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

*Fuminori Tsuchiya[1], Kazuo Yoshioka[2], Tomoki Kimura[3], Go Murakami[4], Chihiro Tao[5], Hajime Kita[1,6], Ichiro Yoshikawa[7], Atsushi Yamazaki[4], Yasumasa Kasaba[6]

1. Planetary Plasma and Atmospheric Research Center, Graduate School of Science, Tohoku University, 2. Graduate School of Science,University of Tokyo, 3. Nishina Center for Accelerator-Based Science, RIKEN, 4. Institute of Space and Astronautical Science, Aerospace Exploration Agency, 5. National Institute of Information and Communication Technology, 6. Graduate School of Science, Tohoku University, 7. Department of Complexity Science and Engineering, University of Tokyo

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.

Keywords: HISAKI, Jupiter

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

*Katherine de Kleer[1], Mizuki Yoneda[2], Imke de Pater[1]

1. University of California Berkeley, 2. Kiepenheuer Institute of Solar Physics

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

*Tomoki Kimura[1], Jonathan D Nichols[2], Rebecca L Gray[3], Chihiro Tao[4], Go Murakami[5], Atsushi Yamazaki[5], Sarah V Badman[3], Fuminori Tsuchiya[6], Kazuo Yoshioka[7], Hajime Kita[6], Denis Grodent [8], George Clark[9], Ichiro Yoshikawa[10], Masaki Fujimoto[5]

1. Nishina-Center for Accelerator Based Science, RIKEN, 2. Department of Physics and Astronomy, University of Leicester, Leicester, UK., 3. Department of Physics, Lancaster University, Lancaster, UK., 4. National Institute of Information and Communications Technology, Tokyo, Japan., 5. Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan., 6. Planetary Plasma and Atmospheric Research Center, Tohoku University, Sendai, Japan., 7. Department of Earth and Planetary Science, Graduate School of Science, University of Tokyo, Tokyo, Japan., 8. Université de Liège, Liège, Belgium., 9. The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA., 10. Department of Complexity Science and Engineering, University of Tokyo, Kashiwa, Japan.

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.

Keywords: juptier, magnetosphere, substorm

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

*Hajime Kita[1], Tomoki Kimura[2], Chihiro Tao[3], Fuminori Tsuchiya[1], Atsushi Yamazaki[4], Kazuo Yoshioka[5], Hiroaki Misawa[1], Takeshi Sakanoi[1], Yasumasa Kasaba[1], Ichiro Yoshikawa[5], Masaki Fujimoto[4]

1. Tohoku Univ., 2. Nishina-Center for Accelerator Based Science, RIKEN, 3. National Institute of Information and Communications Technology, 4. Institute of Space and Astronautical Science / Japan Aerospace Exploration Agency, 5. The University of Tokyo

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.

Keywords: Jupiter, Aurora, solar wind

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

*Chihiro Tao[1], Laurent Lamy[2], Reneé Prangé [2], Nicolas André[3], Sarah V Badman[4]

1. National Institute of Information and Communications Technology, 2. LESIA, Observatoire de Paris-CNRS, 3. IRAP, Université de Toulouse/UPS-OMP/CNRS, 4. Lancaster University

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.

Keywords: Jupiter, aurora, ultraviolet emission

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

*Yasumasa Kasaba[1], Ayumu Sasaki[1], Tomoki Kimura[2], Chihiro Tao[3], Lamy Laurent[4], Baptiste Cecconi[4]

1. Dep. Geophysics, Tohoku University, 2. RIKEN, 3. NICT, 4. LESIA

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].

Keywords: Saturn, SKR (Saturn Kilometric Radiation), seasonal variation, north-south assymetry

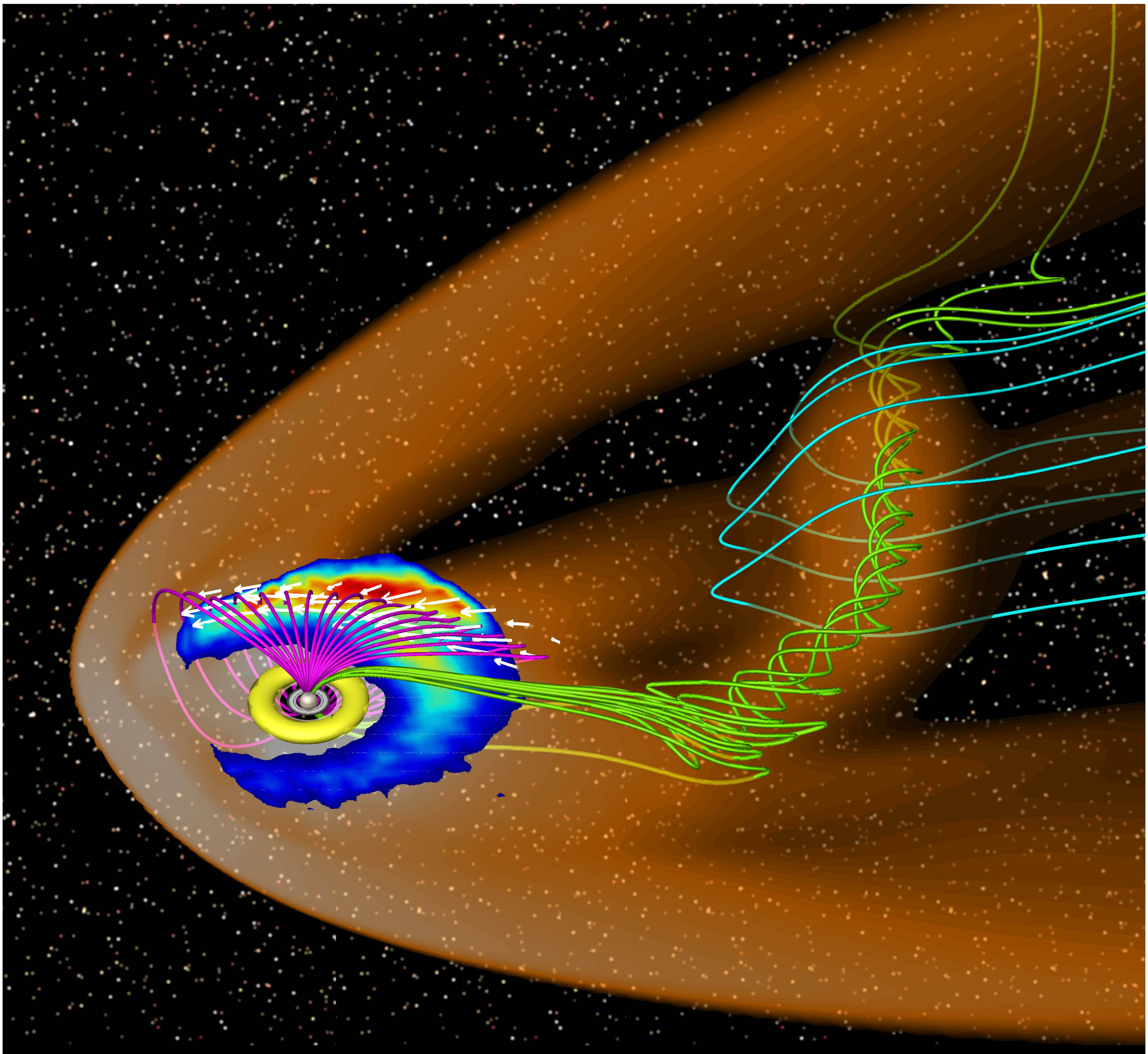
Global MHD Simulations of Saturn's Magnetosphere and Their Implications for Jupiter

