Three-year of observations of Jupiter’s aurora and Io plasma torus variabilities by extreme-ultraviolet spectroscope HISAKI and future directions

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Extreme Ultraviolet spectrograph, EXCEED, on-board the HISAKI satellite is designed for observing tenuous gas and plasma around planets in the solar system. It enables us to obtain fully continuous data set and find time variability in the planetary magnetosphere and ionosphere with time scales of several hours to months. Here, we introduce findings of Jupiter’s UV aurora and plasma emissions from the Io plasma torus (IPT) obtained from the HISAKI observation since Dec. 2013. Jupiter is known to have a huge magnetosphere in which the plasma convection is mainly driven by the planet spin motion. This is caused by the strong intrinsic planetary magnetic field, fast spin motion, and presence of a primary plasma source inside the inner magnetosphere. The plasma source from the satellite Io with a typical rate of 1 ton/sec causes slowly outward transport of plasma from inner to middle magnetosphere. The HISAKI observation found decrease in hot electron density as decreasing radial distance, which is an evidence of steady hot plasma transport into the inner magnetosphere due to interchange instability. HISAKI also found brightening in IPT associated with transient enhancement of Jupiter’s aurora, showing an evidence of transient and rapid inward transport of energy from the outer/middle to inner magnetosphere. The transient enhancement of Jupiter’s aurora is also one of discoveries from HISAKI. It was observed during solar wind quiet period, suggesting that the transient energy release can be drive by the internal plasma circulation process. Wide spectral observation enables us to estimate aurora electron energy and total emission power and showed that enhancements of auroral intensity accompany increases of the electron number flux rather than the electron energy variations. The HISAKI-HST campaign in Jan. 2014 provided unique data set to study time variability in Jupiter’s auroral structure. During this period, Jupiter’s main auroral oval decreased its emitted power by 70% and shifted equatorward by about 1 degree. The decrease in emitted power is attributed to a decrease in auroral current density rather than electron energy, consistent with the HISAKI observation. HST also captured variations in auroral structure during a short-lived transient brightening observed by HISAKI and showed hot plasma inflows from tail reconnection region. Observations of Jupiter’s magnetosphere by HISAKI and HST show us a new picture of the Jovian magnetosphere: significant energy is released in the magnetosphere due to internally driven process and is rapidly re-distributed from outer/middle to inner magnetosphere. HISAKI also reveals new insights about responses of the magnetosphere to the solar wind. Intensification of the aurora brightness is well correlated with enhancement of dynamic pressure of the solar wind. The amplitude is controlled by the duration of a quiescent interval of the solar wind. The response of IPT to the solar wind dynamic pressure is also discovered from the HISAKI observation and is interpreted by the modification of

large scale electric field in the magnetosphere. Satellite-magnetosphere interaction is also a unique topic for outer planet magnetosphere. HISAKI found hot plasma heating around the satellite Io and it is responsible for 10% of total energy input to IPT. The HISAKI mission will extend until the spring of 2020 and provide us an opportunity to make simultaneous observation of Jupiter’s magnetosphere with NASA’s JUNO spacecraft.

キーワード：HISAKI、木星
Keywords: HISAKI, Jupiter

The Impact of Io’ s Volcanism on the Jovian Extended Neutral Environment

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Jupiter's dynamic and volcanically-active moon Io resides in a complex and time-variable system of neutral and ionized particles, which are sourced by volcanic by-products from Io. Establishing the direct impact of Io’ s volcanism on Jupiter’ s neutral and plasma environments requires accurate simultaneous timelines of Io’ s thermal activity, the neutral sodium brightness, and ion emissions. Such an opportunity has been present over the past few years, as the ISAS/JAXA SPRINT-A/EXCEED mission has been observing the EUV emission from ionized S and O in the Jovian system from Earth orbit in order to understand the physical processes and sources of variability. During this time, we have been tracking the thermal emission from ~60 volcanic hot spots on Io using high-cadence near-infrared imaging with adaptive optics on the Keck and Gemini N telescopes. Coverage of Io was particularly high in the spring of 2016, leading up to the *Juno* arrival. The simultaneous timeline of the neutral sodium cloud variability as observed from Haleakala Observatory allows us to correlate brightening events in the sodium cloud with volcanic eruptions on Io. Past studies shown a correlation between the neutral sodium brightness and volcanic events at Io’ s massive lava lake Loki Patera. We detected three events at Loki Patera between 2013 and 2016, but no corresponding sodium brightenings were observed, in direct contrast with past results. However, the timing of several bright transient eruptions coincides with brightenings observed in the extended sodium cloud. These results suggest that Io’ s volcanic controls on the sodium cloud variability are more complex than previously thought, and that the impact of an eruption on the sodium cloud may depend more on the style of the eruption than on the amount of thermal emission produced, even varying between eruptions for a single volcanic center. Continued observations, as well as correlation with plasma variability as observed by EXCEED, will provide insight into these complexities in the future.

Keywords: Io, Volcanism, Io Sodium Cloud

Auroral explosion at Jupiter observed by the Hisaki satellite and Hubble Space Telescope during approaching phase of the Juno spacecraft

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In early 2014, the continuous monitoring with the Hisaki satellite discovered the transient auroral emission at Jupiter during the period when the solar wind was relatively quiet. The simultaneous imaging made by the Hubble Space Telescope (HST) suggested that the transient aurora is associated with the global magnetospheric disturbance that spans from the inner to outer magnetosphere. However, the temporal sequence of the magnetospheric disturbance is not resolved yet because we still lack the sufficient continuous monitoring of the transient aurora simultaneously with the imaging. Here we report the coordinated observation of the aurora and plasma torus made by Hisaki and HST during the approaching phase of the Juno spacecraft in mid-2016. On day of year 142, Hisaki detected the transient aurora with a peak of the total emission power of ~6 TW at the entire ultraviolet wavelengths. This emission power is one of the largest values that have been measured by Hisaki. The simultaneous HST imaging was indicative of the large “dawn storm”, which is associated with the tail reconnection, in the main oval at the onset of the transient aurora. The outer emission, which is associated with the hot plasma injection in the inner magnetosphere, followed the dawn storm. The monitoring of the dawn and dusk side torus with Hisaki indicated that the hot plasma population corotating with Jupiter appeared in the torus during the transient aurora. These results imply that the magnetospheric disturbance associated with the transient aurora is initiated via the tail reconnection, and expands toward the inner magnetosphere, and followed by the hot plasma injection reaching to the plasma torus. This corresponds to the radially inward transport of the plasma and/or energy from the outer to the inner magnetosphere.

