



## **Report**

### **COSPAR Workshop on Planetary Protection for Titan and Ganymede**

**Caltech, Pasadena**

**9-10 December 2009**

### **COSPAR Panel on Planetary Protection**

***John D. Rummel  
François Raulin  
Pascale Ehrenfreund***

***Editors***

***June 2010***

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COSPAR Workshop on Planetary Protection for Titan and Ganymede

held under the auspices of the

Committee On Space Research (COSPAR)

of the

International Council for Science (ICSU)

at

Caltech, Pasadena

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COSPAR Panel on Planetary Protection

*John D. Rummel*

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COSPAR  
Paris, France  
June 2010

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# COSPAR Workshop on Planetary Protection for Titan and Ganymede

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# **COSPAR Workshop on Planetary Protection for Titan and Ganymede**

## **1. Introduction**

During the deliberations of the **COSPAR Workshop on Planetary Protection for Outer Planet Satellites and Small Solar System Bodies** (Rummel et al., 2009), held in Vienna in April 2009, a number of bodies in the outer Solar System were identified as being potentially in the “II<sup>+</sup>” category consistent with the COSPAR categorization scheme, referring to 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 (see Appendix C). Of these objects, Titan is the highest priority target for a near-term robotic flagship mission and Ganymede is also the subject of flagship mission interest. To address the concerns that were raised in Vienna about the categorization of Titan and Ganymede (as “II<sup>+</sup>”) required another dedicated workshop to concentrate on those two bodies, a meeting was planned and held jointly by NASA, ESA, and COSPAR during the winter of 2009-2010. This workshop included additional experts on Titan and Ganymede who were not able to participate in the Vienna meeting, and allowed the attendees to inspect detailed information about the most recent Cassini-Huygens results as well as the most current interpretation of the data available for both Titan and Ganymede. The goal of this workshop was to resolve the mission category for Titan and Ganymede and to develop a consensus on the II versus II<sup>+</sup> dichotomy, taking into account both the conservative nature of planetary protection policy and the physical constraints on the Titan system and on Ganymede—the two largest moons in our solar system.

This report summarizes the findings and recommendations from the workshop. The document will be distributed to the COSPAR Planetary Protection panel for consideration prior to the next General Assembly meeting in Bremen (Germany) during July 2010. Results from the Titan/Ganymede study will also be coordinated in a larger evaluation of outer planet icy satellites that has been requested from the US National Research Council.

## **2. Summary of the Vienna Workshop on Planetary Protection for Outer Planet Satellites and Small Solar System Bodies**

The results from the Vienna workshop identified Titan as a target of high scientific interest due to extensive evidence of organics, the methane-ethane analogues of Earth’s hydrological cycle, and some evidence of a sub-surface liquid water ocean. Titan’s surface temperatures of 90-97K are too low for the growth and reproduction of terrestrial organisms, so Titan was initially recommended as Category II (versus II<sup>+</sup>) due to the lack of a credible mechanism on a reasonable timescale that could provide a conduit to a watery sub-surface ocean.

Tidal activity appears too low to create near-surface heat sources or drive deep transport processes. In addition, cryo-volcanism appears to be very limited in areal extent (10 km<sup>2</sup>). A key question for forward contamination on Titan (or Ganymede) is whether there is a conduit to a subsurface liquid zone. The presence of some tidal heating on Titan has been discussed—although it is thought to be much smaller than that on Europa—but even so, it may be slightly larger than ongoing radiogenic heating (Sotin et al., 2009). Models for cryo-volcanism that suggest shallow oceans are based on up to ~30% water-ammonia mixtures where the eutectic temperature is 176 K (lowest temperature). Outflow would be at lower temperatures (90-176 K) than required for propagation of terrestrial organisms. Models for cryo-volcanism based on pure water suggest the need for deep oceans, and we cannot envision a credible mechanism to reach a deep ocean on Titan on a reasonable timescale. It was concluded 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. However, the lack of a source of heat for strong convection and a mechanism to transport water into the depths appears at this time to be a fundamental limitation to the propagation of contamination. At the Vienna workshop, a possible new COSPAR Category II<sup>+</sup>, applying to targets that may be relevant to life (implicitly that there may be evidence for habitable zones or environments), was defined with inadequate data to assess the risk of contamination.

At the Vienna workshop it also was noted that the same concerns that apply to the potential contamination of Titan could also apply to other large, icy bodies of the solar system. Ganymede, the Pluto/Charon system, Triton, and Ceres are examples of the types of bodies that may support liquid water environments far beneath their surfaces, yet show little recent surface activity related to its existence. Accordingly, and because of abundant data available from the Voyager and Galileo missions as well as the interest in a flagship mission to the Jovian system, it was determined to examine the potential for contamination of Ganymede in concert with that for Titan.

### **3. Agenda Overview: Plan of Workshop**

The workshop was opened with a summary of the “*Workshop on Planetary Protection for Outer Planet Satellites and Small Solar System Bodies*” held in Vienna in April 2009. Issues that were raised in the Vienna workshop on Titan and Ganymede were introduced to the workshop participants. In order to enable a consensus of the planetary protection requirements for the Titan and Ganymede systems, experts discussed the internal structure of Titan and Ganymede as well as the internal ocean habitability. New results on Titan’s surface processes and composition were presented. Since the goal of the workshop was to resolve the mission category for Titan (and Ganymede) and develop a consensus on the Category II versus II<sup>+</sup>/III dichotomy, several other presentations focused on Titan’s (and Ganymede’s) posited surface-ocean exchange processes as well as the details of heat transfer in the Titan environment.

Future proposed missions to Titan and Ganymede were described, in particular the Titan Saturn System Mission (TSSM) in order to understand the future constraints imposed by planetary protection policies. It was also noted that Titan and Ganymede could be targets for upcoming Discovery and New Frontiers missions solicited by NASA. Planetary protection considerations for the end of the Cassini-Huygens mission, as well as the Juno mission, were discussed as examples for the implementation of planetary protection requirements on future Titan/Ganymede missions.

An example calculation of contamination risk has been performed that provided an estimate of the number of organisms that will survive on Titan and Ganymede based on the initial contamination level and various survival factors. It was determined that the probability of contaminating a habitable environment on Titan or Ganymede needs to be less than  $1 \times 10^{-4}$ , which may require some control of the number of organisms originally launched from Earth. Potential future studies about the need for controlling possible chemical contamination of Titan's surface, in particular the lakes, were evaluated. A systematic catalog of possible imported chemicals, including the order of magnitude of their flux/ concentration/total imported mass needs to be elaborated. Finally a COSPAR policy update was discussed.

## 4. Overview of Presentations

### Titan and Ganymede Science

#### 1) Olivier Grasset: *Focus on Ganymede issues raised at the Vienna Workshop*

Facts: As stated in the report on the *COSPAR Workshop on Planetary Protection for Outer Planet Satellites and Small Solar System Bodies* (August 2009), Ganymede's surface displays dark and bright terrains with different characteristics and origins. *"The ancient dark terrain contains tectonic furrows probably related to ancient large impacts, and has been tectonized to various degrees. 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 cryo-volcanism 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 possesses a very thick hydrosphere from the surface down to at least 600 km depth. Galileo data indicate that a liquid layer is most certainly present below a thick (roughly 100 km) icy crust. Based on the characteristics of the phase diagram of pure water, and the pressure and temperature range relevant for the hydrosphere, the liquid layer is necessarily above a thick icy layer of high pressure ices which is several hundreds of kilometers thick. This icy layer, which is also suggested to be present on Callisto and Titan, may be an efficient barrier to prevent exchanges between the hydrothermal products possibly produced on the silicate floor and the habitable zone.

