Bright spot aurorae and magnetic fields at Uranus

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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)

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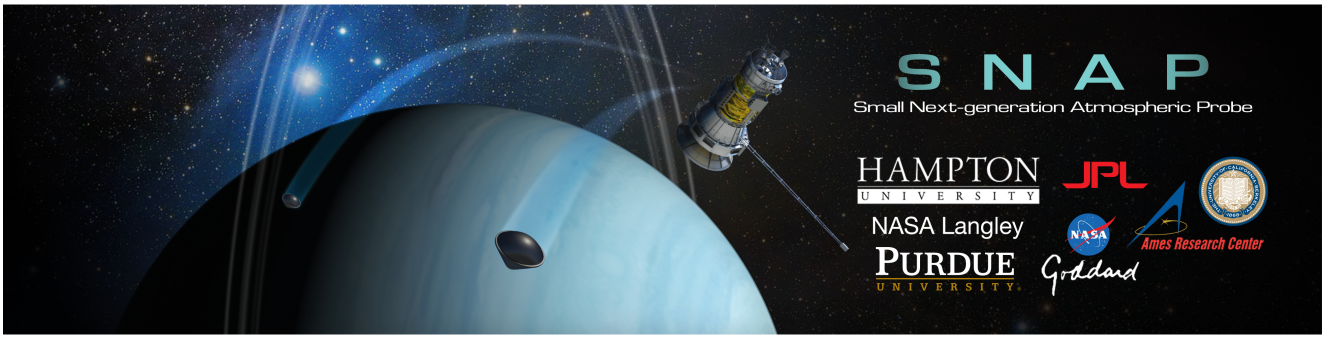
We present a concept for a small atmospheric probe that could be flexibly added to future missions that orbit or fly-by a giant planet as a secondary payload, which we call the Small Next-generation Atmospheric Probe (SNAP). SNAP’ s main scientific objectives are to determine the vertical distribution 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

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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

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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

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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

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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

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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

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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

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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

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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