キーワード：木星、磁気圏、サブストーム
Keywords: juptier, magnetosphere, substorm

Characteristics of solar wind control on Jovian UV auroral activity obtained from Hisaki EXCEED and ground-based observations

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While the Jovian magnetosphere is known to be dominated by the internal source of plasma and energy, it also has an influence from the solar wind. The ultraviolet (UV) aurora and solar wind dynamic pressure are proposed to be anti-correlated in a theoretical model, on the other hand, previous observations such as those by the Hubble Space Telescope showed a positive correlation between them.
We made a statistical analysis of the total power variation of Jovian UV aurora obtained by the spectrometer EXCEED (Extreme Ultraviolet Spectroscope for Exospheric Dynamics) on board the Hisaki satellite. The data set we use was obtained from Dec. 2013 to Feb. 2014 and from Dec. 2014 to Feb. 2015. We compared the total UV auroral power in 900-1480 A with solar wind dynamic pressure at Jupiter estimated from the observation at 1 AU with a one-dimensional MHD model. Superposed epoch analysis supports the positive correlation as the previous observation: Auroral total power increases when solar wind dynamic pressure enhanced around Jupiter. Furthermore, the auroral total power shows a positive correlation to the duration of a quiescent interval of the solar wind before the enhancements of the dynamic pressure with the correlation coefficient of 0.86. It is larger than the correlation to the amplitude of dynamic pressure enhancement with the correlation coefficient of 0.44. A similar trend was observed in the auroral field-aligned currents which are inferred from the color ratio between the two bands of the Hisaki spectrum data. These statistical characteristics define the next step to unveil the physical mechanism of the solar wind control on the Jovian magnetospheric dynamics.
One possible scenario to explain the results is that the magnetospheric plasma content controls the aurora response to the solar wind variation. A long quiescent interval would mean that plasma supplied from Io is more accumulated in the magnetosphere. The solar wind compression of the magnetosphere shifts the plasma inward and cause adiabatic heating to become hot and dense plasma, which leads to an enhancement of the auroral field-aligned current density. The auroral field aligned current also depends on the angular velocity distribution of the magnetospheric plasma, however, it is still unclear how the distribution varies during the solar wind compression. We also made a coordinated observation with Hisaki and CSHELL on Infrared Telescope Facility when Juno measured upstream solar wind condition. The intensity of infrared H_3^+ emission can be used as an index of the atmospheric heating, and the ion wind velocity distribution is related to field aligned current. The initial result indicates that total intensity of H_3^+ emission increases when the UV auroral total power and the dynamic pressure increase, which suggests the atmospheric heating occurs in the thermosphere. However, we cannot find any relation between ion wind velocity and the UV aurora. In this presentation, we will discuss a possible scenario for the solar wind control of the Jovian aurora.

キーワード：木星、オーロラ、太陽風
Keywords: Jupiter, Aurora, solar wind

Auroral Electron Energy Estimation Using H/H_2 Brightness Ratio Applied to Jupiter

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The far-ultraviolet (FUV) aurora seen on giant planets is directly produced by the precipitating auroral electrons. An analysis of Saturn's aurorae taken by the Ultraviolet Imaging Spectrograph (UVIS) instrument onboard the Cassini spacecraft showed that the brightness ratio of H Lyman-α to H_2 auroral emissions statistically decreases with the brightness of H_2 taken as a proxy of the energy of precipitating electrons. This ratio is suggested to provide a sensitive diagnosis of auroral electron energy from modeling studies, and the measurement was then investigated in details for the Saturn's case to show that the brightness ratio provides low energy electrons (typically lower than 10 keV), in contrast with the FUV color ratio (CR) method which is sensitive to the high energyelectrons >a few 10s keV. Energy-flux relationship converted from the observation using models shows different trend in the lower energy range (a few keV), reflecting different magnetosphere-ionosphere processes. The H/H_2 brightness ratio would be also useful for the Jupiter case to investigate the role of low energy auroral electrons, and we investigated the relation as follows.

We use HST/STIS long-slit spectra taken on the first half of January 2014 (ID: GO13035). Since HST observes Jupiter from the orbit around the Earth, it contains Lyman-α emissions from geo-coronal hydrogen atoms, in addition to Jupiter's coronal emission. We remove these contaminations by subtracting the emission at the disc. The H/H_2 brightness ratio is then evaluated by spectral fitting following the previous auroral analysis for Saturn.

As a result, we show that the H/H_2 brightness ratio decreases with increasing H_2 brightness, which is qualitatively similar to the Saturn's case, but with different quantitative values. The H/H_2 brightness ratio, i.e., low energy electron precipitation, does not show clear relationship with the FUV CR, i.e., higher energy electron precipitation. Comparing to the same analysis applied to Saturn aurora, the relation at Jupiter shows decreasing flux with increasing energy without acceleration feature for the low energy range.

キーワード：木星、オーロラ、紫外
Keywords: Jupiter, aurora, ultraviolet emission

North-south asymmetry of Saturn's auroral radio emissions: The seasonal variation of their fluxes in half Kronian year

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The observations by Cassini from 2004 to 2017 is revealing its strange seasonal variation seen in the magnetic field and upper atmosphere. It was first found in the radio emissions, Saturn Kilometric Radiation (SKR), from the northern and southern polar regions in 3-1200 kHz. SKR is generated by field-aligned energetic electrons on the magnetic field lines connecting to the auroral region. For the Saturn’s magnetic field direction, the right-handed circularly polarized (RH) emissions are from the northern region and the left-handed (LH) ones from the southern one. Therefore, we can separately evaluate the SKR variation from Northern and Southern polar regions.
Saturn's rotation period has been evaluated by the modulation period of SKR, because the SKR source is fixed in the planetary magnetic field with highly anisotropic beaming and forms a corotating searchlight of radio emission. Cassini observations in the southern summer (2004-2009) showed that the period of SKR daily variation is variable. It was slightly longer in the southern (summer) hemisphere, but close to each other near the equinox (September 2009).
We also studied the flux variation between northern and southern SKR in 2004-2010, and showed that the LH (summer, south) is stronger than the RH (winter, north) in average [Kimura et al., 2013]. Those characteristics could be related to the north-south asymmetry in the polar ionospheric conductivities, which are related to the seasonal variations of the solar EUV flux illuminating to the polar region. However, its comprehensive explanation has not yet been established. After the equinox in 2010-2013, the northern early summer does not show the clear separation of northern and southern SKR periods [Provan et al., 2014; Fischer et al., 2015]. At last, from the fall of 2014, both SKR periods becomes to be separated [Provan et al., 2016].
In this study, we extend our SKR flux variation study to cover the half Kronian year, from southern summer (2004) to northern summer (2015 DOY264). In this case, the simple extension of the analysis method used in our previous study was not adequate because of the bias in the Cassini orbit. Since the SKR is stronger in the dawn side, we only used the data for 2004-2010 when Cassini was at the dawn side (2-10h LT). However, because of Cassini’s apokrone after 2007 was gradually shifted from dawn to dusk, the same criteria prevents from collecting enough dataset for the analysis after that. For this study to cover 2004-2016, we relaxed this condition and used the data in all local time. In order to avoid the dawn-dusk assymmetry effect, we we selected the data when Cassini was in the latitude within +-5deg. In this condition, both northern and southern SKR are observed simultaneously and the flux ratio between them can be used to evaluate the seasonal effect. We also limit the data with the distance from Saturn in 10-100 Rs, in order to avoid the visibility effect of SKR caused by its propagation. From those data, the SKR flux was evaluated by a running median with a window of +-35 days, enough longer than the daily modulation of SKR (about 11h) and the solar variation by its rotation (about 27 days). In this result, the intensity of LH component in 2004-2009 (south, summer) was ~+10 dB stronger than RH (north, winter), which is consistent with the result in Kimura et al. (2013). In 2010-2012, the both SKR intensities got close to each other. After 2013, RH (north, summer) was slightly stronger by a few dB than LH (south, winter). The flux ratio between Northern and Southern SKR after 2010 seems to be linked with those of