At the Vienna Workshop, a II+ categorization was decided for Ganymede mostly because of the existence of a liquid layer and the fact that the surface was not extremely old everywhere (as indicated by the presence of bright terrains). Thus, it has been decided that further studies are necessary to assess the possibility, the timescale, and the mechanisms of transport of any organism from the surface to the liquid layer.

**Mechanisms and timescale of transport:** In this section, a very preliminary estimate of the time required for any material to go from the surface to the liquid layer is proposed. Bland et al. (2009) have shown that Ganymede may have undergone several passages through a Laplace-like resonance causing tidal heating that was dissipated in the ice shell and silicate mantle. Dissipation in the ice shell lead to thermal runaway and melting, ultimately causing extensive resurfacing.

Nonetheless, the youngest surfaces of Ganymede are older than 200 million years and the thickness of the icy layer at the top is now more than 50 km (diffusive cooling alone would produce such a crust). If there is no convection within this shell, then the time required for diffusion from the top to the bottom scales is several billion years and there is, therefore, no risk of contamination of the liquid layer. The problem becomes more complex if convective motions are assumed, which seems very probable (Deschamps and Sotin, 2001; Spohn and Schubert, 2003; Bland et al., 2009). On one side, convective motions imply an important thickening of the icy crust because the cooling of the planet is much more efficient. That is why the current estimate of the icy layer is closer to 150 – 200 km than several tens of kilometers. But on the other hand, the transport mechanisms of organisms through the layer are strongly enhanced because they can be transported with the ice along the downwellings. A convective layer, similar to the one that should exist on Ganymede can be divided into three parts from top to bottom (see Figure 1):

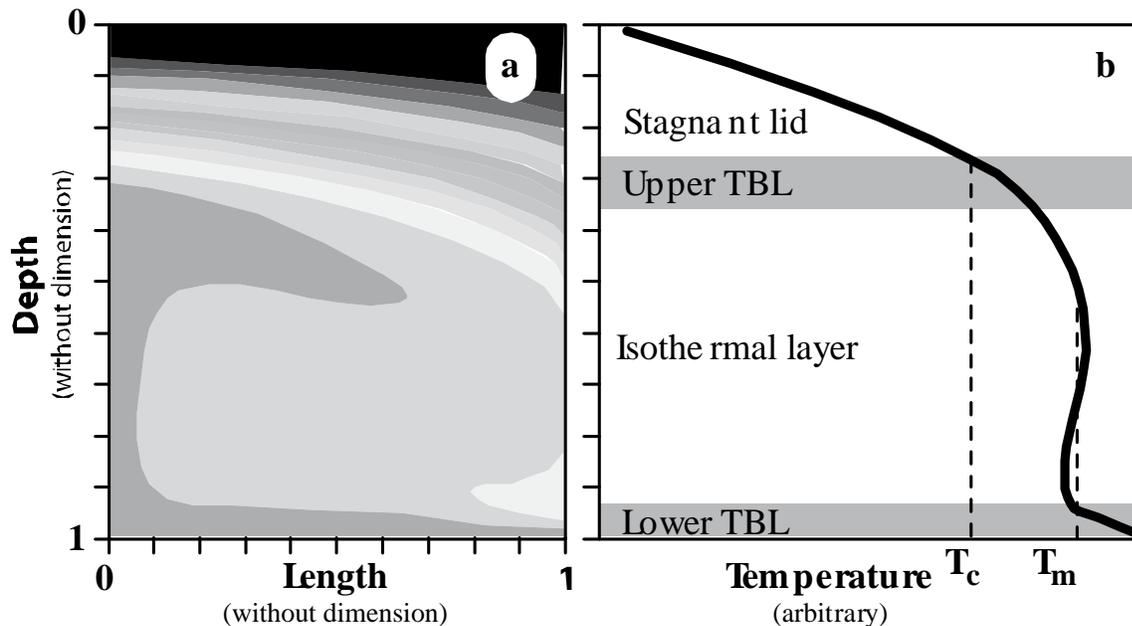
- a cold thermal boundary layer (TBL),
- a convective shell, and
- a hot TBL

The temperature variations are located in TBL's while the convective layer is almost isothermal. The thickness of the TBL's is several kilometers, and depends on the vigor of convection. Finally, it must be noted that the upper TBL is always purely diffusive (Moresi and Solomatov, 1995; Grasset and Parmentier, 1998). It should be noted that the the upper TBL is overlaid by a stagnant lid where heat is transferred only by conduction (Moresi and Solomatove, 1995). If the time required for crossing the TBL's is neglected, it is the convecting process which drives the timescale of exchange processes. Models of convection within the icy shell predict that velocities within the convective zone may be as high as 1 m/year, which means that at least 100 000 years are needed to reach the lower TBL. This 100 000 years estimate can be understood as the lowest time required for exchanging material through the first layer of Ganymede. First of all, 1 m/year is the highest velocity that can be envisaged.

Second, since the upper TBL is purely diffusive, and is overlain by a stagnant lid, the time necessary to cross it may be huge, except if an organism goes into a crack which entirely crosses the TBL. Consequently the probability is very low that an organism will get across.

Similarly, an organism trapped in a downwelling will not easily cross the lower TBL and reach the ocean because the lower TBL is an efficient barrier which generates the upper buoyancy. In general, particles or organisms driven downwards within the cold plume move horizontally along the lower TBL and are slowly heated until a hot rising plume forms and drives them upwards for a new cycle. The only possibility which may allow exchanges through the lower TBL is the erosion of the icy layer (global melting of the planet) or downward migration of the particles due to gravity contrasts. The first assumption occurred in the past (Bland et al., 2009) but the age of the youngest surface and the stability of the Laplace resonance indicate that this has not been the case for at least 200 million years.

A second possibility related to downward migration is not realistic, either, because the timescale required for diffusing the particles through the TBL is much larger than the residence time scale in the TBL along the convective current.

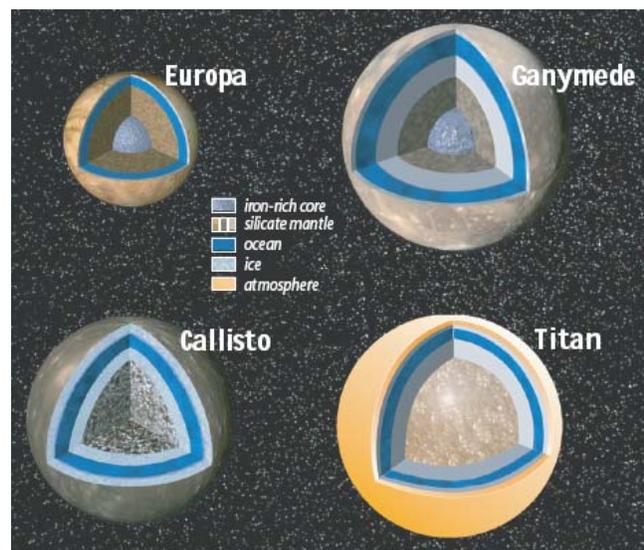


**Figure 1.** a) Convective patterns within an icy shell. Upwelling (left) and downwelling (right) through which material can be transported efficiently are clearly visible. b) Layering of the icy shell into two thermal boundary layers (TBL) with thermal variations and an isothermal convective zone.