*Xianzhe Jia[1]

1. University of Michigan Ann Arbor

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

*Hao Cao[1], David J Stevenson[1]

1. California Institute of Technology

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

Mark David Hofstadter[1], Amy Simon[2], *Elizabeth Turtle[3], Sushil Atreya[4]

1. Jet Propulsion Laboratory/California Institute of Technology, 2. NASA Goddard Space Flight Center, 3. Johns Hopkins University Applied Physics Laboratory, 4. University of Michigan, Ann Arbor

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

*Sushil K Atreya[1], Joong Hyun In[1]

1. University of Michigan Ann Arbor

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

*Kunio M. Sayanagi[1], John J. Blalock[1], Ulyana A. Dyudina[2], Shawn P. Ewald[2], Andrew P. Ingersoll[2]

1. Hampton University, 2. California Institute of Technology

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

Daigo Shoji[1], *Hauke Hussmann[1]

1. DLR Institute of Planetary Research

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

*Kelsi N Singer[1], S. A. Stern[1], Jeffrey M. Moore[2], William M. Grundy[3], G. R. Gladstone[1], William B. McKinnon[4], John R. Spencer[1], Paul M. Schenk[5], Jason C. Cook[6], Harold A. Weaver[7], Cathy B. Olkin[1], Leslie A. Young[1], Kimberly Ennico[2], The New Horizons Geology, Geophysics and Imaging Science Theme Team, The New Horizons Surface Composition Science Theme Team, The New Horizons MVIC Team, The New Horizons LORRI Team

1. Southwest Research Institute Boulder, 2. NASA Ames , 3. Lowell Observatory, 4. Washington University in St. Louis, 5. Lunar and Planetary Institute, 6. Pinhead Institute, 7. Johns Hopkins Applied Physics Labratory

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.

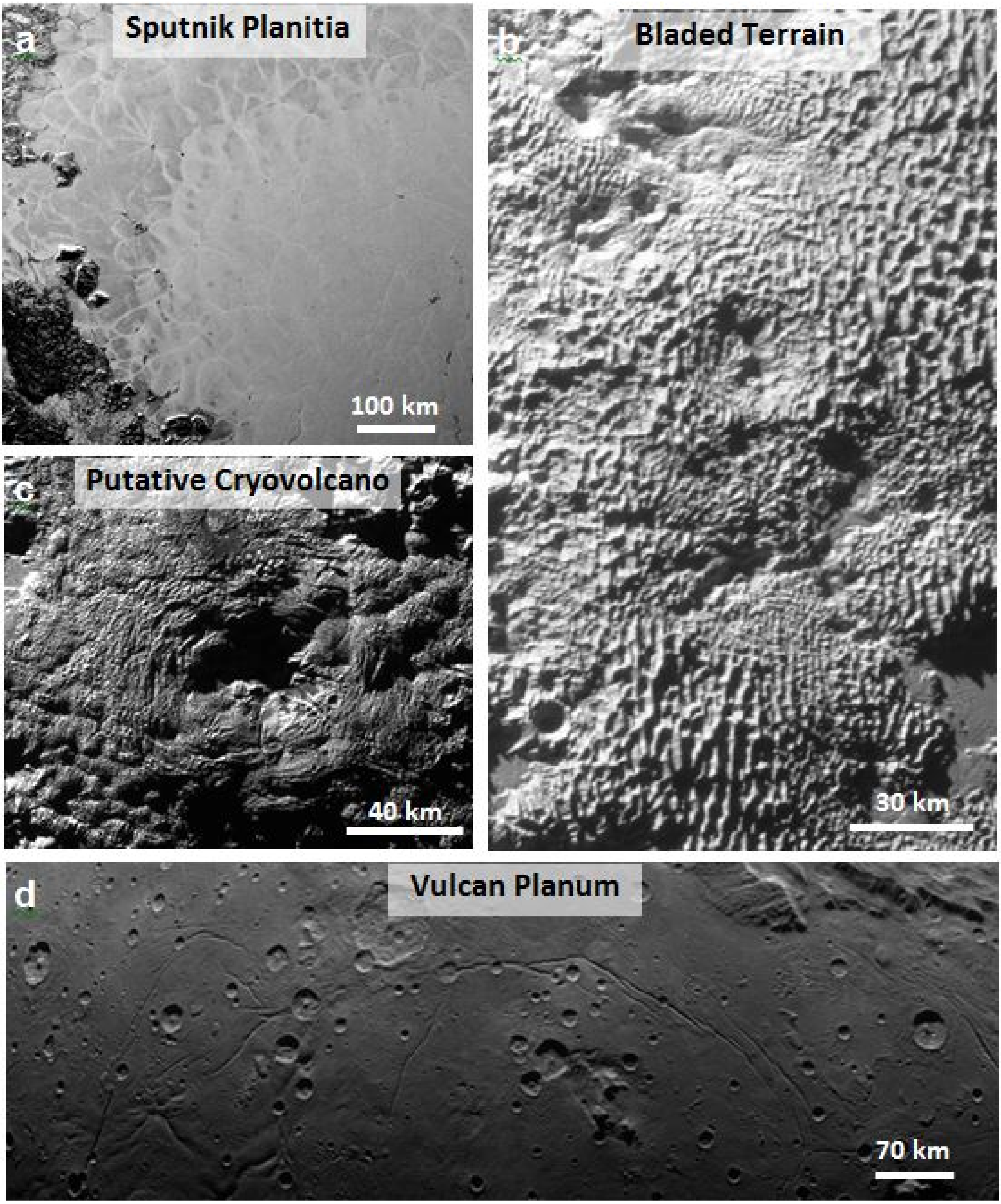
Although Pluto’s lithosphere is thought to be predominantly water ice, the volatile ices N_2, CH_4, and CO dominate much of its surface [4]. Pluto’s terrains contain many features that are likely due to sublimation and re-deposition of these volatile ices during seasonal and climactic cycles. Some examples 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.