the Northern and Southern SKR periods. The flux ratio was more than 10 in southern summer but only 2.5~5 in northern summer, in the analyzed term, even in 2014-2015. On the other hand, in order to check the LT dependence effect, we divided the data with 4 LT sectors (3-9h, 9-15h, 15-21h, 21-3h). We could confirm that the flux ratio changed from 10 to 0.2 in the 3-9h and 9-15h sector and became below or above 1 in 15-21h and 21-3h sector. It shows that the seasonal variation is more effective in the dawn side.
In this paper, we will also investigate the correlations of the SKR flux variations to the solar wind and solar EUV flux, as the extension of the results in 2004-2010 [Kimura et al., 2013].

キーワード：土星、SKR (Saturn Kilometric Radiation)、季節変動、南北非対称
Keywords: Saturn, SKR (Saturn Kilometric Radiation), seasonal variation, north-south assymetry

Global MHD Simulations of Saturn's Magnetosphere and Their Implications for Jupiter

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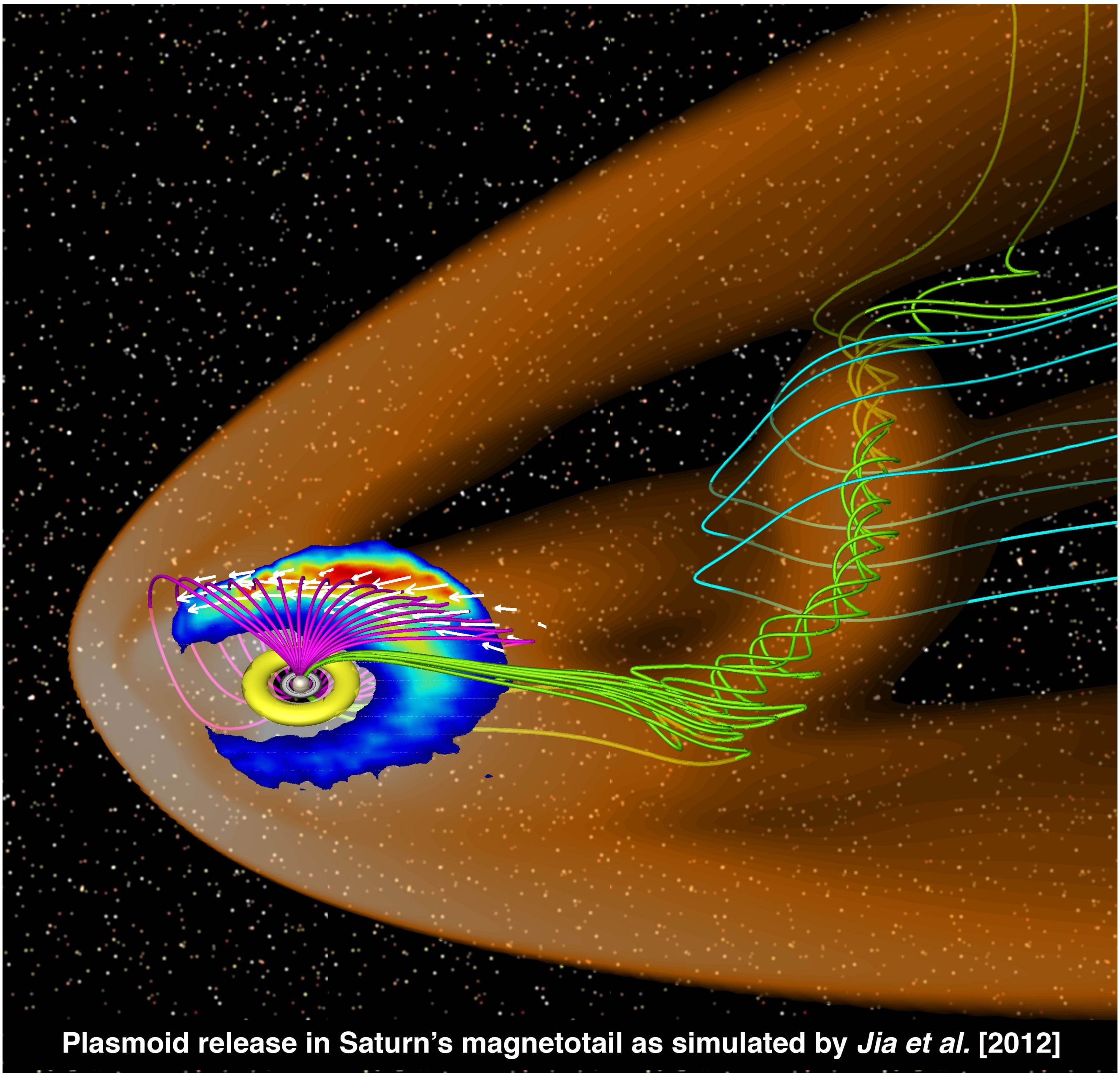
At Saturn's orbital distance of ~ 9.5 AU, the low solar wind dynamic pressure and weak interplanetary magnetic field interact with the planet to create a magnetosphere that dwarfs Earth’s magnetosphere. While the form of Saturn's magnetospheric cavity is still the result of solar wind stresses, many properties of the Kronian magnetosphere are determined largely by internal processes associated with the planet's rapid rotation and the stresses arising from internal plasma sources dominated by the icy moon, Enceladus. Coupling between the planetary ionosphere and the magnetosphere through electric currents plays a vital role in determining the global configuration and dynamics of Saturn's magnetosphere. To understand the large-scale behavior of the solar wind-magnetosphere-ionosphere interaction, we have applied the global MHD model, BATSRUS, to Saturn that self-consistently couples the solar wind, the magnetosphere, and the ionosphere and incorporates key mass-loading processes associated with Enceladus and its extended neutral cloud. Here we present results from our global simulations carried out to understand how the various internally and externally driven processes influence Saturn's magnetosphere, and discuss their implications for interpreting Cassin in-situ observations. We will also show results from an atmospheric vortex model we have developed that offers valuable insight into the physical processes that drive the ubiquitous periodic modulations of particles and fields properties observed by Cassini throughout the Saturnian magnetosphere. Implications of our Saturn simulations for another giant planet, Jupiter, will also be discussed.