## 2) Christophe Sotin & Olivier Grasset: Internal structure of Titan and Ganymede

As long as we don't have the necessary observations, models of the interior structure of planets and moons are based on mathematical solutions of differential equations describing processes suspected to operate, physical information coming from observations and laboratory experiments, and interpretation of geological features. Two main topics were addressed in this presentation:

- What are the evidences for the presence of a deep ocean?
- What are the processes involved in the exchange of heat and material between the interior and the surface?



**Figure 2.** Internal structure of outer solar system Moons

In the case of Ganymede, the Galileo mission detected an intrinsic magnetic field, measured an induced magnetic field, and determined two gravity coefficients which suggest a very high degree of differentiation. Ganymede is believed to be composed of five layers: an inner core made of liquid iron (in order to generate the intrinsic magnetic field), a silicate shell, a high-pressure ice layer, an ocean, and an ice crust. The size of impact craters suggests that the ice crust is several tens of kilometers thick.

Numerical models describing heat transfer through the ice crust predict that heat is transferred by convection with hot icy plumes forming at the ocean-crust interface and cold ice plumes sinking into the crust from the bottom of a conductive lid. The ice crust is subdivided into four layers: the upper conductive, stagnant, lid where heat is transferred by conduction, the cold thermal boundary layer (TBL), the well-mixed interior and the hot thermal boundary layer just above the crust/ice interface.

The velocity of the plumes depends on the viscosity of the ice. We have investigated the time it takes for a plume to travel between the two TBLs. Laboratory experiments suggest that the viscosity of ice at conditions relevant to Ganymede's ice crust is on the order of  $10^{14}$  Pa·s at the melting point. The viscosity is very strongly temperature dependent (activation energy on the order of 50 kJ/mol). For hot plumes, the vertical component of the velocity is on the order of 10 cm/year to 1 m/year. It therefore takes about 100,000 years for a hot plume forming at the bottom TBL to reach the base of the conductive lid.

As the plume gets closer to the surface, adiabatic decompression may lead to cryo-volcanism and differentiation, but this process is still badly constrained and no geological observations on Ganymede's surface support the presence of such a process. For cold plumes forming at the cold thermal boundary layer, the lower temperature makes their viscosity about one order of magnitude larger and their velocity about one order of magnitude smaller. Although additional simulations are needed, this leads to a timescale of about 500,000 years (for a cold plume forming at the cold TBL) to reach the crust/ice interface. Moreover, the hot thermal boundary layer acts as a barrier and particles present in the cold plume would not reach the ocean. Models predict that material contained in the cold plumes would not be transferred to the ocean.

For Titan, the Cassini/Huygens mission has revealed a very active world with rivers, lakes, dunes, impact craters, mountains and cryo-volcanic flows. To date, there is no evidence of present-day cryo-volcanic activity although the surface is geologically young. The interior structure is more difficult to constrain because the presence of a large atmosphere does not allow the Cassini spacecraft to get closer than 1,000 km from Titan's surface. Gravity and magnetic fields have intensities which vary inversely with the square and the cube of the distance, respectively. First results of the gravity field, as determined by Cassini radio tracking (less et al., 2010), suggest that Titan is less differentiated than Ganymede. The signals caused by the presence of an ocean are weak. The Cassini teams are trying to get the best configurations to measure those signals. Future flybys have been specially designed for these investigations during the Cassini Solstice Mission which has been approved in spring 2010 by NASA. Indirect evidence of the presence of an ocean is being discussed. A determination of Titan's rotational state by matching geological features in radar images suggested that Titan has an obliquity of 0.3 deg and a non-synchronous rotation (Bills and Nimmo, 2008; Stiles et al., 2008, 2010; Lorenz et al., 2008a).

The non-synchronous rotation could be explained by the presence of an ocean which would decouple the ice crust from the high-pressure ice layer. Nonetheless, a recent study examined the question and confirms the obliquity but challenges the non-synchronous rotation (Goldreich and Mitchell, 2010). Second, the measurement of a horizontal component of the electric field during the Huygens descent suggests that an electrically conductive layer is present at 45 km depth (Béghin et al., 2010). This layer could be the ocean since the ice is not conductive. Finally, models of Titan's evolution and interior dynamics suggest the presence of an ammonia-rich ocean below the ice crust.

Models describing the dynamics of the ice crust suggest that there is differentiation and transfer of molecules from the interior to the surface and atmosphere (e.g., CH<sub>4</sub> and <sup>40</sup>Ar). But no model predicts exchanges between the surface and atmosphere and the interior; there is no evidence of any plate tectonic features supporting that. Furthermore, simulations suggest that cold plumes behave as they do for Ganymede and that no particle trapped into those plumes would migrate to the ocean.

### **3) Olga Prieto-Ballesteros: *Habitability of Titan's and Ganymede's internal oceans***

Habitability is a broadly defined term in Astrobiology (Lammer et al., 2009). It is generally defined as the measure of a planet's or a natural satellite's potential to develop and sustain life. Based on the life that we know on our planet, habitability has three main requirements: liquid water, chemical building blocks and energy. Considering the evidence of internal oceans in the interiors of Titan and Ganymede, there is clearly a need to assess their habitability. The necessity of liquid water has been invoked because of its function as a good solvent, a medium of transportation or its important role in metabolic reactions. Some authors have proposed other solution chemistry for achieving the same role (such as ammonia or methanol) but none of these liquids has the characteristics which favor biology as well as water does.

From the geophysical evidences we have thus far, it may be assumed that the oceans of Ganymede and Titan are sandwiched between thick ice crusts—dense, high-pressure water ice below and "normal" buoyant water ice above. These ices are important barriers for habitability because they stop the release of energy sources and chemicals to the liquid oceans. For instance, although Ganymede's surface oxidants are produced by solar wind particles directed by Jupiter's magnetic field today, moving these oxidants efficiently into the interior through a thick ice shell is not probable. On Titan's surface, all major essential ingredients for life (CHNOPS) are probably present, but geophysical models suggest it is unlikely that surface materials can reach the ocean through the crust today. In addition, the extremely low temperature and composition of the Titan's ammonia-rich aqueous layer would pose problems for supporting life as we know it, although Fortes (2000) discusses organism survival under such conditions.

*Titan and Ganymede are probably not habitable at present.* Although cryo-volcanism may cycle materials between potential internal habitable environments and the surface, recent work suggests this activity is not possible in the current era. However, vigorous convective transport on either satellite in the past cannot be ruled out. During some stages of the evolution of these icy satellites, liquid water could have been present as well as different geophysical and chemical conditions, and materials from the interior could have been linked with the surface.

### **4) Steve Vance: *Titan and Ganymede: Internal ocean habitability***

In contrast to the very deep "perched" oceans in Ganymede and Titan, Europa's ocean is in direct contact with the moon's rocky seafloor. Accordingly, Europa's ocean is far more likely to have fostered an independent origin of life and even to sustain life today.

Though a high-energy spacecraft impact to any of these moons has only a slight chance of depositing contaminants into an internal ocean, the risk at Europa is greater because the active icy lithosphere has a greater likelihood of cycling material into the interior. These concerns merit COSPAR/NASA planetary protection categorization for Europa of III/IV, particularly with respect to criterion “F7”—the probability that microbes will survive transit from the planetary surface, reach the ocean, and proliferate there—as discussed at the meeting. Nonetheless, limits to transport of subsurface reductants and surface oxidants into oceans of Ganymede and Callisto constitute strong protection from contamination with known Earth organisms. All other factors being equal, these considerations argue for class II categorization for Titan and Ganymede.

