Outer Planet Moon - Magnetosphere Interaction Workshop

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Book of Abstracts

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Contents

Oral presentation

The Io and Europa Plasma Tori as Potential Ultra-Low-Frequency Resonators

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The plasma torus at Io's orbit has been shown to be a locus of intense Alfvén and ion cyclotron waves, which are trapped in the region by the waveguide properties of the torus. Research featuring these waves has progressed towards a detailed understanding of temporal variability in the region, which is vital to the upcoming JUICE mission's aim to characterise the Galilean moons. Here we show that this understanding may be incomplete: an additional population appears to be present in the region, consisting of ultra-low-frequency magnetohydrodynamic waves.

We have used magnetometer data from the Galileo spacecraft to identify intervals of large-amplitude ultra-low-frequency wave activity in the vicinity of the plasma tori. We show how the characteristics of these waves inside the torus is distinct from elsewhere in the magnetosphere, and that the waves may be driven by processes both internal and external to the torus.

We demonstrate that the plasma torus at Io's orbit - and perhaps the torus at Europa's orbit - may act as a localized resonator, absorbing ultra-low-frequency waves from the larger magnetosphere, and thereby potentially acting as a reservoir of energy introduced by perturbations system-wide.

Oral presentation

Ambient magnetic and plasma conditions at moon orbits

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Although magnetospheres are very dynamic environments, models based on magneto-static equilibria can be modified in order to provide realistic predictions of ambient or 'upstream' magnetic field and plasma conditions at the orbital radii of moons like Titan and Ganymede. In this presentation, we present results of such models associated with the ambient magnetospheric environments of both these moons. We also illustrate that such models can be used to quantify the degree to which different types of pressure - magnetic, thermal and dynamic - dominate the conditions at the orbits of these moons. For the case of Titan, we also present comparison between model predictions and observations from the Cassini spacecraft.

Oral presentation

Modelling of Energy-Transfer Processes at Ganymede's Upstream Magnetopause

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Ganymede is the largest moon of Jupiter and the only Solar System moon known to generate a permanent magnetic field. Dynamics inside Ganymede's magnetosphere are thought to be driven by interactions at its upstream magnetopause, including magnetic reconnection and Kelvin-Helmholtz (K-H) instability. Previous numerical simulations of Ganymede speculate existence of transient flux-transfer reconnection events and linear K-H waves, but the natures of both processes remain poorly understood. Here we conduct the first assessments of magnetic reconnection and K-H instability growth under fundamental plasma theory, using an analytical model of steady-state conditions near Ganymede's upstream magnetopause. We find that reconnection may occur at significant rates wherever Ganymede's closed magnetic field encounters Jupiter's ambient magnetic field irrespective of changes to near-magnetopause conditions, allowing for possibilities of multiple X-lines or widespread flux-transfer events on the upstream magnetopause. The average reconnection rate is found to depend on Jupiter's rotation. We also find that linear K-H instability waves can grow along Ganymede's magnetopause flanks, and that instability growth becomes more favorable as Ganymede moves toward Jupiter's plasma sheet center. K-H wave amplitudes are found to grow at rate of ˜0.01-50 s-1 once the finite Larmor radius effect is included, with enhanced growth on the magnetopause flank closest to Jupiter. We explore the possibilities that these growth rates are comparable to those at Mercury's dayside magnetopause, and that nonlinear K-H vortices may contribute to energy transport across Ganymede's upstream magnetopause. Future progress on both topics is highly relevant for the upcoming JUpiter ICy moon Explorer (JUICE) mission.

Oral presentation

Low-energy electrons in Saturn's inner magnetosphere from the Cassini Langmuir Probe

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It is known that Enceladus is one of the main mass sources in Saturn's inner magnetosphere, with other bodies – e.g. Dione, Tethys, Saturn's rings and atmosphere – thought to play a smaller role. In this study we analysed electron density and temperature as estimated from Cassini's Langmuir Probe (LP) for the entire duration of the Cassini mission (August 2004 – September 2017). The main motivation for this work is to understand the impact of Enceladus as a main mass source and search for evidence of additional sources. We also have been investigating the impact of the spacecraft-plasma interaction, and illumination conditions on the LP current-voltage curves and henceforth on the bulk electron parameters.