[1] Stern S.A. et al. (2015) *Science* 350, 6258. doi:10.1126/science.aad1815
[2] Moore J.M. et al. (2016) *Science, 351,* 1284-1293. doi:10.1126/science.aad7055
[3] Gladstone G.R. et al., (2016) *Science, 351.* doi:10.1126/science.aad8866
[4] Grundy W.M. et al., (2016) *Science, 351.* doi:10.1126/science.aad9189
[5] Cook J.C. et al. (2016) *AAS/DPS abstract* id.205.03.
[6] Weaver H.A. et al. (2016) *Science 351,* aae0030. doi:10.1126/science.aae0030

[7] Singer K.N. et al. (2016) *47th LPSC abstract* #2276.

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



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

Kenny Vilella[1], *Frederic Deschamps[1]

1. Academia Sinica

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

*Elizabeth P Turtle[1], Robert T Pappalardo[2], Haje Korth[1], David A Senske[2]

1. Johns Hopkins University Applied Physics Laboratory, 2. Jet Propulsion Laboratory

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

*Simon C Staehler[1,2], Steven Vance[3], Mark Panning[4], Sharon Kedar[3], Sridhar Anandakrishnan[11], W. Bruce Banerdt[3], Bruce G. Bills[3], Fabio Cammarano[5], Julie C. Castillo[3], Hsin-Hua Huang[6,7], Philippe H. Lognonne[8], Jennifer Jackson[6], Ralph D. Lorenz[9], William T. Pike[10], Victor Tsai[6]

1. Ludwig Maximilians University of Munich, Germany, 2. Leibniz-Institute for Baltic Sea Research, Rostock, Germany, 3. Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, United States, 4. University of Florida, Gainsville, United States, 5. U. Roma Tre, Rome, Italy, 6. California Institute of Technology, Pasadena CA, United States, 7. Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, 8. Institut de Physique du Globe de Paris, Paris, France, 9. Johns Hopkins University Applied Physics Laboratory, Laurel, MD, United States, 10. Imperial College London, London, SW7, United Kingdom, 11. Pennsylvania State University Main Campus, University Park, PA, United States

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) .

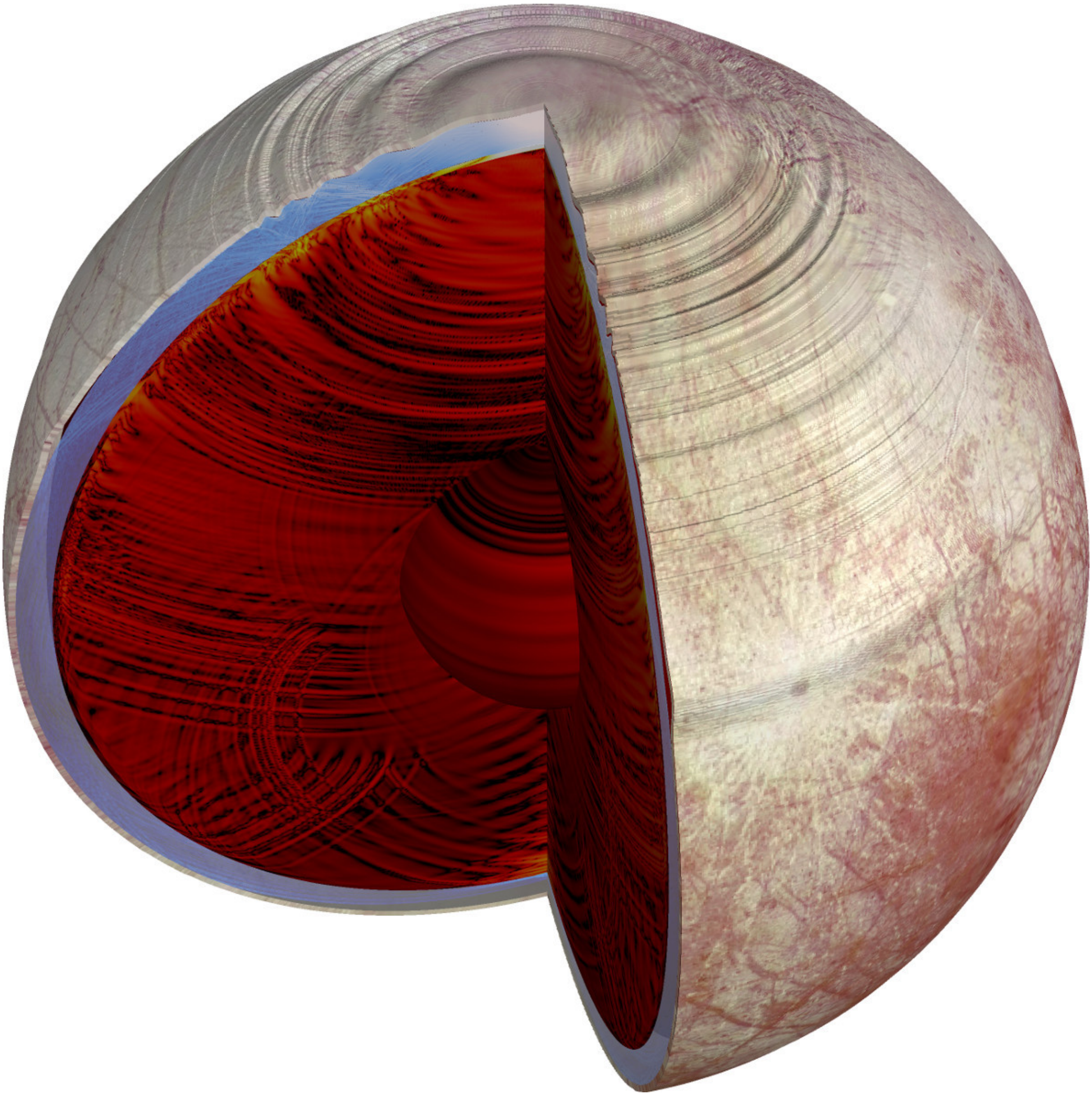
The results show that determination of the ice thickness, the ocean depth and the thickness of a sediment layer on the ocean bottom would be possible with performances comparable to those of an evolution of the *InSight SP* instrument, as proposed in the recent report of the NASA Science Definition Team.

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.

