Slope and roughness characteristics derived from high-resolution images of Galilean satellites

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Topographic data is fundamental information to investigate geology at various scales. The Galileo spacecraft has obtained high-resolution images of the Galilean satellites at a scale up to approximately ten meters per pixel, which provide an insight into diverse geologies and surface materials associated with tectonics, cratering, and sublimation. Putative subsurface oceans on Europa, Ganymede, and Callisto indicated by inductive magnetic fields and aurorae shifting are top priority for the next planetary exploration. Measuring topography at a scale of ten-meter also could be essential for designing radar sounder, laser altimeter, and lander. These instruments are expected to detect putative subsurface oceans on Jovian icy satellites. Nevertheless, no quantitative topographic data at the scale has yet been obtained, except for the surface of Europa. This is mainly consequence of previous digital elevation models (DEMs) with spatial resolutions higher than 50 m being only available for the southeast region of the Tyre crater of Europa (33 m/pixel). Current knowledge of topographic features of the Galilean satellites is only derived from stereo image (SI) analysis or photoclinometry (PC) because of the absence of laser altimetry data. The slopes and roughness strongly depend on the spatial resolution of topographic data. In general, higher spatial resolution provides steeper slope histograms. We reexamined high-resolution images obtained by the SSI camera onboard the Galileo spacecraft using SI analysis and PC.
As for SI analysis, we used Integrated Software for Imagers and Spectrometers (ISIS3) produced by USGS to calibrate the SSI raw images radiometrically and perform bundle adjustment. Then we applied NASA's Ames Stereo Pipeline software (ASP) to compute DEMs. ASP is a suite of automated SI analysis tools developed by NASA and designed for processing planetary images. To compute the slope, we i) selected a pixel from a DEM, ii) computed a least squares plane in a seven-pixel square centered around the selected pixel, iii) obtained the gradient of the least squares plane (the slope is defined as the gradient), and iv) performed (i) to (iii) over the entire DEM. Then, the total surface area of each DEM was normalized to 1. To compute roughness, we defined the roughness as the Allan deviation of differences in height (i.e. RMS deviation). In detail, we i) measured the difference in height between two points separated by a given distance (i.e. window length) along lines of constant longitude, ii) performed (i) over the entire DEM and collected differences in height over the entire DEM, and (iii) computed the Allan deviation of all differences in height obtained in (ii).
PC uses apparent brightness to estimated slope at each pixel, assuming a photometric function. We applied a photometric function that fits lunar-like surface. In order to compute roughness, we converted the slopes into height differences for each pixel. Then we integrated the height differences along the line of sight to construct one-dimensional topographic cross-section from line to line. Here roughness is defined as the Allan deviation of differences in height between two points separated by a given distance along the line of sight. We showed an average of the Allan deviation values for each window length among the all one-dimensional topographic profiles.
As a result, we obtained the slope histograms and roughness from SI analysis and PC. We found that most of Ganymede and the region of Callisto showing abundant knobs appear to be very rough surfaces as steep as 10 to 30º, while Europa and the region of Callisto without knobs mostly appear to be smoother than 10º. These results are far from previous estimates based on topographic data with the lower resolution. Also, this implies that instrument performances are expected to be strongly

affected by the steep slopes in the former areas.

Stability of subsurface oceam in Ganymede

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The outer solar system provides potential habitats for extra-terrestrial life. Past spacecraft’s and telescopic observations support that the Jovian icy moons may harbor water oceans beneath the icy crusts. However evidence for oceans is not definitive and awaits confirmation measurements. Also their depth and composition remain unclear, as do their stability and variability with time. Here we focus on Ganymede, the largest moon in the Solar System and the primary target the Jupiter Icy Moons Explorer (JUICE). To investigate the stability of an ocean (structural, thermal and compositional change through time) assumed to be initially in an entirely liquid state, we performed numerical simulations for the internal thermal evolution using an one-dimensional spherically symmetric model for the convective and conductive heat transfer, with radial dependence of viscosity, heat source distribution, and other material properties. We take into account the energy due to decay of long-lived radioactive elements and also evaluate the effect of tidal heating. To see the temporal change of the boundary position between solid ice layers including ice shell and high-pressure ice mantle, we also evaluate the energy balance at the phase boundaries between the solid and liquid H_2O layer, and the movements of the positions of these boundaries are calculated by evaluating the heat balance between incoming and outgoing flux at the boundaries considering with latent heat (classically known as a Stefan problem).