One particular facet of this work is the discrimination of spacecraft-generated photoelectrons in the current-voltage curves so that they can be excluded from further analysis of the ambient magnetospheric electrons. To develop a robust algorithm to identify photoelectrons we have been working with data during transitions in and out of shadow caused by two main events: i) when the LP is shadowed by the spacecraft, or ii) during eclipses by Saturn or its moons.

With a cleaned data set we focused on analysing data within $0.5R_S$ of the Kronian in the inner magnetosphere (r<$7R_S$). We compared our data with the hybrid power-law model, as described in Persoon et al. (2013, JGR), that used the electron densities estimated from the upper hybrid resonance frequency. We also looked for local time asymmetries in electrons, as reported in ion plasma in the same region (e.g. Holmberg et al., 2007, GRL).

Oral presentation

Reconnection-driven Dynamics at Ganymede's Upstream Magnetosphere: 3D Global Hall MHD and MHD-EPIC Simulations

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The largest moon in the solar system, Ganymede, is the only moon known to possess a strong intrinsic magnetic field and a corresponding magnetosphere.
Using the latest version of Space Weather Modeling Framework (SWMF), we study the upstream plasma interactions and dynamics in this sub-Alfvenic system.
Results from the Hall MHD and the coupled MHD with embedded Particle-in-Cell (MHD-EPIC) models are compared.
We find that under steady upstream conditions, magnetopause reconnection occurs in a non-steady manner, and the energy partition between electrons and ions is different in the two models.
Flux ropes of Ganymede's radius in length form on the magnetopause at a rate about 3/minute and create spatiotemporal variations in plasma and field properties.
Upon reaching proper grid resolutions, the MHD-EPIC model can resolve both electron and ion kinetics at the magnetopause and show localized non-gyrotropic behavior inside the diffusion region.
The estimated global reconnection rate from the models is about 80 kV with 60% efficiency, and there is weak evidence of about 1 minute periodicity in the temporal variations due to the dynamic reconnection process.

Oral presentation

Moon-magnetosphere interactions of Io and Enceladus: A high-resolution, in-situ parametric study

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The Juno spacecraft crosses high-latitude magnetic flux tubes connected to Io's orbit at least once in each hemisphere during every orbit. Similarly, the Cassini spacecraft crossed those connected to Enceladus' orbits. This enables the first in-situ comparative study between the two systems. The electrodynamic coupling between a dynamic moon and a magnetosphere gives rise to a variety of field and particle phenomena. Here we show evidence of cross-scale wave-particle interactions in Io's flux tube, clearly differentiating between MHD, ion, and electron scales. We find (i) evidence of inertial Alfvén waves undergoing a turbulent cascade, suggesting Alfvénic acceleration processes together with observations of bi-directional, broadband electrons; (ii) intense ion cyclotron waves with an estimated heating rate that is consistent with the generation of observed ion conics; and (iii) whistler-mode auroral hiss radiation excited by field-aligned electrons. Such high-resolution wave and particle measurements provide an insight into satellite interactions in unprecedented detail. We further anticipate that these spatially well-constrained results can be more broadly applied to better understand processes of Jupiter's main auroral oval. Key similarities and differences are highlighted to measurements of Enceladus' flux tube by Cassini, and we reveal how the power of their interactions compare.

Oral presentation

Fast and Slow Water Ion Populations in the Enceladus Plume

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Ion velocities have been measured during the Enceladus E3 and E5 flybys using the Cassini Plasma Spectrometer (CAPS) instrument on the Cassini spacecraft. Data from three sensors in the CAPS instrument have been examined from two flybys that occurred during 2008. Positive ion measurements from the CAPS Ion Beam Spectrometer and Ion Mass Spectrometer have been used to measure positive ion velocities. The CAPS Electron Spectrometer has been used to complement the positive ion findings with measurements of negative ion velocities. Two velocities for the positive ions are found, with the fast ions (2.3–5.8 km/s) originating from the high-speed neutral gas emission and slow ions (0.2–2.2 km/s) associated with the low-speed thermal gas emission from Enceladus. Negative ions were found to be near stationary or northerly traveling, implying a deceleration mechanism within the plume. A tentative detection of fast negative ions was also recorded for one of the flybys. These findings will aid in future modeling of plume dynamics.

Oral presentation

Interaction of plasma with the surface of icy moons: insights from laboratory experiments

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The surfaces of Jupiter's icy moons are continually irradiated by charged particles from the Jovian plasma environment. This irradiation triggers chemical reactions in the surface ice and also acts as an atmospheric release process. Remote observations, theoretical modelling, and laboratory experiments must be combined to understand this plasma-ice interaction. This contribution summarizes recent experimental work at the University of Bern.