Kovach, R. L., & Chyba, C. F. (2001). Seismic Detectability of a Subsurface Ocean on Europa. Icarus, 150(2), 279–287. https://doi.org/10.1006/icar.2000.6577
Lee, S., Zanolin, M., Thode, A. M., Pappalardo, R. T., & Makris, N. C. (2003). Probing Europa’s interior with natural sound sources. Icarus, 165, 144–167. https://doi.org/10.1016/S0019-1035(03)00150-7
Cammarano, F., Lekic, V., Manga, M., Panning, M. P., & Romanowicz, B. (2006). Long-period seismology on Europa: 1. Physically consistent interior models. Journal of Geophysical Research, 111(E12), E12009. https://doi.org/10.1029/2006JE002710

Panning, M. P., Lekic, V., Manga, M., Cammarano, F., & Romanowicz, B. (2006). Long-period seismology on Europa: 2. Predicted seismic response. Journal of Geophysical Research, 111(E12), E12008. https://doi.org/10.1029/2006JE002712
Leighton, T. G., & Petculescu, A. (2008). Hydroacoustics Sounds in Space : the Potential Uses for Acoustics in the Exploration of Other Worlds. Hydroacoustics, 11, 225–238.
Zhan, Z., Tsai, V. C., Jackson, J. M., & Helmberger, D. (2014). Ambient noise correlation on the amery ice shelf, east Antarctica. Geophysical Journal International, 196(3), 1796–1802. https://doi.org/10.1093/gji/ggt488
Podolskiy, E. A., & Walter, F. (2016). Cryoseismology. Reviews of Geophysics, S4. https://doi.org/10.1002/2016RG000526

Keywords: Seismology, Icy ocean worlds, Europa



JUICE: A European Mission to Jupiter and its Icy Moons

Olivier Witasse[1], *Hauke Hussmann[2]

1. ESA ESTEC, 2. DLR Institute of Planetary Research

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

*Brent Sherwood[1], Adrian Ponce[1], Michael Waltemathe[2]

1. Jet Propulsion Laboratory, 2. Ruhr-Universitaet Bochum

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.

References: [1] Melzer, M., When Biospheres Collide: A History of NASA’s Planetary Protection Programs, 2011, NASA, Washington DC, p.78-84. [2] Conley, C. Planetary Protection for Icy Moons: Update to the 2012 SSB Europa Report, cited 2017, 1/8/2017, https://planetaryprotection.nasa.gov/missiondesign/. [3] Werber, M., Objectives and Models of the Planetary Quarantine Program, 1975, NASA, Washington DC, p. 9-11.

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

Bright spot aurorae and magnetic fields at Uranus

*Hiroaki TOH[1]

1. Data Analysis Center for Geomagnetism and Space Magnetism, Graduate School of Science, Kyoto University

One of the two ice giants in our solar system, Uranus, is as far as ~20 astronomical units away from the Earth and has been flown by Spacecraft Voyager 2 alone.

The unique spacecraft provided legendary vector magnetic data of the planet to reveal that Uranus has a strong magnetic field of its own. However, it was also found that its dipolar magnetic field, if any, is peculiar in the sense that it is not only offset from the centre of the planet but also tilted from the rotation axis as large as 60 degrees (Ness et al., 1986). Since discovery of the peculiar intrinsic magnetic field, a couple of higher-degree magnetic field models than Ness et al's (1986) offset and tilted dipole model have been proposed by analyzing the vector magnetic data precisely (Connerney et al., 1987) or adding other kind of data such as auroral ultraviolet emission observed by Voyager 2 (Herbert, 2009).

The peculiar magnetic fields at Uranus may tell us what dynamics takes place inside the ice giants, if fully understood. Which part of the Uranus’ interior is responsible for its dynamo actions? What kind of conductive fluid is the major constituent of that part? Is that part a globally distributed shell? Why is the planet’s magnetic field different from the dipolar magnetic fields like the one that the Earth bears? Doesn’t the fast rotation of the planet as fast as a slightly longer rotation period than 17 hrs influence the dynamo regime?

Lamy et al. (2012) recently reported the very first detection of the Uranus’ aurorae by Hubble Space Telescope. Their far-ultraviolet images captured two bright spot aurorae occurred in November, 2011, both of which were results of a pair of large CME events traced all the way from the Sun to the region of outer planets by the authors. The estimated latitudes of the aurorae on Uranus are between 5 degrees S and 15 degrees S, which overlaps the larger northern auroral oval of either Q3 Model (Connerney et al., 1987) or AH5 Model (Herbert, 2009) of the planet's magnetic field. Because Lamy et al. (2012) conclude that the bright spot aurorae were results of dayside reconnections, it is possible to use the far-ultraviolet images as constraints of the magnetic field at Uranus by assuming L-values of the reconnection locations and utilizing the knowledge of the interplanetary magnetic field provided by the mSWiM simulation code (Zieger and Hansen, 2008).

This paper reports the attempt of the magnetic field modelling at Uranus using the new constraints.

Keywords: magnetic fields, dayside reconnection, space telescope, Uranus, bright spot aurorae, L-value

Small Next-generation Atmospheric Probe Concept (SNAP)

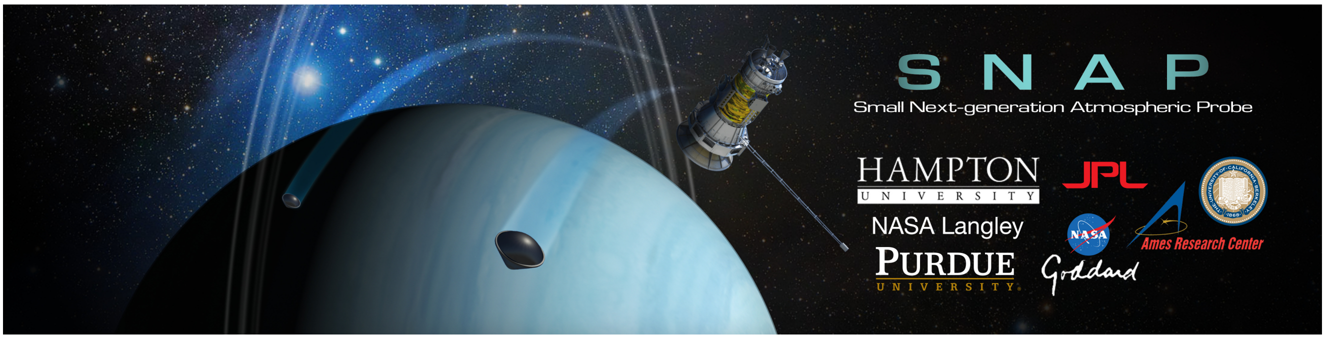
*Kunio M. Sayanagi[1], Robert A. Dillman[2], David H. Atkinson[4], Sarag Saikia[7], Amy A. Simon[3], Thomas R. Spilker[6], Michael H. Wong[5], Drew J. Hope[2]