Feasibility of the exploration of the subsurface structures of Jupiter’s icy moons by Jovian hectometric radiation

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A new method for detection of the subsurface structures in the ice crust of Jupiter’s moons by using interference patterns found in the spectrogram of the Jovian hectometric radio emissions (HOM) have been proposed. In Jupiter icy moon explorer (JUICE) mission, plasma wave observation around icy moons are planned by using radio and plasma wave instrument (RPWI). In this observations, we will be able to obtain spectrograms of the HOM propagating from Jupiter. Because the emissions directly from Jupiter can be interfered with the emissions reflected at the icy moon’s surface and subsurface boundaries, we will find interference patterns in the measured spectrograms. In case of the Earth's Moon, the lunar orbiter SELENE detected the interference patters in the spectrograms of auroral kilometric radiation (AKR) [Ono et al., 2010; Goto et al., 2011]. Because the interference occurs between AKR directly from the earth and AKR reflected at the lunar surface, the amplitude of the interference patterns are almost constant. In case of Jupiter’s icy moons, HOM directly from Jupiter, HOM reflected at the icy crust surface, and HOM reflected at the fully-freezed/partial-melted or high/low-porosity boundary in the ice crust. Due to slight phase difference between HOM emissions reflected at the surface and subsurface boundaries, the amplitude of the interference patterns will be modulated. The depth of the liquid ocean can be determined the frequency width of the modulation. Assuming that the frequency of HOM is ~10 MHz, the permittivity of the icy crust is 3, permittivity of the melted ice is 87, loss rate in the icy crust is 2-9 dB/km, and spacecraft height is 500 km, the maximum detection depth is estimated to be 6-23 km, which is less than the estimated ice thickness of the Ganymede, 150 km [Kivelson et al., 2002]. On the other hand, we can also expect lower attenuation rate than 2-9 dB/km in a depth range where the ice temperature is much lower than 240 K. The receiver’s specifications needed for measurement of the interference patterns in the spectrogram are as follows: (1) Frequency resolution: 100 Hz, and (2) The interval of spectrum measurements: 30 sec. In addition, the following two issues have to be considered in actual application: (a) HOM itself has band structures in the spectrogram due to anisotropy of the emission at the source. (b) The roughness of the surface and subsurface boundaries has to be within the half wavelength (~15 m). (c) The delay by inhomogeneity of TEC of the moon’s ionosphere has to be less than the half of the period of the HOM (~0.05msec), which corresponds to the dTEC ~ 9.3×10^{12} m^{-2}.

Keywords: Passive subsurface radar, Jupiter Icy Moon Explorer (JUICE), Radio and plasma wave instrument (RPWI)

Software-type Wave-Particle Interaction Analyzer (SWPIA) by RPWI for JUICE: Science objectives and implementation