Oxidized materials are produced on Ganymede’s surface by the same mechanisms that occur on Europa’s, but a less active surface lowers the likelihood that such materials will cycle downward into the moon’s ocean. Arguments for the habitability of an ocean within Titan are also hampered for this reason. In addition the only obvious mechanism for oxidation on Titan is photolytic polymerization of Titan’s atmospheric alkanes, which has not been demonstrated as having any biological use. Nevertheless, clathrate dissociation and fluid alkane infiltration into the subsurface present possible mechanisms for cycling materials between the moon’s surface and its convecting ice shell. Lastly, while Titan’s ~92-94K surface precludes the growth and replication of Earth organisms, it does provide a potential means for preserving organisms transported there by a spacecraft.

The rocky interiors of Titan and Ganymede are the hottest among icy satellites if long-lived radiogenic heating alone is considered. This heat increases the likelihood that the interiors of Titan and Ganymede underwent volcanic activity, generating reduced compounds such as hydrogen and methane. However, more than 100 km of high-pressure ices probably serve as an effective barrier to prevent transport of reductants into an overlying ocean, and may inhibit the occurrence of liquids underneath. Also, production of reduced material may be limited by extreme pressures at the water rock interfaces on these moons, which deter extensive fluid rock interactions by promoting closure of fractures.

##### ***5) Dennis Matson & Torrence Johnson: Cryo-volcanism on Titan and implications for planetary protection***

Titan's surface temperature is about 90 K. This is far too cold for the processes needed for life. The key issues for Titan planetary protection are whether warmer environments exist and whether material deposited on the surface could be transported to these environments. Cryo-volcanic deposits on Titan's surface are conjectured to be such environments. Cryo-volcanism is a process analogous to volcanism in which the magma is cold, well below the freezing point of pure water (e.g., aqueous solutions of ammonia, methane, salts, etc.).

Here, we use as our definition of volcanism, “the manifestation at the surface of a planet or satellite of internal thermal processes through the emission at the surface of solid, liquid or gaseous products” (Francis, 1993). On Titan, internal heating (e.g., radiogenic and tidal) may succeed in generating a “cryo-magma” which erupts on the surface as a “cryo-lava” at temperatures that are much lower than those of mafic silicate lavas that commonly erupt on Earth and Io (Davies et al., 2010).

With regard to Titan, the conjecture is twofold: 1) that the magma or liquid lava could be a habitat conducive to life processes, and 2) cryo-volcanic deposits exist on the surface of Titan. In the first case it is impossible to fully assess the habitat possibilities because the chemical properties of the putative magma or lava are unknown. In the second case, the existence of cryo-volcanic features on the surface is problematic, being much discussed but yet unproven. Some of the arguments for such deposits will now be discussed.

The discovery of  $^{40}\text{Ar}$  in Titan's atmosphere is proof that some form of communication occurs between the interior and the surface.  $^{40}\text{Ar}$  is produced by the decay of  $^{40}\text{K}$ . Potassium minerals are in Titan's core and dissolved in its internal ocean. The communication process is probably some form of very slow seepage that may also allow methane to escape from the interior. There is no expectation that the emerging gases would be at a temperature other than the local ambient surface temperature (i.e., about 90 K).

We should note that there are very few impact craters on Titan, perhaps one to two dozen good examples. From these it has been inferred that the surface is about half a billion years old, (Artemieva and Lunine, 2003, 2005; Le Mouelic et al., 2008; Lorenz et al., 2007), not too different from the average ages of the Earth and Venus. This means that resurfacing has been a major process for Titan's surface. Burial and/or erosion are the processes that have removed the many craters that would otherwise saturate the surface. Such resurfacing may involve reworking of the surface through erosion by wind action, other weather phenomena (e.g., rain), deposition in hydrocarbon lakes and channels, erosion of channels, and impact cratering. Tectonic disruption of the surface may also render craters undetectable.

Endogenic geological and geophysical processes have created hydrocarbon lakes (Stofan et al., 2007; Turtle et al., 2009) and mountains (Barnes et al., 2007). Meteorologically, mass transport by winds causes erosion and has created extensive dune fields (Lancaster, 2006; Lorenz and Radebaugh, 2009; Lorenz et al., 2006a; Radebaugh et al., 2008; Tokano, 2008). There is a complex global hydrological circulation system (e.g., Mingalev et al., 2006), and seasonal climate variability. Methane rains (Karkoschka and Tomasko, 2009; Lorenz et al., 2008b; Toon et al., 1988) carve channels and fill lakes (Lorenz et al., 2008c; Stofan et al., 2007, Davies et al., 2010).

Whereas resurfacing is conjectured to occur endogenically on Titan via some manifestation of either hydrocarbon-based hydrogeology or hydrology, tectonics, or cryo-volcanism (where a low-temperature lava is erupted), the actual emplacement of such a “cryo-lava” has never been observed, and is therefore poorly understood. Thus, while cryo-volcanic flows are candidates for the burial process, specific correlative evidence is lacking.

Immediately upon arrival, Huygens discovered uplands deeply incised by fluvial networks. It was possible that such uplands could be built up rapidly by vast cryo-lava flows. However, vast mountain chains were later discovered and tectonic explanations are currently believed to be better explanations of the uplands. On the basis of early data several surface features were suggested as candidate cryo-volcanic structures. However, radar altimetry showed the strongest candidate among these features to be a depression. There are few, if any, topographic features that appear to be likely candidates for large volcanic constructs. As for erosion, there is abundant evidence for aeolian processes as well as the fluvial processes mentioned earlier. Some of the material in the great equatorial seas of sand dunes may result from erosion of topography. At present there is no consensus among the experts about the efficacy of this type of erosion.

Other features that may indicate cryo-volcanic flow are the lobate and fan-shaped features seen in radar images. Unfortunately, in many cases it is difficult to unambiguously distinguish volcanic origins for these from fluvial deposits. The case for ongoing volcanic activity on Titan is best made by citing tentative identifications of possible cryo-volcanic features in *Cassini* Radar data (such as a circular structure named Ganesa Macula that was interpreted as a possible cryo-volcanic dome (Lopes et al., 2007); diffuse, flow-like features in the same region that may be cryo-volcanic; and flows with discrete margins that emanate from structures that are caldera-like) and the occurrence of some photometric variability seen in data from the *Cassini* Visible-Infrared Mapping Spectrometer (VIMS; Nelson et al., 2009a; Nelson et al., 2009b).

These features are described in detail, and previous analyses summarized by Jaumann et al. (2009). Other data obtained by VIMS (Barnes et al., 2006; Barnes et al., 2007) and, more recently, by the *Cassini* Radar (Wall et al., 2009) indicate that sites at Hotei Arcus and in western Xanadu are distinctively different from other landforms and areas on Titan. Cryo-volcanic activity is one possible explanation. A joint analysis of both VIMS and Radar data suggests that Hotei Regio is a basin filled with cryo-volcanic flows, and some features have been tentatively identified as calderas (Soderblom et al., 2009). Apparent albedo changes have been reported by VIMS in these two locations.