1. Hampton University, 2. NASA Langley Research Center, 3. NASA Goddard Space Flight Center, 4. NASA Jet Propulsion Laboratory, 5. University of California, Bekerkeley, 6. Independent Consultant, 7. Purdue University

We present a concept for a small atmospheric probe that could be flexibly added to future missions that orbit or fly-by a giant planet as a secondary payload, which we call the Small Next-generation Atmospheric Probe (SNAP). SNAP's main scientific objectives are to determine the vertical distribution of clouds and cloud-forming chemical species, thermal stratification, and wind speed as a function of depth. As a case study, we present the advantages, cost and risk of adding SNAP to the future Uranus Orbiter and Probe flagship mission; in combination with the mission's main probe, SNAP would perform atmospheric in-situ measurements at a second location, and thus enable and enhance the scientific objectives recommended by the 2013 Planetary Science Decadal Survey and the 2014 NASA Science Plan to determine atmospheric spatial variabilities.

We envision that the science objectives can be achieved with a 30-kg entry probe ~0.5m in diameter (less than half the diameter of the Galileo probe) that reaches 5-bar pressure-altitude and returns data to Earth via the carrier spacecraft. As the baseline instruments, the probe will carry an Atmospheric Structure Instrument (ASI) that measures the temperature, pressure and acceleration, a carbon nanotube-based NanoChem atmospheric composition sensor, and an Ultra-Stable Oscillator (USO) to conduct a Doppler Wind Experiment (DWE). While SNAP is applicable to multiple planets, we examine the feasibility, benefits and impacts of adding SNAP to the Uranus Orbiter and Probe flagship mission.

Keywords: Giant Planets, Planetary Mission, Atmospheric Probe



Study of the solar wind influence on the Jovian inner magnetosphere using an ionospheric potential solver

*Koichiro Terada[1], Chihiro Tao[2], Naoki Terada[1], Yasumasa Kasaba[1], Hajime Kita[1], Aoi Nakamizo[2], Akimasa Yoshikawa[3], Shinichi Ohtani[4], Fuminori Tsuchiya[1], Masato Kagitani[1], Takeshi Sakanoi[1], Go Murakami[5], Kazuo Yoshioka[6], Tomoki Kimura[7], Atsushi Yamazaki[5], Ichiro Yoshikawa[8]

1. Graduate School of Science, Tohoku University, 2. Applied Electromagnetic Research Institute, National Institute of Information and Communications Technology, 3. Department of Earth and Planetary Sciences, Faculty of Science, Kyushu University, / International Center for Space Weather Science and Education, Kyushu University, 4. The Johns Hopkins University Applied Physics Laboratory, 5. Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 6. Department of Earth & Planetary Science, Graduate School of Science, The University of Toky, 7. Nishina-Center for Accelerator Based Science, RIKEN, 8. Graduate School of Frontier Sciences, The University of Tokyo

The solar wind hardly influences the plasma convection in the Jovian inner magnetosphere, because the corotation of magnetospheric plasma dominates the convection there. However, the extreme ultraviolet spectroscope (EXCEED) onboard the Hisaki satellite observed that the brightness distribution of the Io plasma torus (IPT) changed asymmetrically between the dawn and the dusk sides. Furthermore, it was confirmed that this asymmetric change coincided with a rapid increase in the solar wind dynamic pressure. This asymmetric change can be explained by the existence of a dawn-to-dusk electric field of ~4-9 [mV/m] around Io’ s orbit [Murakami et al., 2016]. The dawn-to-dusk electric field shifts the position of IPT toward dawn side. The plasma in the torus is heated adiabatically at dusk and cooled at dawn. The following processes generated by the solar wind interaction have been suggested as a possible cause of the electric field. First, the solar wind compresses the Jovian magnetosphere. Then, the magnetosphere-ionosphere coupling current system is modified, and the field-aligned current (FAC) at the high-latitude ionosphere increases. As a result, the ionospheric electric field increases and penetrates to low-latitude regions. It is mapped to the equatorial plane of the magnetosphere along the magnetic field line, and the dawn-to-dusk electric field is created in the vicinity of Io’ s orbit (~6 R_J) in the inner magnetosphere. Here the distribution and density of the FAC was observationally estimated from the divergence of the ring current on the equatorial plane using the Galileo spacecraft data [Khurana, 2001].

We have constructed a 2-D ionospheric potential solver in order to demonstrate this scenario quantitatively. We investigate how the global distribution of the ionospheric potential changes responding to the input of the FAC using the potential solver. We use the intensity of the total FAC obtained from the Galileo observation [Khurana, 2001] and adopt a Gaussian function for its horizontal distribution in a similar way to the Earth’ s modeling. Also, we model the ionospheric conductivities from the collision frequencies, the cyclotron frequencies of charged particles and the density distribution in the Jovian upper atmosphere. We deduce the collision frequencies from ion-H_2 and electron-H_2 collisions [Tao, 2009]. We need to use more accurate global distributions of the conductivities because the dawn-to-dusk electric field of at Io’ s orbit strongly depends on the spatial distributions of the ionospheric conductivities. The limited area of the ionosphere was observed by Galileo and Voyager, therefore we use a Jovian thermosphere-ionosphere-magnetoshere coupling model [Tao et al., 2014] to obtain the global thermospheric and ionospheric distributions of the density and the temperature in this study. The model considers heating caused by the precipitation of aurora electrons and provides the distributions of the conductivities around the footprint of FACs.

We calculate the Jovian electric potential distribution and the magnetospheric dawn-to-dusk electric field for the aforementioned FAC and conductivity distributions. We assume that the plasma of the IPT flow along the equipotential lines. Under this assumption, we estimate the dawnward shift of the equipotential lines which results from the dawn-to-dusk electric field and the corotation field, and the dawn-to-dusk ratio of plasma brightness. The estimated values are compared with the Hisaki observations in order to evaluate the validity of the above scenario. We will present these results.