Keywords: Saturn, Jupiter, Magnetosphere, Cassini


Plasmoid release in Saturn's magnetotail as simulated by *Jia et al.* [2012]

Deep Zonal Flow and Time Variation of Jupiter's Magnetic Field

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All four giant planets in the Solar System feature zonal flows on the order of 100 m/s in the cloud deck, and large-scale intrinsic magnetic fields on the order of 1 Gauss near the surface. The vertical structure of the zonal flows remains obscure. The end-member scenarios are shallow flows confined in the radiative atmosphere and deep flows throughout the entire planet. The electrical conductivity increases rapidly yet smoothly as a function of depth inside Jupiter and Saturn. Deep zonal flows will advect the non-axisymmetric component of the magnetic field, at depth with even modest electrical conductivity, and create time variations in the magnetic field.

The observed time variations of the geomagnetic field has been used to derive surface flows of the Earth's outer core. The same principle applies to Jupiter, however, the connection between the time variation of the magnetic field (dB/dt) and deep zonal flow (U_phi) at Jupiter is not well understood due to strong radial variation of electrical conductivity. Here we perform a quantitative analysis of the connection between dB/dt and U_phi adopting Jupiter's interior electrical conductivity profile. This provides a tool to translate expected measurement of the time variation of Jupiter's magnetic field to deep zonal flows. We show that the current upper limit on the dipole drift rate of Jupiter (3 degrees per 20 years) is compatible with 10 m/s zonal flows with < 500 km vertical scale height below 0.972 Rj. We further demonstrate that fast drift of resolved magnetic features (e.g. magnetic spots) at Jupiter is a possibility.

Keywords: Jupiter, Zonal Flow, Magnetic Field

Ice Giant Exploration: Results of the NASA-ESA Science Definition Team Study

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The most recent Planetary Science Decadal Survey, "Vision and Voyages for Planetary Science in the Decade 2013-2022", recognized the scientific importance of the Uranus and Neptune planetary systems and prioritized their exploration. In 2016, NASA and ESA established a Science Definition Team (SDT) to assess science priorities and affordable mission concepts for exploration of the Ice Giant planets in preparation for the next Decadal Survey. This study has now been completed and the resulting mission concepts, which demonstrate the feasibility of compelling missions, will be presented.

Since the Voyager 2 flybys of Uranus (1986) and Neptune (1989), the ice giant systems have intrigued and tantalized. Studies of the these systems encompass all disciplines of planetary science, with much cross-disciplinary overlap, particularly when looking at system-wide interactions. Although the SDT initially considered each discipline individually (interiors, atmospheres, magnetospheres, classical satellites, small satellites and rings), broad themes quickly emerged. The SDT compiled 12 main science objectives, which answered more than 50 science questions. That this list is by no means all-encompassing underscores the great breadth of science that could be achieved at either of these planets.

The most important science investigations are ones that address the fundamental questions "What is an ice giant?" and "How do they form?" We therefore consider the objectives of determining interior structure and bulk composition (including noble gases and key isotopic ratios) as the highest priorities. The SDT did not prioritize among the other objectives, and they are listed here in no particular order.

Science Objectives:
1. Constrain the structure and characteristics of the planet's interior, including layering, locations of convective and stable regions, internal dynamics
2. Determine the planet's bulk composition, including abundances and isotopes of heavy elements, He and heavier noble gases
3. Improve knowledge of the planetary dynamo
4. Determine the planet's atmospheric heat balance
5. Measure planet's tropospheric 3-D flow (zonal, meridional, vertical) including winds, waves, storms and their lifecycles, and deep convective activity
6. Characterize the structures and temporal changes in the rings
7. Obtain a complete inventory of small moons, including embedded source bodies in dusty rings and moons that could sculpt and shepherd dense rings
8. Determine surface composition of rings and moons, including organics; search for variations among moons, past and current modification, and evidence of long-term mass exchange / volatile transport
9. Map the shape and surface geology of major and minor satellites
10. Determine the density, mass distribution, internal structure of major satellites and, where possible, small inner satellites and irregular satellites
11. Determine the composition, density, structure, source, spatial and temporal variability, and dynamics

of Triton's atmosphere
12. Investigate solar wind-magnetosphere-ionosphere interactions and constrain plasma transport in the magnetosphere

Multiple mission architectures and instrument complements were considered. A Uranus orbiter with atmospheric probe, launching near 2030, is our recommended baseline mission. The orbiter payload will ideally be in the 90 to 150 kg range, though significant science can be achieved with smaller payloads. Our understanding of ice giants and solar system evolution will be maximized, however, by launching two spacecraft, one to Uranus and one to Neptune. We encourage consideration of these dual-spacecraft, dual-planet missions. We also encourage international collaboration as a way to minimize the cost to individual nations while maximizing the science return from what will likely be the only *in situ* exploration of an ice giant system for the next generation.