It has been suggested that these brightenings may be due to the deposition of surface frosts, or similar coatings, or possibly low-lying fog (Nelson et al., 2009a; Nelson et al., 2009b), but Soderblom et al. (2009) offer the explanation that the brightening effect at Hotei Regio was a function of emission angle and does not necessarily require a surface or near-surface brightness change.

This matter has not been resolved and what is going on remains uncertain. Interestingly, the radar signature of these two areas is also anomalous, and on that basis, lava flows have been suggested (Wall et al., 2009). However, the radar data are sensitive only to the morphology and do not indicate when the suggested units may have been emplaced. Thus, the two types of circumstantial evidence are not able to fully confirm each other and the exact nature of this mystery remains to be elucidated.

Lava flows are of interest for planetary protection studies because of the elevated temperatures they offer when they are active. The flow of hypothetical cryo-lavas on the surface of Titan has been studied by Davies et al. (2010). They found that the cooling of a lava flow was chiefly by convection. Wind was a particularly effective cooling agent. Once a cryo-lava begins flowing on the surface it very quickly (within a few minutes) develops an outer shell that acts like a cocoon and seals off the liquid lava from communication with the exterior except for the outward diffusion of heat and the escape of any pressurized gases that might evolve. The thickness of the cocoon shell continues to grow as long as any liquid remains inside. While the temperatures inside the cocoon may be significantly higher than 90 K, they are well protected and not easily reached by invasive bio-contaminants. Within a few hours to a few days, depending upon the particulars of the situation, the lava has all frozen and the opportunity of finding higher temperatures has passed. For more information the reader is referred to the recently published book on Titan (Brown et al., 2009) which summarizes the current state of knowledge.

#### **6) Robert T. Pappalardo: Titan (and Ganymede) surface-ocean exchange**

To understand the probability that a subsurface ocean at Titan or Ganymede might be contaminated by organisms brought to the surface of either satellite from Earth, it is important to consider the geological processes that might be capable of transporting materials from the surface through the ice shell and into the ocean. Potential surface-ocean exchange processes have been previously considered for Europa, but to date they have been little considered for Titan or Ganymede.

At Europa, some researchers argue that the ice shell is very thin (just several kilometers thick) and might crack fully through to liquid water, and that it could completely melt through in places (e.g., Greenberg et al., 2000). Such processes would allow for direct contact between the surface and the subsurface global ocean, potentially on a rapid time scale.

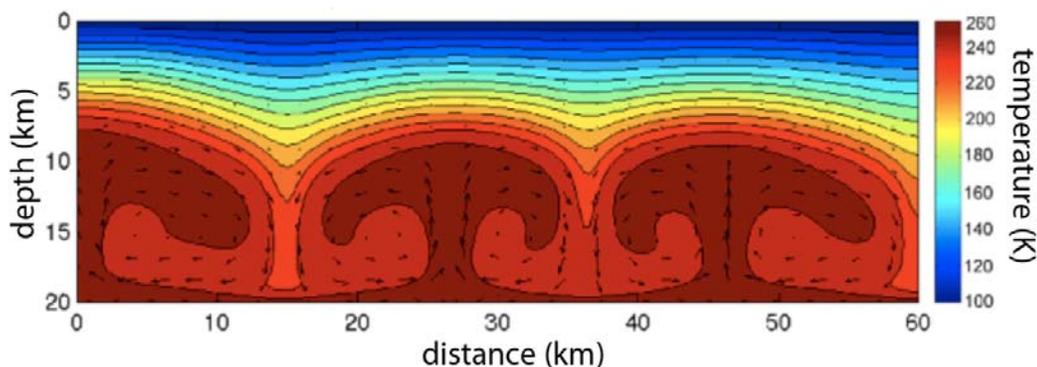
Other researchers argue that Europa's ice shell is thicker (~15–30 km thick, or more), precluding melt-through or separation of cracks all the way to the ocean (see Greeley et al., 2004, and references within), but permitting indirect exchange between the surface and ocean via solid-state convection of warm ice (Pappalardo and Barr, 2004).

A principal issue in material exchange between the surface and ocean in a convective model is that icy satellite convection should occur between a “stagnant lid.”

The stagnant lid is a relatively cold and stiff conductive layer atop the warmer convective icy interior (Figure 3). This layer would impede the rise of warm ice within the convective zone, and would prevent cold near-surface ice from sinking down toward the ocean. At Europa, it is hypothesized that concentrated tidal heating in rising diapirs and/or compositional gradients could allow convective upwellings to rise through the stagnant lid to the surface; moreover, any near-surface melt (such as produced along ridges, or induced by impinging warm diapirs) would drain downward through the ice shell and into the ocean, at the rapid rate of  $\sim 10\text{--}100$  m/yr (Barr et al., 2002; Pappalardo and Barr, 2004).

The probable oceans of Titan and Ganymede are likely to be  $\sim 50\text{--}150$  km below the surfaces of these satellites (Spohn and Schubert, 2003; Mitri et al., 2010). Such thick ice shells preclude melting or cracking as a means of direct exchange between the surface ice and a subsurface ocean. On the other hand, thicker ice layers are more likely to convect, and the icy shells of Titan and Ganymede may be undergoing stagnant lid convection today, depending on the uncertain parameter of ice grain size (McKinnon, 2006).

Other important factors affecting the likelihood of convection for Titan are the composition of its icy shell and the composition (and thus the temperature) of its ocean (Sohl et al., 2003). Some theoretical models predict that Titan might not convect today (Mitri et al., 2010). Indeed, the global shape of Titan suggests that, instead, its ice shell is conductive today (Nimmo and Bills, 2010).



**Figure 3.** Simulation of convection within Europa’s ice shell, assuming a simple (Newtonian) ice viscosity. A cold “stagnant lid” exists in the upper ice shell, above a warm convecting region. Superimposed velocity arrows illustrate convective motions of up to 1 cm/yr (Barr et al., 2002). Analogous convection may be occurring beneath a stagnant lid within the thicker ice shells of Titan and Ganymede, where the stagnant lid may provide a barrier to material exchange between the surface and ocean.

If Titan or Ganymede has a conductive ice shell today, then it is difficult to envision plausible processes that could transport material from the surface to subsurface oceans that reside beneath  $\geq 50$  km of ice. If cryo-volcanism occurs at Titan (Lopes et al., 2007), then it might be possible that melts generated from this process could rapidly drain downward to the ocean. It is plausible to imagine a very thick pile of cryo-volcanic material burying material once at the surface such that it then resides deep in the interior, but a kilometer or two deep seems a viable limit to a cryo-volcanic deposit thickness in such a scenario, which would transport surface material to only a similar depth. In fact, some recent work questions the very existence of cryo-volcanism at Titan (Moore and Pappalardo, 2010).

If the ice shells of Titan and Ganymede are convecting, then the issue is whether the convective surface materials can move down through the relatively thick stagnant lid and into the underlying convective zone, where it can then be carried to the ocean in  $\sim 10^5$  yr. Some models predict the stagnant lid could be more than half the thickness of the ice shell (Sohl et al., 2003). There is no clear geological evidence that the stagnant lid is breached by upwelling convective plumes in the geologically recent past similar to those inferred at Europa.

If cryo-volcanism occurs at Titan, then, analogous to the discussion above, melt might percolate downward through the stagnant lid in such warm active regions—but such regions, if they exist, are expected to be really small. This suggests that if the interior ice layers of Titan or Ganymede are convecting, they are isolated beneath the thick stagnant lid today, except plausibly for very small surface patches.