Keywords: Jupiter, Io plasma torus

Time and spatial variations in atomic oxygen emission around Io during the volcanic active event observed with Hisaki/EXCEED

*Ryoichi Koga[1], Fuminori Tsuchiya[1], Masato Kagitani[1], Takeshi Sakanoi[1], Mizuki Yoneda[2], Ichiro Yoshikawa[3], Kazuo Yoshioka[3], Go Murakami[4], Atsushi Yamazaki[4], Tomoki Kimura[5]

1. Planetary Plasma and Atmospheric Research Center, Tohoku University, 2. Kiepenheuer Institute of Solarphysics, 3. University of Tokyo, 4. JAXA/ISAS, 5. RIKEN

We report time and spatial variations of atomic oxygen supplied from Io during the volcanic active event. The atmosphere of a Jovian satellite Io has been thought to be mainly supplied by volcanism and sublimation of surface frost. Dominant atmospheric gases are sulfur dioxide, and dissociative product such as atomic oxygen and sulfur, which are produced mainly by electron impact dissociation and photolysis. Neutral oxygen and sulfur escape from exobase to neutral cloud (> 5.8 Io radius) mainly by atmospheric sputtering (torus ions collide with several neutrals). However, the characteristics of spatial and time variations of atomic oxygen and sulfur escaping from Io are not well understood.
The brightening event of the Io’ s extended sodium nebula was reported by the ground imaging observation in the spring of 2015 [*Yoneda et al.,* 2015]. We therefore examined the time variation of atomic oxygen emission at 130.4 nm around Io obtained with Hisaki/EXCEED from 27 November 2014 to 14 May 2015 (from day of year (DOY) -35 to 134) and compare the result with the brightening event of the Io's extended sodium nebula. We accumulated observed counts within 46” centering at Io for one day to obtain enough signal to noise ratio. We found the atomic oxygen emission increased by 2.5 during the volcanically active period of DOY 20-110 of 2015. The time variation of atomic oxygen emission was well correlated with that of sodium emission until the brightness maximum on DOY 50 of 2015. In the meanwhile, the duration of atomic oxygen brightness declining from the maximum to the quiet level (60 days) was longer than that of sodium nebula (40 days).
In addition, we investigated Io phase angle (IPA) dependence of atomic oxygen emission at 130.4 nm averaged for the distance range of 4.5-6.5 Jupiter radius from Jupiter in the dawn and dusk sides, respectively during volcanically quiet period (DOY -35 and -1). Then, we found following two important observation fact. First, weak atomic oxygen emission (4-6 Rayleighs (R)) continuously existed on both dawn and dusk sides not depending on the phase angle. This suggests that small amount of atomic oxygen distributes uniformly along the Io's orbit. Second, the emission averaged between IPA 60-90 degrees (14.0 R) was larger than that between IPA 90-120 degrees (10.5 R) for the dawn side, and the emission between IPA 240-270 degrees (15.8 R) was larger than that between IPA 270-300 degrees (12.3 R) for the dusk side. We can explain this difference if the large amount of atomic oxygen spread inward and ahead of Io’ s orbit and shape like banana expected by the model of atomic oxygen neutral clouds such as *Smyth and Marconi* [2003]. The emission of this banana-shape neutral oxygen cloud was almost included in the region between the distance of 4.5-6.5 Jupiter radius from Jupiter when IPA 60-90 degrees, but that was partly excluded in the same region when IPA 90-120 degrees. The similar tendency was also seen in the dusk side. In this poster, we also present the IPA dependence of atomic oxygen emission during volcanically active period (DOY 20-110), and show different and common points between atomic oxygen distribution around the Io's orbit during volcanically quiet period and that during volcanically active period.

Keywords: Io, Jupiter, Hisaki

Variation of ion and electron temperature on Io plasma torus during an outburst measured with Hisaki/EXCEED and gourd-based telescope

*Masato Kagitani[1], Mizuki Yoneda[2], Fuminori Tsuchiya[1], Kazuo Yoshioka[3], Tomoki Kimura[5], Go Murakami[4], Atsushi Yamazaki[4], Ichiro Yoshikawa[3]

1. Planetary Plasma and Atmospheric Research Center, Graduate School of Science, Tohoku University, 2. Kiepenheuer Institute for Solar Physics, 3. The University of Tokyo, 4. ISAS/JAXA, 5. RIKEN

Volcanic gases (mainly composed of SO_2, SO and S) originated from jovian satellite Io are ionized by interaction with magnetospheric plasma and then form a donut-shaped region called Io plasma torus. Ion pickup is the most significant energy source on the plasma torus thought, additional energy source by hot electron is needed to explain energy balance on the neutral cloud theory (e.g. Daleamere and Bagenal 2003). In fact, *in-site* measurements by Galileo indicates some injections of energetic particles in the middle magnetosphere. Recent EUV spectroscopy from the space shows fraction of hot electron increases as increase of radial distance in the plasma torus (Yoshioka et al., 2014; Steffl et al., 2004). On this study, we focus on variability of electron temperature derived from EUV diagnostics measured by HISAKI/EXCEED after a volcanic outburst in 2015, as well as ion temperatures parallel and perpendicular to the magnetic field measured from the ground-based spectroscopy.

The ground-based observation of sulfur ion emission, [SII] 671.6nm and 673.1nm from Io plasma torus was made at Haleakala Observatory in Hawaii from November 2014 through May 2015 with the high-dispersion spectrograph (R = 67,000) with an integral field unit (IFU) coupled to a 40-cm Schmidt-Cassegrain telescope. The IFU consist of 96 optical fibers (core/crad/jacket diameter are 50/125/250 micro-meters, respectively). The fibers are arranged in 12 by 8 array at the telescope focus which makes high-resolution spectroscopy over field-of-view of 41" by 61" with a spatial resolution of 5.1" on the sky. Two-dimensional Doppler measurements enables to derive spatial distribution of [SII] emissions as well as their temperatures parallel and perpendicular to the magnetic field. We also made observation of neutral sodium cloud extending up to several hundred of jovian radii as a proxy of supply of neutral particles from Io (Yoneda et al., 2015).

We also employee EUV spectroscopy of Io plasma torus with EUV space telescope Hisaki EXCEED from December 2014 through May 2015. We have made spectral fitting as the following method. First, we made series of EUV spectra averaged over five days. Next, assuming azimuthal homogeneity of Io plasma torus, Abel inversion is made to reduce line-of-sight integration effect. Then, we made fitting of observed EUV spectra (60 - 140 nm) with CHIANTI model spectra by changing electron density and temperature, mixing ratio of ions (S^+, S^{++}, S^{+++}, O^+ and O^{++}) and fraction of hot electron (Te = 100 eV).

Based on observation of neutral sodium cloud (Yoneda et al., 2015), neutral supply started to increase at around DOY= 10, was at maximum at around DOY = 50, and has backed into the initial levels at around DOY = 120. In contrast, plasma diagnostics indicates that hot electron fraction at 7.0 jovian radii was less than 2 % before DOY = 50, started to increase after DOY = 50, and have reached 8(+/-1) % at DOY = 110. In addition, ion temperatures from ground-based observation started to increase after DOY=50 as similar tread of increase of hot electron fraction. EUV emission from aurora was also activated after DOY = 50 as increase of hot electron fraction on the plasma torus. In the presentation, we will introduce a possible scenario that explain variations of ion and electron temperatures after the outburst in early 2015.