Keywords: Outer Planets, Ice Giants, Future missions

Cloud Structure, Elemental Abundances, and the Formation of Uranus and Neptune

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Migration is all but essential for the formation of Uranus and Neptune. These ice giant planets most likely began and completed much of their formation in the orbital neighborhood of the gas giants, Jupiter and Saturn. The core accretion is the preferred model for the formation of the giant planets. Abundances of the heavy elements (mass greater than helium), in particular, are key to the formation and evolution scenarios. Those abundances are derived from the bulk composition. That bulk lies in the well-mixed atmosphere well below the cloud levels for condensible constituents. In this talk, we will show that current thermochemical equilibrium models place the well-mixed region of water –the deepest condensible –at several hundreds of bars in Uranus and Neptune [1]. In fact, that is an utterly optimistic scenario, as water is expected to form a superionic phase much deeper, between 50-75 GPa (500-750 kilobars) [2,3], which would in effect remove much of the water at those levels. Removal of ammonia, and possibly hydrogen sulfide, the other condensibles, is also quite likely in the water ionic ocean. Greatly subsolar ammonia at shallow tropospheric levels [4; M. Hofstadter, personal comm., 2016] and an intrinsic magnetic field [5] may be an evidence of the purported ionic ocean in Uranus and Neptune [1]. Thus, it is crucial to determine with high precision the elemental abundances and isotope ratios of the noble gases, He, Ne, Ar, Kr and Xe, that can be measured at relatively low tropospheric pressures, but not chase after the illusive, condensible gases, water, ammonia and hydrogen sulfide (methane is also condensible, but it can be accessed in the same shallow region as the noble gases). Entry probes are the only means to carry out the measurements of the noble gases, deep methane, and the isotopes. Those data in the atmospheres of the ice giant planets and their comparison with Jupiter and Saturn will then provide robust constraints to the models of the formation and evolution of the ice giant planets. References: [1] S. K. Atreya and Joong Hyun In (2016) Role of entry probes in the exploration of the solar system giants, Proc. 67th IAC, Paper ID IAC-16-32269. [2] N. Goldman, et al. Phys. Rev. Lett. 94 (2005) 217801. [3] A. F. Goncharov, et al. (2005) Phys Rev Lett 94, 125508. [4] I. de Pater, et al. (1991) Icarus 91 (1991) 220. [5] N. Ness, et al., Science 233 (1986) 85.

Keywords: Uranus, Neptune, Giant Planets, Origin and Evolution, Entry Probes

View of Saturn from Cassini Grand Finale Orbits

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Cassini spacecraft has been in orbit around Saturn since 2004 and made numerous new discoveries in the Saturn system. The mission entered its final phase on November 29, 2016 when it raised its orbital inclination and lowered its periapsis to 90,000 km from the cloud-top of Saturn at the edge of the main ring system. These high-inclination orbits offer a unique chance to observe the high-latitude regions of Saturn. The north-polar region is now covered in yellowish photochemical haze layer, presumably in response to the increasing solar insolation since the 2009 equinox. On April 22nd, 2017, the Cassini orbiter will change its orbit one last time and lower its periapsis inside the inner-most ring, about 3000 km above the clouds. The spacecraft will orbit the planet 22 times before it enters the atmosphere on September 15, 2017. We will present preliminary findings in images captured during the Grand Finale orbits.

Keywords: Cassini Mission, Saturn, Atmosphere

Tidal Dissipation in a Viscoelastic Saturnian Core and Expansion of Mimas’ Orbit

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Tidal dissipation in Saturn is usually parameterized by Saturn’s quality factor Q. However, there remains a discrepancy between conventional estimates and the latest determination that has been derived from astrometric observations of Saturn’s inner satellites. If dissipation in Saturn is as large as the astrometric observations suggest and independent of time and tidal frequency, conventional models predict that Mimas’ initial orbit should be located inside Saturn’s synchronous orbit or even inside its Roche limit, in contradiction with formation models. Using simple structure models and assuming Saturn’s core to be viscoelastic, we look for dissipation models which are consistent with both the latest observations and with Mimas’ orbital migration. Firstly, using a two-layer model of Saturn’s interior structure, we constrain the ranges of rigidity and viscosity which are consistent with Saturn’s dissipation derived from astrometric observations at the tidal frequencies of Enceladus, Tethys and Dione. Next, within the constrained viscosity and rigidity ranges, we calculate Mimas’ semi-major axis considering the frequency dependence of viscoelastic dissipation in Saturn’s core. We show that Mimas can stay outside the synchronous orbit and the Roche limit for 4.5 billion years of evolution. In the case of a frequency dependent viscoelastic dissipative core, the lower boundary of the observed Saturnian dissipation can be consistent with the orbital expansion of Mimas.In this model, the assumption of a late formation of Mimas, discussed recently, is not required.

Keywords: Saturn, Mimas, Tidal Dissipation

Pluto System and Beyond –Results from New Horizons

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In July 2015 the New Horizons spacecraft flew through the Pluto system, completing reconnaissance of the classical planets and commencing the in situ exploration of the Kuiper Belt [1]. Pluto turned out to be a world of remarkable geologic diversity, and its terrains display a range of ages, suggesting geologic activity of various forms has persisted for much of Pluto's history [2]. Images looking back at Pluto's atmosphere led to the discovery of numerous haze layers in its thin nitrogen atmosphere [3]. We are in the early stages of understanding this complex world, but I will highlight what we have learned so far and present the latest results focusing on Pluto's unique geology. I will also outline the plans for the New Horizons observations of distant KBOs and its close flyby of the small Kuiper Belt Object 2014MU$_{69}$ on January 1, 2019.

Although Pluto's lithosphere is thought to be predominantly water ice, the volatile ices N_2, CH_4, and CO dominate much of its surface [4]. Pluto's terrains contain many features that are likely due to sublimation and re-deposition of these volatile ices during seasonal and climactic cycles. Some examples include pitting on various scales, a unique region referred to as "bladed terrain", and patterns of bright and dark material (such as bright methane ice on the high altitude peaks of some mountains). The darker material found on Pluto is likely due to surface tholins, which are produced when methane is photolytically processed into heavier hydrocarbons. Additionally, NH_3 is observed on Pluto's large moon Charon [4] and on Pluto's smaller moons Nix and Hydra [5,6].

Several aspects of Pluto and Charon's geology are, or were, driven by internal heat. Polygonal and cellular planform shapes in Pluto's vast nitrogen ice plains (informally known as Sputnik Planitia) are likely formed by ongoing solid state convection. Two enormous domes on Pluto (one 4 km high and 150 km across and the other 6 km high and ~225 km across) with large central depressions may have formed through cryovolcanism [7]. There are few craters on these broad mountains, indicating they are relatively young constructs. These observations challenge us to re-evaluate how smaller bodies retain heat and drive volcanism without tidal forcing. We note also that the southern portion of Charon (informally known as Vulcan Planum) appears to have been almost completely resurfaced by a thick, viscous cryovolcanic flow early in its history.