### **7) Ralph Lorenz: Heat transfer in the Titan environment**

This presentation reviewed some of the interactions between the Huygens probe and the Titan surface environment. It was noted that the thick, cold Titan atmosphere is a powerful heat sink that quenches surfaces to close to the 94K ambient temperature: to maintain internal heat, the Huygens probe was equipped with a 5cm thick foam insulation layer beneath its outer shell. During the mission, the battery-powered probe dissipated some 250 W of electrical power as heat; during descent, the rush of cold air past (and through) the probe removed 600W, so the probe cooled slowly (Lorenz, 2006). On the surface, the much weaker free convective heat transfer (and conduction into the ground) removed only about 350W, so the net rate of cooling was quite modest. The outer shell was likely within a few K of the ambient temperature.

One area which was more strongly heated locally was the inlet of the gas-chromatograph/mass-spectrometer (GC/MS) instrument. The 5W heater (some cm of pipework away from the actual inlet, which was driven a few cm into the soft ground at impact) was monitored, and the rate of temperature rise post-impact suggests that something effectively wicked heat away from the inlet—likely methane moisture in the ground (much as a finger ‘feels’ colder in damp sand at the beach than in dry sand). Although the heater rose to some 350K, models suggest the inlet and the Titan surface material in contact with it rose to only about 140K (Lorenz et al., 2006b).

Nevertheless, this was warm enough to sweat out several compounds which were detected by the GC/MS—methane, ethane, cyanogen, and likely also carbon dioxide and benzene (Niemann et al., 2005).

Another area of local heating was the patch of ground illuminated by the 20W surface science lamp of the descent imager/spectral radiometer (DISR) instrument. This patch of ground received a flux density several orders of magnitude stronger than ambient sunlight, and it appears some methane was sweated out of the ground. This is evidenced by a transient feature (quite distinct from a number of cosmic ray hits identified in the post-landing images) which is best-matched by a 4mm dewdrop (Karkoschka and Tomasko 2008) falling at 0.5 m/s about 9cm in front of the imager. The statistics of the detection of one drop out of 63 images suggests 0.5-50 drops/min—the middle of this range would imply about 3% of the methane that could have been sweated out of the ground by the available lamp energy condensed on the cold camera baffle.

These 'real world' interactions suggest that the thick, cold Titan atmosphere should be much more effective than radiation alone in cooling surfaces (e.g., radioisotope systems). Free convective heat transfer coefficients of 3-10 W/m<sup>2</sup>/K are indicated—the ~500 W/m<sup>2</sup> power density of Advanced Stirling Radioisotope Generator (ASRG) radiators will likely be kept to surface temperatures of 200K or less. In a liquid hydrocarbon environment on Titan (such as one of the northern lakes or seas) experiments on boiling rates of liquefied natural gas suggest heat transfer rates of 20-90 kW/m<sup>2</sup>—such liquids would therefore keep even the surfaces of radioisotope power sources at temperatures well below those needed for life.

It was further noted that the low gravity and the dense atmosphere leads to low terminal velocities in the Titan environment. Thus, a crashing spacecraft will have a relatively modest kinetic energy—and would not cause hypervelocity impact melting, nor would it be able to punch through a layer of ice more than a meter or two thick. To put matters in context, the terminal velocity of a VW Beetle (1000kg, 6m<sup>2</sup>) is 350 and 50 m/s on Mars and Earth, respectively, but only 10 m/s on Titan.

### **8) *Athena Coustenis & Jonathan Lunine: Future exploration of Titan and the Saturnian System beyond Cassini-Huygens***

The Titan Saturn System Mission (TSSM) builds upon the ESA Cosmic Vision proposal TandEM and the NASA 2007 Flagship Titan Explorer study. As such, it greatly benefited from several years of past studies of future Titan missions at NASA and the experience gained with the Cassini-Huygens mission both for orbital and *in situ* exploration.

The Cassini-Huygens mission is revealing the Earth-like world of Saturn's moon Titan and it discovered current geophysical activity potentially involving liquid water on another moon of Saturn, Enceladus. Titan, a complex, Earth-like moon with organics, shares features with both other large icy satellites and the terrestrial planets.

Indeed, Cassini revealed that Titan has the largest known abundance of organic material in the solar system aside from Earth, and Titan's active hydrological cycle is analogous to that of Earth, but with methane replacing water. Titan's clouds, rain, flash floods, and greenhouse and anti-greenhouse effects may provide important analogs for Earth's long-term climate evolution. Albeit with dramatically different components, Titan's landscape appears remarkably Earth-like, featuring dunes, liquid-carved channels, and mountain ridges, as well as polar lakes filled with liquid hydrocarbons. Also like Earth, Titan's dearth of impact craters demonstrates that its surface is young and geologically active. In addition to pervasive aeolian and fluvial erosion, it is likely that cryo-volcanism exists where liquid water, perhaps in concert with ammonia and carbon dioxide, makes its way to the surface from the interior.

Titan is also subject to tidal stresses which may have helped to shape its mountains, although, as on Earth, erosion complicates the interpretation of tectonic structures. Titan's dense atmosphere is mostly nitrogen—like Earth's—with methane as its second major constituent, and it includes other hydrocarbons and nitriles.

Titan's complex atmosphere varies seasonally in temperature, dynamical behavior, and composition, including a winter polar structure analogous to Earth's ozone hole. Finally, although Titan is similar to Earth in many ways, its atmosphere is unique in the solar system—experiencing strong dynamical forcing by gravitational tides generated by Saturn (a trait Titan may share with many extrasolar planets). Enceladus, a small satellite close to its planet, produces a localized atmosphere of water vapor through plumes, rich in organics, emerging near its south pole.

There are several mission concepts currently addressing the above issues, exploring Titan's atmosphere, surface and interior. An extensive mission to Titan, as well as to Enceladus, TSSM, was studied in 2008 and prioritized second for a launch around 2023-2025 by the space agencies. It consists of an orbiter that would carry two in situ elements: the Titan montgolfière hot-air balloon and the Titan Lake Lander (Coustenis et al., 2009).

The TSSM Science Goals responded directly to NASA's science objectives, ESA's Cosmic Vision themes, and science questions raised by the extraordinary Cassini-Huygens discoveries. In particular, TSSM science would embrace geology, meteorology, chemistry, astrobiology, comparative planetology, dynamics, geophysics, space physics, hydrology, and a host of other disciplines, engaging a wider community than for virtually any other target in the outer solar system.

The mission would arrive at Saturn around 2032-2034 for a ~4-year mission. Soon after arrival at Saturn, the montgolfière would be delivered and deployed in Titan's atmosphere for a mission of airborne, scientific observations of Titan from an altitude of about 10 km. The montgolfière would have a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) power system designed for a 6-12 months mission in Titan's atmosphere. With the predicted winds and weather, this system would be sufficient to circumnavigate the globe at least once.

In addition to other measurements, valuable information on the troposphere of Titan would be gathered by the balloon. The Titan Lake Lander would descend through the atmosphere, making measurements of the atmospheric properties, much like Huygens did, then land and float on one of Titan's seas.

After delivery of the in situ elements, the TSSM Orbiter would explore the Saturn system via a ~2-year tour that includes in situ sampling of Enceladus' plumes as well as Titan flybys. After the Saturn system tour, the TSSM Orbiter would enter orbit around Titan and begin a global survey phase. Synergistic and coordinated observations would be carried out between the TSSM Orbiter and the in situ elements.