Temperature variation of sulfur ions in the Io plasma torus associated with a volcanic event with the Hisaki/EXCEED and ground-based observations

Mika Shishido[1], *Takeshi Sakanoi[1], Masato Kagitani[1], Fuminori Tsuchiya[1], Ichiro Yoshikawa[2], Atsushi Yamazaki[3], Kazuo Yoshioka[4], Go Murakami[3], Tomoki Kimura[5]

1. Planetary Plasma and Atmospheric Research Center, Graduate School of Science, Tohoku University, 2. Graduate School of Frontier Sciences, The University of Tokyo, 3. Institute of Space and Astronautical Science, JAXA, 4. Graduate School of Science, The University of Tokyo, 5. Riken

We report the time and spatial variation of sulfur ion emission lines from the Io plasma torus to understand the dynamical process in the torus associated with Io's volcanic event during the period from December 2014 to March 2015, using the data obtained with Hisaki/EXCEED (Extreme Ultraviolet Spectroscope for Exospheric Dynamics).

A large quantity of gas is ejected from Io's volcanoes, principally oxygen and sulfur atoms and their compounds. Once they are ionized through electron impact or charge exchange, the ions are accelerated to the nearly corotational speed of the ambient plasma to form a torus of ions (the Io plasma torus, about 6 from the center of Jupiter) surrounding Jupiter. The fresh ions lose their pickup energy to the ambient electrons through Coulomb collisions. Ultimately, the torus electrons lose energy by transiting electron energy state of ions into higher states, leading to the prodigious extreme ultraviolet (EUV), ultraviolet, and visible emissions from the torus.

During the period from December 2014 to March 2015, Io's outburst was observed by EXCEED, and the increase in the pickup ions were anticipated along with the increase in the neutral gas. To investigate energy flow from ions to electrons during the Io's outburst period, we derived sulfur ion temperatures parallel to magnetic field lines from the brightness scale height of the ion along the field line. From the spectral images of sulfur ion emission at 76.5 nm (SII), 68.0 nm (SIII) and 65.7 nm (SIV) observed by EXCEED, we identified the time variation of sulfur ion temperature increasing associated with enhanced volcanic activities, and interpreted that this was due to increase in the fresh ions by ion-pickup process. We also carried out the measurement of SII 671.6 nm emission with a monochromatic imager on the T60 telescope at Haleakala, Hawaii, which has a high spatial resolution capability, and found similar variation in ion temperature. We also evaluated the spatial resolution of EXCEED by comparing the brightness scale heights which were derived from EXCEED and T60, and then corrected the value of broadened scale height by EXCEED.

Furthermore, in order to interpret how electrons and ions exchange their energy, we reproduced the observation result (i.e., time variations of sulfur ion temperature, hot electron fraction, core electron temperature, and ion composition in the torus) using the zero-dimensional time evolution model based on *Delamere and Bagenal* [2003]. From the model we found that increase of hot electron fraction causes increase of core electron temperature, and makes the subsequent increase of new ion pickup via electron impact due to the increase of core electron temperature. Concerning the difference in the magnitude relationship among the sulfur ion temperature of SII, SIII, and SIV obtained from observed data and modeled value, we reproduced the spatial distribution of the Io torus along the magnetic field and found that the brightness scale height of roughly decreases by 60 % under conditions of the temperature anisotropy (T_S+perp / T_S+para) of 5. Related to the decrease in the brightness scale height of SII, the magnitude relationship among three of ion species obtained with our model significantly approached to that in the observed EXCEED data.

Keywords: Jupiter, Io, Hisaki

Variations of System IV period of the sulfur ions in the Io torus for the volcanic event in 2015

*Arakawa Ryo[1], Hiroaki Misawa[1], Fuminori Tsuchiya[1], Masato Kagitani[1], Ichiro Yoshikawa[2], Kazuo Yoshioka[2], Fumiharu Suzuki[2], Tomoki Kimura[3], Go Murakami[4], Atsushi Yamazaki[4]

1. Planetary Plasma and Atmospheric Research Center, Graduate School of Science, Tohoku University, 2. Department of Earth and Planetary Science, Graduate School of Science, University of Tokyo, 3. Nishina-Center for Accelerator Based Science, RIKEN, 4. Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency

Previous ground-based and probe observations of Io plasma torus (IPT) in visible, near-infrared and extreme ultraviolet (EUV) wavelengths have detected a periodic time variation whose period is longer than System III Jupiter’s rotation period (9.925 h). It has been called System IV period (~10.21 h). The “dual hot electron model” in which hot electron populations has two azimuthal variations corotating at System III period and sub-corotating at System IV period is proposed to account for the System IV period measured by the Cassini UVIS observation (Steffl et al., 2008). However, little progress has been made in explaining an origin of the System IV period.

The Cassini UVIS observation of IPT was made just after Io’s volcanic eruption in 2000. It is reported that the System IV period derived from the Cassini observation was 10.07 h, which was shorter than the typical System IV period of 10.21h (Steffl et al., 2006). The causal relationship between plasma source enhancement due to the volcanic event and change in the System IV period is not clear from the Cassini observation. Here, we analyzed time variations in EUV emissions from IPT obtained by the HISAKI satellite to understand the mechanism responsible for the System IV period and the influence of Io volcanic activity on IPT.

The observation period used in this study is from December 2014 to the middle of May 2015. During this period, enhancement of Io volcanic activity from January to March 2015 was reported from the observation of Iogenic sodium emission (Yoneda et al., 2015). To find variations of the System IV period in the EUV brightness, the System III longitude at peak EUV intensity was derived by the following procedure: (1)Extracting the time variations of sulfur ion emission intensity at S II 76.5 nm + 126 nm , S III 68 nm, and S IV 65.7 nm + 140.5 nm every 10 days (data window) from the HISAKI Level-2 data. (2) Selecting the data of Io phase angle range from 0-45 degrees (180-225 degrees) in dawn (dusk) side, which corresponds to the downstream region of Io, to remove the dependence of EUV brightness on Io’s position. (3) Plot the data as a function of the System III longitude. (4) Fitting a second order sinusoidal curve to the data, where the first and second order terms correspond to the System III period and the half of System III period, respectively. The half of the System III period is produced because the rate of electron impact ionization of sulfur ions increases at the intersection of the centrifugal and rotational equator. The time variation in the phase of the component of the first order term indicates the System IV modulation. From the analysis, the System IV periods of SII 68 nm before and after the volcanic event (Dec. 1, 2014 - Jan. 20, 2015 and April. 20 - May 14, 2015, respectively) were roughly 10.10 h and 10.07 h, respectively. During the volcanic event, the System IV period was 9.97 h. This is the first observational evidence which shows that the System IV period has shortened after the enhancement of Io volcanic activity.

