/Jens Romstedt
10:45am	Break	
11:00am	Titan Flagship / L-class Mission	D. Matson/J. Romstedt
12:10am	Translation of Priorities to Categorization	J. Rummel
12:30pm	Lunch (at ESPI)	
1:30pm	Discussion of Required Science to Reduce Uncertainties	All
3:00pm	Break	All
3:15pm	Proposed COSPAR Policy Modification, Categorization Language	All
4:00pm	Writing Group Assignments	All
4:30pm	Final Plenary	
5:00pm	Adjourn	

Appendix B: Participant List

Attendee	Institution	Country	E-mail
Abe, Masanao	Jaxa	Japan	*abe@planeta.sci.isas.jaxa.jp*
Bolton, Scott	SWRI	USA	*scott.bolton@swri.org*
Brucato, John	INAF-OAA	Italy	*jbrucato@arcetri.astro.it*
Buxbaum, Karen	JPL	USA	*Karen.L.Buxbaum@jpl.nasa.gov*
Clark, Benton	Space Science Inst.	USA	*bclark@SpaceScience.org*
Clark, Karla	JPL	USA	*Karla.b.clark@jpl.nasa.gov*
Conley, Catharine	NASA HQ	USA	*cassie.conley@nasa.gov*
de Vera, Jean-Pierre	DLR	France	*jean-pierre.devera@dlr.de*
Ehrenfreund, Pascale	GWU	Austria/US	*pehren@gwu.edu*
Grasset, Olivier	U. Nantes	France	*Olivier.grasset@univ-nantes.fr*
Greeley, Ronald	Arizona St. U.	USA	*greeley@asu.edu*
Hipkin, Victoria	CSA	Canada	*Victoria.Hipkin@asc-csa.gc.ca*
Johnson, Torrence	JPL	USA	*torrence.v.johnson@jpl.nasa.gov*
Kminek, Gerhard	ESA/ESTEC	Austria	*gerhard.kminek@esa.int*
Lammer, Helmut	Space Research Inst.	Austria	*helmut.lammer@oeaw.ac.at*
Magner, Thomas J.	APL	USA	*Thomas.Magner@jhuapl.edu*
Matson, Dennis	JPL	USA	*Dennis.L.Matson@jpl.nasa.gov*
Owen, Tobias	U. of Hawaii	USA	*owen@IfA.Hawaii.Edu*
Pappalardo, Robert	JPL	USA	*robert.pappalardo@jpl.nasa.gov*
Peter, Nicolas	ESPI	Germany/France	*nicolas.peter@espi.or.at*
Romstedt, Jens	ESA/ESTEC	Netherlands	*jens.romstedt@esa.int*
Rummel, John	East Carolina U.	USA	*rummelj@ecu.edu*
Schwehm, Gerhard	ESA/Spain	Germany	*gerhard.schwehm@esa.int*
Senske, David	JPL	USA	*david.senske@jpl.nasa.gov*
Spry, J. Andrew	JPL	USA	*james.a.spry@jpl.nasa.gov*
Stabekis, Pericles	Northrop Grumman	USA	*pstabeki@hq.nasa.gov*
Voytek, Mary	NASA/USGS	USA	*mary.voytek-1@nasa.gov*
Viso, Michel	CNES	France	*michel.viso@cnes.fr*

COSPAR Categorization Proposal (Workshop on Outer Planet Satellites and Small Solar System Bodies)

Designated Planet Priority: A / B, B-, C
Interest / Potential for Contamination: Not / Increasing >>>

OCE: Organic Chemical Evolotion
OOL: Origin of Life

Group / Body of Interest	Consensus Priority	Current Categorization	Proposed Categorization	Justification
Asteroids				
S-Type	A	I	I	Not of interest to OCE & OOL
P, D, C-Types	B	II	II	Of interest to OCE & OOL, but remote contamination concern
Comets	B	II	II	Of interest to OCE & OOL, but remote contamination concern
Io	A	tbd	I	Not of interest to OCE & OOL
Europa	C	III / IV	III / IV	Of interest to OCE & OOL, significant contamination concern
Ganymede	B-	tbd	II*	TBC/Of interest to OCE & OOL, non-zero contamination concern
Callisto	B	tbd	II	Of interest to OCE & OOL, but remote contamination concern
Other Jovian satellites	B	tbd	II	Of interest to OCE & OOL, but remote contamination concern
Titan	B-	tbd	II*	TBC/Of interest to OCE & OOL, non-zero contamination concern
Enceladus	C	tbd	III / IV	Of interest to OCE & OOL, significant contamination concern
Other Saturnian satellites	B	tbd	II	Of interest to OCE & OOL, but remote contamination concern
Uranian satellites	B	tbd	II	Of interest to OCE & OOL, but remote contamination concern
Triton	B-	tbd	II*	TBC/Of interest to OCE & OOL, non-zero contamination concern
Other Neptunian satellites	B	tbd	II	Of interest to OCE & OOL, but remote contamination concern
Pluto-Charon	B-	II	II*	TBC/Of interest to OCE & OOL, non-zero contamination concern
Other KBOs: >1/2 Size of Pluto	B-	II	II*	TBC/Of interest to OCE & OOL, non-zero contamination concern
Other KBOs: ≤ 1/2 Size of Pluto	B	II	II	Of interest to OCE & OOL, but remote contamination concern

* Indicates further data required; all missions except Cat. I need to avoid spacecraft-induced habitats