Recent discoveries of the complex interactions of Titan's atmosphere with the surface, interior, and space environment demand focused and enduring observation on a range of temporal and spatial scales. A ~20-months mission in orbit around Titan, complemented by in situ exploration would be able to monitor dynamic conditions in the ionosphere where complex organic chemistry begins, observe seasonal changes in the atmosphere, and make global near-infrared and radar altimetric maps of the surface. This study of Titan from orbit and in situ with conceptually new and technologically enhanced instruments would provide the potential for an increase in Titan science return by 2–3 *orders-of-magnitude* over that of the Cassini mission.

Chemical processes, which operate in Titan's upper atmosphere, can be extensively sampled by a spacecraft in Titan orbit down to about 600 km. However, there is a substantial additional benefit to extending the measurements into Titan's lower atmosphere and down to the surface. Key steps toward the synthesis of prebiotic molecules that may have been present on the early Earth as precursors to life may be taking place high in the atmosphere, with products falling down and possibly replicating the conditions of early Earth on Titan's surface. *In situ* chemical analysis, both in the atmosphere and on the surface, would enable assessment of the kinds of chemical species that are present in the lower atmosphere and on the surface, and how far such putative reactions have advanced. Titan's thick atmosphere and low gravity make the deployment of *in situ* elements using parachutes vastly easier than for other large solar system bodies, as we proved with the Huygens probe. The rich inventory of complex organic molecules that are known or suspected to be present in the low atmosphere or at the surface gives Titan a strong astrobiological potential. *In situ* elements would also enable powerful techniques such as subsurface sounding and seismic techniques, to be applied to exploring Titan's crustal structure. Our understanding of the forces that shape Titan's diverse landscape will benefit greatly from detailed investigations at a range of locations, a demanding requirement anywhere else, but one that is uniquely possible at Titan: a Montgolfière hot-air balloon can circumnavigate Titan carried by winds, exploring with high-resolution cameras and subsurface-probing radar. Such a combination of orbiting and *in situ* elements would provide a powerful and, for Titan, unprecedented opportunity for synergistic investigations—synthesis of data from these carefully selected instrumentation suites is the pathway to understanding this profoundly complex body.

On the way to Titan and once in orbit around Saturn, opportunities exist to significantly extend our understanding of Saturn's magnetosphere and its influence on Titan. Furthermore, the tour through the Saturn system will take the proposed orbiter through the plumes of Enceladus, allowing the spacecraft to take samples and to analyze them using instrumentation not currently available on the Cassini spacecraft. These investigations would not only inform us about these fascinating components of the Saturn system, but help us address important questions about Titan as well.

**9) Catharine Conley: *Planetary protection considerations for the end of the Cassini-Huygens mission***

Establishing planetary protection requirements for missions investigating locations about which little previous knowledge is available presents interesting challenges for both regulators and practitioners.

The first flagship mission to Jupiter, Galileo, was assigned planetary protection Category II; however, this categorization contained the caveat that, should data be obtained suggesting an object in the Jovian system might merit protection at a level more stringent than Category II, then the project must negotiate with the NASA Planetary Protection Officer regarding how the mission would comply with those more stringent requirements. Having returned data that suggested strongly the presence of a subsurface water ocean on Europa, the Galileo project was given the option to dispose of the spacecraft onto Io, or into Jupiter, at the recommendation of the US National Research Council's Space Studies Board (SSB). Upon its descent into the Jovian atmosphere, Galileo became the first operational spacecraft to be destroyed deliberately, for purposes of planetary protection.

A similar categorization was assigned to the Cassini-Huygens mission to Saturn, with a similar caveat, and although the mission is not yet over, a similar end-of-mission scenario pertains. Data returned by the Huygens probe confirmed hypotheses regarding the surface temperature of Titan, which is sufficiently cold (at the surface) that no Earth organisms could replicate there in the absence of a local heat source. The discovery of warm areas at the south pole of Enceladus, releasing jets of salty water-ice, means that the Cassini spacecraft must avoid impacting that object both during its active mission and after the mission ends. Although the formal end-of-mission scenario for Cassini has not yet been finalized, the options are to leave Saturnian orbit, impact one of the smaller frozen moons, or deorbit into Saturn—the latter option is likely to provide the greatest science return. The project's proposed end-of-mission scenario will be reviewed by the Planetary Protection Subcommittee (or equivalent body) of the NASA Advisory Council as part of the negotiation process.

The Juno mission to Jupiter has no planned encounters with Europa or other Jovian satellites, thus it was assigned Category II; however, additional constraints were imposed on the Juno mission in accordance with recommendations from the SSB.

Those were: 1) Juno must avoid impact with Europa at a probability of less than  $1 \times 10^{-4}$  and the other icy Galilean satellites at a probability of less than  $1 \times 10^{-3}$  over its prime mission; and 2) the Juno project must “provide an end-of-mission plan that will address the disposition of the spacecraft and ensure continued avoidance of Galilean satellite impact after the mission has completed its observations.” It is virtually impossible to construct a spacecraft that is sufficiently reliable to meet these constraints, so the Juno project is demonstrating by appropriate modeling and analysis that the proposed mission will avoid contaminating Europa or impacting the other icy Galilean satellites. The proposed end-of-mission scenario involves a controlled deorbit into Jupiter, with a demonstration that the spacecraft will either deorbit into Jupiter on its’ own on a slightly longer timescale or, should an impact on Europa occur, that the impact energy is sufficient to destroy organisms on the spacecraft that remained viable in the Jovian radiation environment.

Although the probabilistic formulation used to set requirements for the diverse collection of icy objects in the outer solar system is somewhat complicated to implement, the three missions described above provide examples of implementation approaches that have been or are likely to be successful. In particular, the experience of the Juno project, which found that additional factors beyond those specifically called out by the Space Studies Board (SSB)—such as impact energy—were critical to meeting the probabilistic requirement, and in the event permitted them to far exceed it. Such flexibility is key when setting requirements for missions exploring poorly-understood objects.

## 5. Proposed Future Scientific Studies

### SSB's Example Calculation of Contamination:

The number of organisms that will **survive on Titan and Ganymede** is based on the initial contamination level [ $N_0$ ] and various survival factors:

$$N_s = N_0 F_1 F_2 F_3 F_4 F_5 F_6 F_7$$

$F_1$ —Bioburden Reduction Treatment	1
$F_2$ —Cruise Survival Fraction	$10^{-1}$
$F_3$ —Radiation Survival in the Near-Surface/Orbital Environment	$10^{-1}$
$F_4$ —Probability of Landing at an Active Site	$2 \times 10^{-3}$
$F_5$ —Burial Fraction (Below the “Cap”)	$1 \times 10^{-4}$
$F_6$ —Probability of Getting “There” on the Conveyor	1
$F_7$ —Probability that an Organism Survives and Proliferates	
During Landing ( $F_{7a}$ )	1
On the Surface ( $F_{7b}$ )	1
During Transport ( $F_{7c}$ )	$10^{-2}$
In Ocean ( $F_{7d}$ )	1
$N_0$ One Million Microbes...or More	$10^{6+}$
$N_s$	$2 \times 10^{-5}$

***We need  $N_s$  to be less than  $1 \times 10^{-4}$  to meet the contamination probability (< 1 live organism to a habitable portion of Titan or Ganymede)***

There is a need for controlling the potential chemical contamination of Titan’s surface. Of special concerns are the organics, particularly O-organics, polyphenyls and polycyclic aromatic hydrocarbons (PAHs), and compounds of biological interest such as amino-acids, urea, purines and pyrimidines. Special care should be taken with the lakes, very rich in a large variety of organics. Their analysis could provide key information on the chemical evolution of the atmosphere and potential interaction with the surface. A documentation should be enough, with a systematic catalog of the imported chemicals, including the order of magnitude of their flux / concentration / total imported mass. However, their contribution is likely to be negligible, taking into account the possible composition of Titan’s surface in organics of “natural” origin, including the lakes. Further studies are needed on that subject.