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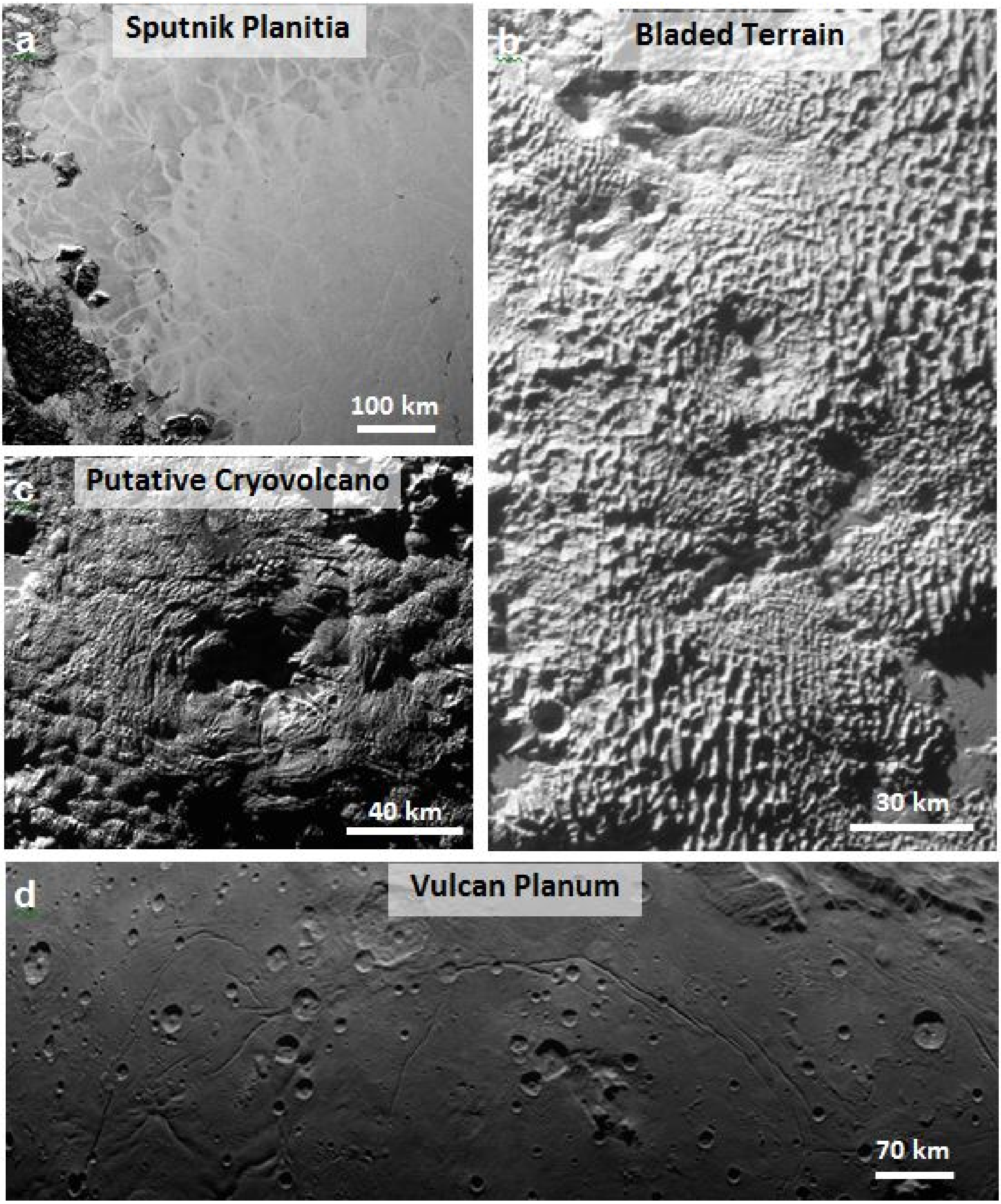
Keywords: Pluto, Charon, Geology, Geophysics, Kuiper Belt, Spacecraft Missions



Thermal convection as a mechanism at the origin of Sputnik Planum polygonal patterns on Pluto

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High resolution pictures of Pluto’ s surface obtained by the New Horizons spacecraft revealed a large nitrogen ice glacier informally named Sputnik Planum. The surface of this glacier is separated into a network of polygonal cells with a wavelength of 20–40 km. This network is similar to the convective patterns obtained under certain conditions by numerical and experimental simulations, suggesting that it is the surface expression of thermal convection within Sputnik Planum glacier. Here, we investigate the surface planform (sub-surface temperature and dynamic topography) obtained for different convective systems in 3D-Cartesian geometry with different modes of heating and rheologies. We find that bottom heated systems do not produce surface planforms consistent with those observed at the surface of Sputnik Planum, even when temperature dependent viscosity are taken into account. Alternatively, for a certain range of Rayleigh-Roberts number, Ra_H, a volumetrically heated system produces a surface planform very similar to the one found on Sputnik Planum. Combining scaling laws published in earlier studies with values of Ra_H within its possible range, we then establish relationships between the critical parameters of Sputnik Planum. In particular, for reasonable vertical temperature jump across the glacier (5–25 K) and nitrogen ice viscosities (10^{14}–10^{15} Pa s), our calculations indicate that the glacier thickness and the surface heat flux are in the ranges 2–10 km and 0.1–10 mW/m^2, respectively. However, if volumetrically heated convection operates within Sputnik Planum, a diffculty is to identify a proper source of internal heating. The most likely source may be induced by the cooling of Sputnik Planum, but it remains uncertain. Additional studies are thus required to determine a possible source of volumetric heating, or another mechanism than thermal convection to explain Sputnik Planum polygonal patterns.

Keywords: Pluto, Sputnik Planum, Thermal convection

The Europa Multiple Flyby Mission: Synergistic Science to Investigate Habitability

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Europa is a complex geophysical and geochemical system, illustrating a wide range of processes relevant to understanding ocean worlds, including: tectonics; tidal deformation and heating; impact cratering; mass wasting; surface-plasma, exospheric, and magnetospheric interactions; solid state convection; and cryovolcanism, possibly including plumes. It is a key target for astrobiological exploration, potentially hosting the ingredients for life: liquid water, bioessential elements, and chemical energy.

The overarching science goal of the planned Europa Multiple Flyby Mission is to explore Europa to investigate its habitability, with Objectives (roman numerals) and Investigations (numbered, with applicable investigations), including the searching for any current activity, e.g., plumes, thermal anomalies:
I. Ice Shell & Ocean: Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface-ice-ocean exchange
1. Characterize the distribution of any shallow subsurface water and the structure of the icy shell *(EIS, REASON)*
2. Determine ocean salinity and thickness *(ICEMAG, MISE, PIMS, SUDA)*
3. Constrain the regional and global thickness, heat-flow, and dynamics of the ice shell *(E-THEMIS, EIS, Gravity, ICEMAG, PIMS, REASON)*
4. Investigate processes governing material exchange among the ocean, ice shell, surface, and atmosphere *(EIS, ICEMAG, MASPEX, MISE, REASON, SUDA)*

II. Composition: Understand the habitability of Europa's ocean through composition and chemistry
1. Characterize the composition and chemistry of endogenic materials on the surface and in the atmosphere, including potential plumes *(EIS, Europa-UVS, ICEMAG, MASPEX, MISE, PIMS, REASON, SUDA)*
2. Determine the role of the radiation and plasma environment in creating and processing the atmosphere and surface materials *(EIS, Europa-UVS, MASPEX, MISE, PIMS, Radiation, REASON, SUDA)*
3. Characterize the chemical and compositional pathways in the ocean *(EIS, ICEMAG, MASPEX, MISE, SUDA)*