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We present science objectives of Software-type Wave-Particle Interaction Analyzer (SWPIA), which will be realized as a software function of Low-Frequency receiver (LF) running on the DPU of RPWI (Radio and Plasma Waves Investigation; PI: J.-E. Wahlund, IRF-Uppsala, Sweden) for the ESA JUICE mission. SWPIA conducts onboard computations of physical quantities indicating the energy exchange between plasma waves and energetic ions. Onboard inter-instruments communications are necessary to realize SWPIA, which will be implemented by efforts of RPWI, PEP (Particle Environment Package; PI: Stas Barabash, IR-Kiruna, Sweden) and J-MAG (JUICE Magnetometer; PI: M. Dougherty, ICL, UK). By providing the direct evidence of ion energization processes by plasma waves around Jovian satellites, SWPIA contributes scientific output of JUICE as much as possible with keeping its impact on the telemetry data size to a minimum.
SWPIA measures the energy transfer process between energetic particles and electromagnetic plasma waves [Fukuhara et al., EPS 2009; Katoh et al., AnGeo 2013]. SWPIA will be firstly realized in the ERG satellite mission of JAXA to measure interactions between relativistic electrons and whistler-mode chorus in the Earth's inner magnetosphere. We will apply SWPIA to ion-scale wave-particle interactions occurring in the Jovian magnetosphere. SWPIA clarifies where/when/how heavy ions are energized by waves in the region close to Ganymede and other Jovian satellites. In SWPIA of RPWI for JUICE, we focus on the interactions between energetic ions (a few to tens of keV) and ion cyclotron waves (typically less than 1 Hz). SWPIA uses wave electromagnetic field and ion velocity vectors provided by RPWI sensors and PEP, respectively, with referring three-components of the background magnetic field detected by J-MAG. SWPIA measures a relative phase angle between the velocity vector vi of i-th particle of charge qi and the wave electric field vector at the timing of particle's detection (E(ti)) and computes an inner product of W(ti) = qiE(ti) dot vi, where W(ti) corresponds to the variation of the kinetic energy of the i-th energetic particle. We accumulate W for detected particles to obtain Wint = Sigma_i W(ti), and we expect statistically significant values of Wint for the case of the measurement at the site of efficient wave-particle interactions. In this presentation, we discuss details of the implementation of SWPIA of RPWI and inter-instruments communications among RPWI-PEP-J-MAG of JUICE.

Keywords: Jovian magnetosphere, Jovian satellite, wave-particle interactions

evelopment of a low-energy energetic neutral atom analyzer (PEP/JNA) for JUICE

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We are developping a low-energy (10eV-3keV) energetic neutral atom analyser (PEP/JNA) which is to be onboard European JUICE spacecraft. Ganymede has its own intrinsic magnetic moment. There is considered to be a mini-magnetosphere around Ganymede because of interactions between plasma in Jovian magnetosphere and Ganmede's magnetic field. However, its characteristics will be different from terrstrical one, since Alfven mach number of upstream plasma flow (corotational plasma flow around Jupiter) is small. JNA (Jovian Neutral Analyzer) will reveal characteristics of Ganymede's magnetosphere in terms of measurement of scattered/sputtered particles generated by precipitation of plasma particles onto Ganymede's surface. Measurement of these particles will provide spatial distribution of plasmas in remote sense, since electric/magnetic field do not affect trajectories of neutral particles. We will discuss current status of JNA.

Keywords: Energetic neutral atom, JUICE

Responses of Io Plasma Torus to middle magnetosphere of Jupiter

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The satellite of Jupiter, Io, is volcanically active and ejects ionized gas such as sulfur and oxygen into space. This gas forms a torus encircling Jupiter along the orbit of Io, and called Io Plasma Torus (IPT). Jupiter has by far the most energetic and brightest aurorae in the solar system. During the Cassini spacecraft’s flyby of Jupiter (October, 2000-March, 2001), the UV spectrometer witnessed a puzzling phenomenon. Both of IPT and Jupiter’s aurorae were sometimes brightened almost simultaneously. The torus emissions reflect the state of the inner magnetosphere while the aurora emissions are an index of activity in the middle magnetosphere. This fact might suggest an energy transport process from the middle to inner magnetosphere, but it has not been understood yet. The dataset of Cassini was insufficient to reveal the process due to its low-temporal resolution. The HISAKI/EXCEED was launched in September 2013 by the Epsilon rocket. Now it is orbiting around the Earth. EXCEED is a space telescope dedicated for planets and has an advantage of long-term and continuous monitoring of the aurorae and IPT at the same time. We find that electron temperature in IPT increases 11 hours after the transient aurora brightening events. It suggests inward flow of hot electrons from the middle magnetosphere to IPT. On middle of January 2015, EXCEED observed gradual increase in EUV brightness of IPT. This observation suggests enhancement of Io’s volcanic activity. Characteristics of the transient IPT brightening events also changed during the volcanic event. In this presentation, we will show the energy transport process in the Jovian magnetosphere by analyzing of the EXCEED observation.