Origin of the System IV period has been discussed with sub-corotation of plasma in IPT; since the sub-corotation occurs due to mass loading of newly picked-up ions into IPT, it is expected that the System IV period becomes long during the Io volcanic event. However, the result derived from the HISAKI observation shows the opposite feature and will give important information to constrain the origin of the

System IV period.
We plan to derive the ion composition, electron density, electron temperature, and hot electron fraction in IPT by EUV spectral diagnosis analysis. Comparing the plasma parameters with the change in the System IV period presented here, we try to understand the influence of Io volcanic activity on the Jovian magnetosphere in detail.

Keywords: Io plasma torus, Io volcanic eruption, System IV period

Short-term variation of Jupiter's synchrotron radiation associated with solar-wind-driven electric field: a simulation study

*Sooman Han[1], Hajime Kita[2], Atsushi Yamazaki[3], Go Murakami[3], Fuminori Tsuchiya[2], Masato Nakamura[3]

1. Department of Earh and Planetary Science, Graduate School of Science, The University of Tokyo, 2. Planetary Plasma and Atmospheric Research Center, Graduate School of Science, Tohoku University, 3. Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency

Radiation belt is a layer of energetic particles (~few tens MeV) held by geomagnetic fields, ranging up to several planetary Radii in distance. Jovian Radiation Belt, where in-situ measurement is limited, Jupiter's synchrotron radiation (JSR) observation is a key tool for determining physical process therein, and various diffusion models have been proposed to account for observed JSR's short-term and long-term variations as well as the steady profile of it. As for the short-term variation, where the toal JSR flux density varies by a few % over a few days or weeks, it is theoretically backed by fluctuating dynamo electric field at Jupiter's upper atmosphere correlated with solar UV/EUV flux [Brice and Mcdonough, 1973], supported by a number of researches. Amid the situation, Extreme ultraviolet spectroscope HISAKI has found evidence of another type of electric field - solar-wind-driven convection electric field inside Jupiter's magnetosphere [G. Murakami et al. 2016], from which one can expect enhanced radial diffusion inside the magnetosphere too.
In this research, I show the result of my numerical calculation on radial diffusion driven by the estimated convection electric field correlated with solar wind dynamic pressure and synchrotron radiation variation resulted therefrom and suggest that observed short-term variation in the past can be explained by solar-wind-driven convection electric field as well.

Keywords: Jupiter, Synchrotron, HISAKI

Thermal evolution and stability of subsurface ocean in Pluto

*Jun Kimura[1], Shunichi Kamata[2]

1. Osaka University, 2. Hokkaido University

NASA's New Horizons spacecraft made its close flyby of the dwarf planet Pluto on July 14, 2015. The LORRI imaging system aboard spacecraft has acquired surface images and unveiled a diverse range of landforms, from rugged mountainous region to extremely smooth plains, indicating geological processes that have modified the surface substantially and recently. Accurate determinations of Pluto's radius from different images suggest that Pluto is almost perfectly spherical and had or has a relatively warm interior (maybe an ocean) for the most part of its history.

The New Horizons spacecraft has confirmed that N_2, CH_4 and CO ices are enriched in the heart-shaped bright smooth plains, e.g., Sputnik Planitia (SP). In parallel, water ice is widely distributed on Pluto, in particular, on rugged mountainous region and normal faults having relatively older age than SP. It implies that Pluto is covered by huge amount of water ice and few-km thickness nitrogen presents above water ice “bedrock” based on the molecular abundances in the Solar System.

Assuming the Pluto’s interior consists of two components, water and rock, and completely differentiated state, we find that a high-pressure ice layer could appear at the bottom of the water layer in case of a denser (smaller) rock core according to the Pluto’s bulk density. Here we are going to show the results of numerical simulation for the thermal history in Pluto considering various interior structures and initial thermal states, and to discuss this dwarf planet far away from the Sun could have a potential to harbor an ocean.

The effect of clathrate formation on concentrations of ammonia and ammonium ion in a subsurface ocean of Enceladus

*Ryusuke Nishitani[1], Atsushi Tani[2], Sho Sasaki[1], Jun Kimura[1]

1. Department of Earth and Space Sciences, School of Science, Osaka University, 2. Graduate School Human Development and Environment, Kobe University

The Saturn's icy moon Enceladus could have a global subsurface ocean beneath the icy shell. Cassini spacecraft has found water plumes near the south pole and investigated those components. The Cassini INMS (Ion and Neutral Mass Spectrometer) data showed that the plume includes H_2O, CH_4, CO_2, NH_3, and many other organic materials. Basically, these components reflect those of subsurface ocean but it might be affected by clathrate formation in the ocean and its decomposition process through the pluming activity. Clathrate hydrates are crystalline inclusion compounds, in which hydrogen-bonded water molecules form cages containing hydrophobic gases called guest molecules. Bouquet et al. (2015) suggests that clathrate hydrate should be stable in the icy shell deeper than 22 km in Enceladus. To understand the chemical environment of the subsurface ocean, we need to evaluate the effect of clathrate formation on chemical concentrations in the seawater and/or the plume. We considered an inclusion of ammonium ion into clathrate hydrate. Cassini INMS data showed that a mixing ratio of ammonia in the plume is 0.8%. Ammonia does not form clathrate hydrate, while ammonium ion can be replaced with a part of water cages of clathrate hydrate. The inclusion of ammonium ion into clathrate hydrate could affect the concentration of ammonium ion in the subsurface ocean, therefore, we experimentally investigated the amount of ammonium ions that can be included into clathrate hydrate and evaluated the concentration of ammonium ions and ammonia in Enceladus's subsurface ocean.

Clathrate hydrate was crystallized in the ammonium salts solution and the concentration of ammonium ion in the hydrate and that in the residual solution were measured. As a guest molecule of clathrate hydrate, we used tetrahydrofuran (THF) as an analogue for CH_4 and CO_2. And we used ammonium chloride as an ammonium salts because chloride has been detected in the Enceladus plume. Finally, we measured the concentration of ammonium ion in THF hydrate (C_s) and the concentration of ammonium ion in residual solution (C_L) and determined the partition coefficient, the ratio of C_s to C_L ($K_D=C_s/C_L$). From the partition coefficient and the ammonia concentration observed by Cassini, we calculated a change of concentration of ammonium ion in the plume with time and estimated a possible range of concentration of ammonium ion and that of ammonia in the present subsurface ocean.

Keywords: Enceladus, clathrate hydrate, ammonia, ammonium ion