III. Geology: Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities
1. Determine sites of most recent geological activity, including potential plumes, and characterize localities of high science interest and potential future landing sites *(E-THEMIS, EIS, Europa-UVS, MASPEX, MISE, PIMS, Radiation, REASON, SUDA)*
2. Determine the formation and three-dimensional characteristics of magmatic, tectonic, and impact landforms *(EIS, REASON)*
3. Investigate processes of erosion and deposition and their effects on the physical properties of the surface *(E-THEMIS, EIS, Europa-UVS, PIMS, Radiation, REASON, SUDA)*

To address Europa science objectives, NASA selected a suite of instruments, including remote-sensing

covering wavelengths from ultraviolet through radar:
- *Europa Ultraviolet Spectrograph (Europa-UVS)*
- *Europa Imaging System (EIS)*
- *Mapping Imaging Spectrometer for Europa (MISE)*
- *Europa Thermal Imaging System (E-THEMIS)*
- *Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)*

and *in situ* instruments that measure fields and particles:
- *Interior Characterization of Europa using Magnetometry (ICEMAG)*
- *Plasma Instrument for Magnetic Sounding (PIMS)*
- *MAss Spectrometer for Planetary Exploration (MASPEX)*
- *SUrface Dust Analyzer (SUDA)*

Gravity science can be achieved via the spacecraft telecom system in combination with REASON altimetry, and a planned radiation monitoring system will provide valuable scientific data. Together, these investigations will test hypotheses relevant to the interior, composition, and geology of Europa and to provide a synergistic framework to address the potential habitability of this intriguing moon.

An overview of planned Europa mission science will be presented along with the EIS camera suite, designed to provide global decameter-scale coverage, topographic and color mapping, unprecedented sub-meter-scale imaging, and plume searches.

Keywords: Europa, Habitability, Europa Multiple Flyby Mission

Beyond InSight - Seismological Exploration of Ocean Worlds

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Since the *Viking* mission, no successful planetary lander mission has been equipped with a seismometer. This is unfortunate, given that most of the knowledge about Earth's deep interior was derived from seismological observations. Spring 2018 will see the launch of the *InSight* mission, which will install broadband seismometers on Mars. Analyses of these exciting new data will be able to harness the enormous progress that has taken place in the last 40 years in seismological signal processing.

Plans for a proposed NASA *Europa Lander* include a seismometer, which could operate for more than 20 days on the surface. Together with gravity and magnetometry studies from the *JUICE* and NASA's *Europa Mission*, the seismometer would allow measurements of the radial depths of compositional interfaces in the ice, the ocean and the deeper interior. We present estimations of Europa's seismic wavefield using state-of-the-art finite-element simulations, taking into account seismic sources from tidal ice cracking as well as ocean circulation, building on prior studies (Kovach and Chyba 2001, Lee et al. 2003, Cammarano et al. 2006, Panning et al. 2006, Leighton et al. 2008) .

The results show that determination of the ice thickness, the ocean depth and the thickness of a sediment layer on the ocean bottom would be possible with performances comparable to those of an evolution of the *InSight SP* instrument, as proposed in the recent report of the NASA Science Definition Team.

We will also describe preliminary analyses of other ocean worlds, Enceladus, Titan, Ganymede, and Callisto, where seismic investigations may address unique science questions about their structure, composition, and possible habitability through time. Seismology may provide information about fluid motions within or beneath ice, and can record the dynamics of ice layers, which would reveal mechanisms and spatiotemporal occurrence of crack formation and propagation. Investigating these structures and processes in the future calls for detailed modeling of seismic sources and signatures, building on observations in terrestrial cryoseismology (Zhan et al. 2014, Podolskiy & Walter 2016) in order to develop the most suitable instrumentation.

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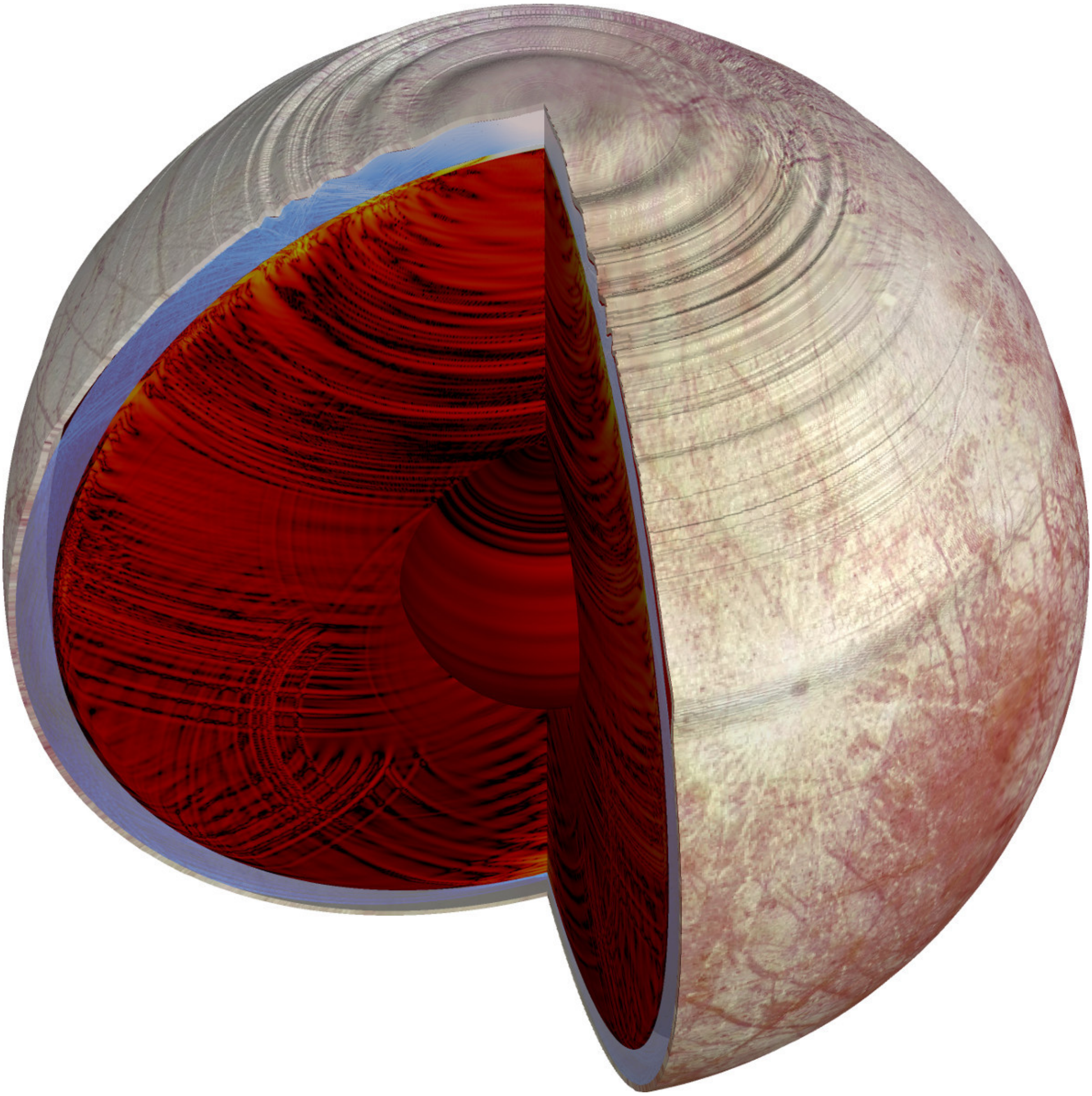
Keywords: Seismology, Icy ocean worlds, Europa