Keywords: Jupiter, magnetosphere, aurora, Io plasma torus

Horizontal and vertical structures of the Jovian IR aurora from plasma and neutral atmospheres: Observation by SUBARU/IRCS with Adaptive Optics

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In the rotational driven magnetosphere of Jupiter, the momentum and energy transfers between thermosphere and ionosphere is the key part of the magnetosphere, ionosphere and thermosphere (MIT) coupling. Jovian aurora, emitted from this region through this process, does not only shows the strength of magnetospheric activities but also affects to the ion-neutral interactions.
Previous observations have shown the morphological difference between plasma (H_3^+) and neutral (IR H_2) emissions. It suggests the difference between strong electron precipitating area exciting the plasma emissions and the heated area exciting the neutral emissions. In order to investigate their emission mechanisms and relationships to the energy injection processes, the comparison between H_3^+ fundamental (v2=1→0) and overtone (v2=2→0) lines is also important. The different emission altitude of both emissions is caused by their different sensitivity to surrounding atmospheric temperature and density.
We first executed the quasi-simultaneous comparisons of the horizontal and vertical emission profiles in H_3^+ fundamental, H_3^+ overtone, and H_2 polar emissions, by the near infrared spectroscopy of Jovian polar emissions using SUBARU/IRCS on 31 January 2015. H_2 IR emission and H_3^+ overtone emissions are seen simultaneously in K-band spectra (2.03-2.22 μm), and H_3^+ fundamental emission in L-band (3.31-3.98 μm) is quasi-simultaneously taken by short interval, ~5 min. We also simulateounly took the slit viewer image of the H_3^+ fundamental line or K-band filter. During these observations, we used the adaptive optics system (AO188) when Galilean satellites could be used as a guide star, and achieved high spatial resolution, ~0.2 arcsec (~320 km of Jupiter). The slit was set along the rotational axis when AO188 could be used.
First, we compared the horizontal flux profiles. The morphological difference between H_3^+ fundamental and overtone emissions are small. Both have clear main oval emissions like the averaged UV aurora profile. On the other hand, IR H_2 emission does not show clear enhancement at the main oval. We also derived the horizontal profiles of temperature and column density from those emissions. H_3^+ fundamental lines have a better correlation with column density. H_3^+ overtone lines are more related to temperature. On the other hand, IR H_2 emission intensity does not show clear correlations.
Next, we derived the vertical structures of their volume emissivity profiles by “onion peeling” method. We confirm the result of Uno et al. (2014), the similar emission peak altitude between IR H_2 and H_3^+ overtone emissions in K-band. We also found that the peak altitude of H_3^+ fundamental emission was lower than them. Although the derived H_3^+ vertical emission profiles are not contradict to the theoretical models, and their derived temperatures represent those of emission peak altitudes, it is hard to explain the vertical profiles of IR H_2 volume emissivity by a simple ‘thermal excitation model’. It is also hard to explain the fact that the derived temperature from H_2 emissions from higher altitude (~700 K) is lower than that from H_3^+ fundamental emission in lower altitude (~1,000 K). We are now investigating possible scenarios for those points.
In May 2016, we will observe Jovian IR emission again, simultaneously with UV aurora by Hubble Space Telescope, EUV aurora and Io torus by Hisaki/EXCEED, and the upstream solar wind by NASA Juno spacecraft approaching to Jupiter. It will be the chance to solve the problems raised in this study.

Keywords: Jupiter, infrared aurora, horizontal profiles, vertical profiles

Statistical study of the response of Jovian EUV aurora to the solar wind from Hisaki observations