## 6. Proposed COSPAR Policy Update

The workshop participants concluded that the risk of entering a potentially habitable environment on Titan/Ganymede is “Remote”. A remote risk is defined as “*absence of environments where terrestrial organisms could survive and replicate*” or “*very low likelihood of transfer to environments where terrestrial organisms could survive and replicate.*”

The workshop participants framed a recommendation to bring to the COSPAR Panel on Planetary Protection at the Bremen Assembly in 2010. The wording of that recommendation, which references the definitions for “Remote” and “Significant,” is in the form of a revised section on Categorizations for the COSPAR Planetary Protection Policy. The workshop recommendation is given in Appendix C.

In the 2009-2010 timeframe, NASA may request the Space Studies Board (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/Ganymede 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.

Oceans of Titan and Ganymede, if present, are likely to ~50–150 km below the surface. If Titan or Ganymede has a conductive ice shell today, then it is difficult to envision plausible processes that could transport material from the surface to subsurface oceans. Through unconfirmed cryo-volcanic processes, melts may be drained downward in the planet’s interior. However, 1-2 km depth seems a viable limit to cryo-volcanic deposits. The proposed planetary protection category for both objects remains Category II, but with a requirement to address contamination concerns through a probabilistic model of the sort provided for Europa, prior to any formal Categorization being assigned for a particular mission.

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## APPENDIX A

### AGENDA: TITAN-GANYMEDE PLANETARY PROTECTION WORKSHOP

Salvatori Room, South Mudd Bldg (building 21, 3<sup>rd</sup> floor), Caltech

1200 E California Blvd (corner California & Wilson)

Pasadena, California, USA

FINAL (As of December 9, 2009)

#### ***Wednesday, December 9, 2009***

- 09:00 Welcome / Introduction Francois Raulin & John Rummel
- 09:10 Local arrangements Catharine Conley & Amy Baker
- 09:20 Introduction of Participants All
- 09:30 Summary of the Workshop on Planetary Protection for Outer Planet Satellites and Small Solar System Bodies (Vienna, 15-17 April 2009) John Rummel
- 10:15 A Focus on Titan Issues Raised at the Vienna Workshop Dennis Matson
- 10:30 A Focus on Ganymede Issues Raised at the Vienna Workshop Olivier Grasset
- 10:45 Discussion All
- 11:15 Break
- 11:30 ***Titan and Ganymede science***
- Internal Structure of Titan and Ganymede Christophe Sotin, Olivier Grasset
  - Titan and Ganymede Internal Ocean Habitability Olga Prieto-Ballesteros, Steve Vance
  - Discussion All
- 12:45 Lunch
- 13:45 ***Titan (and, for comparison, Ganymede) science (following)***
- Short welcome Andy Ingersoll
  - Titan's surface Robert Brown
  - Titan (and Ganymede) surface-ocean exchange processes Robert Pappalardo
  - Heat Transfer in the Titan Environment Ralph Lorenz
- 14:45 Discussion (specially on the interior-surface exchange processes and the internal ocean habitability) All

15:30 Break

15:45 ***Titan (and, for comparison, Ganymede) science (following)***

- Titan surface: potential liquid water bodies and prebiotic chemistry  
Jonathan Lunine, Francois Raulin
- Future mission to Titan & Ganymede  
Athena Coustenis, Olga Prieto Ballesteros, Olivier Grasset

16:30 Discussion All

17:45 Adjourn

18:00 Reception at the Atheneum

***Thursday, December 10, 2009***

09:00 Welcome back... Francois Raulin & John Rummel

09:10 ***Implications for Titan/Ganymede Planetary Protection***

- Summary of Titan/Ganymede science for PP aspects using the Europa formulation as an example John Rummel
- Planetary protection aspects of the end of the Juno and (?) Cassini-Huygens mission Catharine Conley
- Discussion of Titan/Ganymede Formulation in Practice All

10:50 Break

11:05 Translation of Priorities to Categorization (Do the Numbers) John Rummel

12:30 Lunch

13:30 Proposed Categorization All

14:00 Discussion of Required Science to Reduce Uncertainties All

14:30 Writing Group Assignments All

15:00 Final discussion All

17:00 Adjourn

## APPENDIX B

### Participant List

Amy Baker, TAS  
Bob Brown, U. of Arizona  
Cassie Conley, NASA HQ  
Athena Coustenis, Observ. de Paris  
Olivier Grasset, U. of Nantes  
Vicky Hipkin, CSA  
Torrence Johnson, JPL  
Gerhard Kminek, ESA  
Ralph Lorenz, APL  
Jonathan Lunine, U. of Arizona  
Dennis Matson, JPL  
Bob Pappalardo, JPL  
Olga Prieto- Ballesteros, CAB  
John Priscu, Montana State U.  
François Raulin, U. of Paris-12  
John Rummel, East Carolina U.  
David Smith, NRC  
Christophe Sotin, JPL  
J. Andrew Spry, JPL  
Perry Stabekis, Northrup-Grumman  
Steve Vance, JPL

### Host

Andy Ingersoll, Caltech

## APPENDIX C

### Proposed COSPAR Categorization of Target Body/Mission Types

#### Category-Specific Listing of Target Body/Mission Types

Category I: Flyby, Orbiter, Lander: Undifferentiated, metamorphosed asteroids; others TBD

Category II: Flyby, Orbiter, Lander: Venus; Moon (with organic inventory); Comets; Carbonaceous Chondrite Asteroids; Jupiter; Saturn; Uranus; Neptune; Ganymede\*; Titan\*; Triton\*; Pluto/Charon\*; Ceres; Kuiper-Belt Objects > 1/2 the size of Pluto\*; Kuiper-Belt Objects < 1/2 the size of Pluto; others TBD

Category III: Flyby, Orbiters: Mars; Europa; Enceladus; others TBD

Category IV: Lander Missions: Mars; Europa; others TBD

Category V: Any Earth-return mission.

“Restricted Earth return”: Mars; Europa; others TBD;

“Unrestricted Earth return”: Venus, Moon; others TBD.

\*The mission-specific assignment of these bodies to Category II must be supported by an analysis of the “remote” potential for contamination of the liquid-water environments that may exist beneath their surfaces (a probability of introducing 1 viable terrestrial organism of  $<1 \times 10^{-4}$ ), addressing both the existence of such environments and the prospects of accessing them.

#### Definition of “Remote”

Absence of environments where terrestrial organisms could survive and replicate  
*or*

Very low likelihood of transfer to environments where terrestrial organisms could survive and replicate.

#### Definition of “Significant”

Presence of environments where terrestrial organisms could survive and replicate  
*and*

Some likelihood of transfer to those places by a plausible mechanism.