JUICE: A European Mission to Jupiter and its Icy Moons

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JUICE - JUpiter ICy moons Explorer - is the first large mission in the European Space Agency Cosmic Vision programme. The implementation phase started in July 2015. JUICE will be launched in June 2022 from Kourou, and will arrive at Jupiter in October 2029. It will spend three years characterizing the Jovian system, the planet itself, its giant magnetosphere, and the giant icy moons Ganymede, Callisto and Europa. JUICE will then orbit Ganymede for almost a year. The main goal is to explore the habitable zone around Jupiter. Ganymede is a high-priority target because it provides a unique laboratory for analyzing the nature, evolution and habitability of icy worlds, including the characteristics of subsurface oceans, and because it possesses unique magnetic fields and plasma interactions with the environment. On Europa, the focus will be on recently active zones, where the composition, surface and subsurface features (including putative water reservoirs) will be characterized. Callisto will be explored as a witness of the early Solar System. JUICE will also explore the Jupiter system as an archetype of gas giants. The circulation, meteorology, chemistry and structure of the Jovian atmosphere will be studied from the cloud tops to the thermosphere and ionosphere. JUICE will also investigate the 3D properties of the magnetodisc, and will study the coupling processes within the magnetosphere, ionosphere and thermosphere. The mission also focuses on characterizing the processes that influence surface and space environments of the moons. The payload consists of 10 instruments plus a ground-based experiment (PRIDE) to better constrain the S/C position. A remote sensing package includes imaging (JANUS) and spectral-imaging capabilities from the UV to the sub-mm wavelengths (UVS, MAJIS, SWI). A geophysical package consists of a laser altimeter (GALA) and a radar sounder (RIME) for exploring the moons, and a radio science experiment (3GM) to probe the atmospheres and to determine the gravity fields. The in situ package comprises a suite to study plasma and neutral gas environments (PEP) with remote sensing capabilities via energetic neutrals, a magnetometer (J-MAG) and a radio and plasma wave instrument (RPWI).

Keywords: Jupiter, Galilean Satellites

CASE FOR RECONSIDERING THE PLANETARY-PROTECTION REQUIREMENT FOR OCEAN WORLD EXPLORATION

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Introduction: Planetary-protection requirements for exploring solar system ocean worlds rest on a key value: limiting to one in ten thousand the probability that a single viable Earth organism will enter an alien liquid water reservoir [1]. Enforceable under international treaty, the 10^{-4} forward-contamination requirement governs missions by NASA, JAXA, and ESA. Its relevance increases as these international partners focus on places “with real water” far out in the solar system, where life unrelated to Earth life may have arisen. So it is important to understand the origin of this key requirement, and periodically to revisit the assumptions behind it. Even NASA anticipates that “these requirements will be refined in future years” [2].

The 10^{-4} requirement traces to the 1940s in the US [1, 3]. Many changes in the intervening half-century justify revisiting the requirement’s rationale: 1) vastly improved technology for assaying biomolecules and organisms; 2) expansion of the definition of self-replicating organisms; 3) expansion of the environmental ranges known to be habitable; 4) deeper understanding of how multi-cellular communities behave differently from single organisms; 5) expansion of the habitable exploration target list to include several icy moons containing vast liquid-water oceans; and 6) a sociological and international context for setting policy quite evolved since the mid-20th century.

The 10^{-4} requirement may still be appropriate for today’s exploration of places that meet textbook criteria for being habitable. But the requirement might be either technically or socio-culturally outdated, or both. Without validation by an explicit conversation among a broad, international cross-section of stakeholders, mission plans by any nation could be severely disrupted downstream. If the requirement should be modified by international consensus, starting this process now would be advisable.

Pedigree and evolution of the 10^{-4} requirement: We describe the rationale for the current requirement: its source; quantification drivers in the original debate; how it was determined to be appropriate for humanity’s first contact with Mars in particular and habitable alien environments in general; and its verifiability. We lay out the rationale for reconsidering it now, including how it has been handed down, and its validity given a prospect not envisioned in the 1970s: multiple, vast, interior salt-water oceans, with seafloor hydrothermal activity and organic chemistry.

Viability of life: Many fields affecting our understanding of how life might take hold in ocean-world environments have emerged since the Viking era: 1) biology of extremophiles; 2) detailed scenarios for the origin of life; 3) replication of non-life macromolecules including retroviruses and prions; 4) rapid evolution for survivability as environmental conditions change; and 5) how communities of microorganisms maintain local habitability. This new knowledge affect quantification of survival and replication probabilities.

Planning for low-probability, high-consequence events: We analyze limitations in how humans rationalize events with low probability but high consequence; how systematic human perception biases can be compensated; and how perceptions of risk are normalized and acculturated. We compare the current requirement to other risks in the range from 10^{-2} to 10^{-10}. We assess how decision responsibility might be distributed across stakeholders, and what voice planetary scientists can have.

Ethical basis for contaminating an alien ecosystem: We frame the low risk of contaminating an off-world ecology as one of many techno-ethical decisions facing humanity today, that must weigh consequences, compare ethical values, and accept uncertainty based on the comparison. The 10^{-4} requirement may not deserve automatic perpetuation. What status should it have within an international, ethical decision-making process? We contrast a meta-ethical discussion about absolute values with reliance on an arbitrary number governing the absolute necessity of preserving scientific discovery or protecting alien life. We describe how can an enlightened understanding and evolving consensus can flow down into governing policy.

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Keywords: Astrobiology, Planetary Protection, Ocean Worlds, Icy Moons, Exploration