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In order to reveal the solar wind response of Jovian extreme ultraviolet (EUV) auroral activity, we made a statistical analysis of Jovian EUV aurora obtained from long term Hisaki observation.
The EUV emission from hydrogen molecule is excited by collision with high energy electron. The main oval is one of the components of Jovian EUV aurora where the auroral particle precipitations are caused by the rotationally driven field-aligned current system. It is theoretically expected that angular velocity of magnetospheric plasma increases when the Jovian magnetosphere is compressed by enhanced solar wind pressure, which decreases the field-aligned current. Regarding this scenario, increase of the solar wind dynamic pressure is expected to be anti-correlated with the intensity of the EUV aurora. A previous observation such as that by International Ultraviolet Explorer (IUE) or Hubble Space Telescope (HST) showed the time variability of the EUV aurora, while their data still limited in continuity over solar wind variation with good time resolution. On the other hand, Hisaki satellite is an earth-orbiting EUV spectroscope launched in 2013 which has been continuously monitoring Jovian EUV auroral activity. Therefore, the Hisaki data sets are effective for investigating the solar wind response of Jovian aurora.
The purpose of this study is to investigate the solar wind response of Jovian EUV aurora observed by Hisaki. We used the EUV data set obtained from Dec. 2013 to Feb. 2014 and from Dec. 2014 to Feb. 2015. We compare the total EUV power over 900-1480 A and solar wind dynamic pressure which is extrapolated at Jupiter using a one-dimensional magnetohydrodynamic (MHD) model.
Superposed epoch analysis indicated that Jovian EUV aurora increases with the enhancement of the solar wind dynamic pressure. We also found a correlation between the total power of EUV aurora and the duration of the rarefaction region of the solar wind before the enhancement of the dynamic pressure. The similar trend could also be found in the thermal current, i.e., incoming electron flux increased with the duration of rarefaction region.
One possible scenario is that mass loading from Io increases the electron density in the Jovian middle magnetosphere and it also increases seed electron of the thermal current whose energy is several keV. The solar wind compression causes adiabatic acceleration of thermal current and then EUV aurora increases. However, it is still unclear how the angular velocity distribution and brightness distribution vary during the solar wind compression.

Keywords: Jupiter, Aurora, Solar wind response

Variation in SII and SIII brightness distribution of Io plasma torus based on Hisaki/EXCEED and ground based observation data

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We report the time and spatial variation of sulfur ion emission line from the Io plasma torus ([SII]76.5nm and[SIII]68nm) 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 by Hisaki/EXCEED. The large quantities of gas were ejected by Io's volcanoes, principally oxygen and sulfur atoms and their compounds. Once they are ionized through electron impact and charge exchange, the ions are accelerated to the nearly corotational flow of the ambient plasma to form a torus of ions (the Io plasma torus, about $6R_J$ 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 moving electrons bound to ions into excited states, leading to the prodigious extreme ultraviolet (EUV), ultraviolet, and visible emissions from the torus. Hisaki/EXCEED is an EUV spectrograph launched in September 2013. 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. During this period, we identified the time variation of sulfur ion temperature associated with enhanced volcanic activities from images of sulfur ion emission at 76.5nm(SII) and 68nm(SIII) (an integration time for each image is about 50 min) to find increase in ion temperature through the ion-pickup process and cooling by transferring energy to electrons. In addition, we carried out the measurement of SII 673 nm emission with visible spectrograph on T60 telescope at Haleakala, Hawaii, which has high spatial resolution. In this talk we give the results on the scale height and ion temperature of sulfur torus derived from spatial distribution of Io torus with EXCEED associated with the Io's volcanic event, and the comparison with ground-based visible data obtained with T60.

time variation of 130.4nm atomic oxygen emission near Io observed by hisaki/EXCEED

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Io, one of the Jupiter moon, is the most volcanically active body in the solar system because of its large tidal force from Jupiter. Main components of Io’s atmosphere are SO2, and its dissociative sulfur and oxygen atoms. The rest components (a few percent) are neutral sodium and potassium. Origins of the atmosphere are thought to be gaseous plume driven by volcanic activity and sublimation of SO2 frost, but it is not clear which is dominant. The object of this study is to understanding the atmospheric generation process through the time variation of 130.4nm atomic oxygen emission near Io.
The brightening event of the extended sodium nebula was reported by the ground imaging observation from December 2014 to May 2015 (Yoneda et al., 2015). To show the behavior of atomic oxygen during the period, we analyzed the time variation of atomic oxygen, one of the main components of volcanic gas, -near Io (1 Jupiter radius) by using data observed by hisaki/EXCEED. We selected observed data when Io was in the dawn side (Io’s phase angle of 45~135) and in the dusk side (225~315), and accumulated photons which came from around Io within a range of 60" on each day to acquire enough S/N. We carefully selected data when the local time of Hisaki was in the range of 20-4h to avoid the contamination from geocorona. As a result, it is found that the brightness of atomic oxygen emission was 11R at the beginning of January, but started to increase in the middle January and showed the maximum of -32R in the middle of February. It decreased by the end of May and returned the normal brightness (10R). We also confirmed that the emission in the dusk side more intense than that in the dawn side by about 1.2 times throughout the period.
The result shows amount of atomic oxygen near Io increases when Io is volcanically active. To discuss the relation between the atmospheric generation process and volcanic activity, we need to derive atomic oxygen column density from emission brightness of atomic oxygen at 130.4nm. While both solar resonant scattering and electron impact excitation could contribute to 130.4nm atomic oxygen emission, we estimate the contribution of electron impact excitation is several hundred times as high as that of solar scattering. The estimation shows electron impact excitation is dominant and it is likely to explain dawn-dusk asymmetry of 130.4nm atomic oxygen emission because thermal electron temperature in the dusk side is higher than that in the dawn side. In this talk, we drive the atomic oxygen column density and discuss how volcanic activities influence characteristic of Io’s atmosphere according to the estimation.

Keywords: Jupiter, Io, hisaki/EXCEED, volcanic activity

Science Experiments with the Trojan Asteroid Lander in the Solar Powered Sail Mission

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Scientific exploration on the Jupiter Trojan asteroid is under study for the solar-powered sail (SPS) mission. This mission includes a scientific lander jointly studied by Japanese and European engineers and scientists [1]. We present the objectives and the strawman payloads for this mission. The SPS is a candidate as the next medium class space science mission in Japan. This engineering mission is based on the technologies such as the solar sail and the ion engine system inherited from Ikaros and Hayabusa missions, respectively. With this hybrid propulsion system, the spacecraft will cruise to the Jupiter and beyond, even if a radioisotope thermoelectric generator (RTG) is not used. A Trojan asteroid will be investigated by remote sensing after rendezvous, and then a small lander will be deployed from the mothership to conduct *in situ* experiments on the asteroid. As an option, sample will be returned to the Earth. Mission duration is typically 15 years to arrive at the Trojan asteroid, and 30 years in total for Earth return. The shortest one way trip to the asteroid is less than 12 years. The lander should be designed within 100 kg wet mass. Total mission payloads should be within 20 kg, including all the science payloads, sampling and sample return systems [2].

Jupiter Trojan asteroids are located around the Sun-Jupiter Lagrange points. Most of them are volatile-rich D- or P-type asteroids, and their origin and evolution, composition and physical conditions still remain unknown. In a classical model of solar system evolution, they formed around the Jupiter orbit and survive until now. But in a recent model such as Nice model [3], they formed at the far end of the solar system and transferred inward due to dynamical migration of giant planets. Physical, mineralogical, and isotopic studies of surface materials could solve their origin and evolution processes, as well as the solar system formation [4]. To achieve these goals, *in situ* observations using the lander is planned, as well as the asteroid global characterization with a near-infrared hyperspectral imager.

Geological, mineralogical, and geophysical observations will be conducted to characterize the landing site, by using a panoramic camera, an infrared hyperspectral imager, a magnetometer, and a thermal radiometer. The surface conditions and composition will be investigated with a close-up imager and a Raman spectrometry. The imager is also used to check the conditions whether the sampling could be done or not. If the configuration is unsuitable for sampling, the lander must relocate and change the configuration. The surface and subsurface materials will be collected into a carousel by bullet-type and pneumatic drill type samplers, respectively. Samples in the each case of carousel will be viewed by infrared microscope to identify them. Those samples will be transferred for evaporation of volatiles for high resolution mass spectrometry (HRMS). Some samples will be heated for pyrolysis for isotopic analysis. Mass resolution $m/\Delta m > 30,000$ is required to investigate isotopic ratios of D/H, $^{15}N/^{14}N$, and $^{18}O/^{16}O$, as well as molecules from organic matters (M = 30 to 1000).The MULTUM type in Japan and the Cosmorbitrap type in France are being

investigated for the HRMS. A set of strawman payloads are now considered to meet the science, mission, and system requirements and constraints (total mass < 20kg, and total energy consumption < 600 WHr). They will be finally determined by the international announce of opportunity.

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Keywords: Trojan asteroid, Solar Sail, Lander, High Resolution Mass Spectrometry, Solar-Powered Sail, Subsurface sample