The University of Bern is developing the neutral gas mass spectrometer for ESA's Jupiter Icy moons Explorer, planned to reach the Jupiter system in 2029. We therefore strive to fill knowledge gaps about the basic physics of the surfaces and atmospheres of Jupiter's icy moons before the arrival of JUICE. We combine the available facilities for developing and calibrating mass spectrometers and ion/electron spectrometers with reflectance spectrum diagnostics for icy surfaces.

To study the effects of electrons irradiating water ice, we subjected a variety of ice samples (thin amorphous ice films and macroscopic samples of porous ice with customizable grain size) to an electron beam of energies between 200 eV and 10 keV at pressures and temperatures representative for the surfaces of Jupiter's icy moons. The physical and optical properties of these macroscopic ice samples make them realistic analogues for planetary surfaces beyond the ice line. The effect of chemical impurities in the water ice, such as NaCl, can also be investigated. The particles released from the ice were monitored with a newly designed time-of-flight (TOF) mass spectrometer and (in the case of the water ice film) with a microbalance.

Oral presentation

Variability of the Galilean moon plasma environment and implications for moon-magnetosphere interactions

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The plasma conditions surrounding the Galilean moons varies considerably with time, the variability increasing farther from Jupiter. We review the in situ plasma observations from Voyager, Galileo and Juno and present a statistical analysis for each moon. Since JUICE will not directly observe the Io plasma torus, we discuss what remote observations would assist with monitoring variations in the source population near Io and their propagation to the outer Galilean satellites.

Oral presentation

The Io-Torus Interaction as Seen Through a Telescope

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The Io plasma torus offers our only opportunity to take a picture of a planetary magnetosphere. Torus ion emissions are excited through electron impact and so line ratios of like ions species can effectively map the plasma density and electron temperature. This provides us with some empirical constraints on the upstream plasma conditions that sweep past the moon. A rich spectrum of emission features is seen local to Io because of its interaction with the torus, and dozens of transitions in Io's atmosphere are not observable anywhere else. Photochemical and plasma-induced channels emissions can be disentangled by comparing telescope spectra in sunlight to eclipsed spectra in Jupiter's shadow. The vapor pressure equilibrium of Io's bulk SO2 atmosphere is tipped out of balance during Io's ingress and egress. Comparing the temporal response of SO2 to Io's atomic emissions reveals important new clues on the production pathways for the atoms, as well as the complex factors that regulate their photon flux. Plasma induced atomic lines are confluence of several processes including direct excitation of the atoms, dissociative excitation of molecules, recombination reactions in Io's ionosphere, and, in the case of forbidden transitions, collisional quenching. Sunlight and electron impacts can also ionize, and any ions created in collisionless regions of Io's atmosphere are ripped out by Jupiter's magnetic field. This ion population not only re-supplies the torus, causing feedback, it can also dissociatively recombine or charge exchange to form streams of energetic neutral atoms. Doppler shift can distinguish such neutrals borne of ionic parents. With velocities well above the jovian escape speed, these energetic neutral atoms can paint the surfaces of the other satellites or populate Jupiter's diffuse and dynamic nebulae as one of the largest structures in our solar system.

Oral presentation

Effects of Titan's magnetospheric environment on its atmosphere

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Titan's dense atmosphere, together with the highly variable magnetospheric environment that it encounters while orbiting Saturn, leads to what is arguably the most complex magnetospheric interaction in the solar system. In this contribution, we examine the variability of the upstream conditions encountered by Cassini and analyze the effect that this variable environment has on its atmosphere, focusing on the energy deposition by energetic particles.

Oral presentation

Europa plume studies

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Outgassing from plumes might enhance the neutral density in Europa's atmosphere locally and affect the electromagnetic interaction of the moon. In the last seven years, various studies have claimed evidence for plumes erupting from Europa's surface using a variety of methods from remote-sensing observations from Earth to in-situ plasma measurements. We discuss the studies claiming such plume evidence and compare the results in terms of derived plume properties such as location, density or duty cycle. We also discuss the general advantages and disadvantages of the different methods. Finally, we look at ongoing and future remote sensing programs and elaborate on the prospects for JUICE and Europa Clipper.

Oral presentation

Multi-fluid MHD Modeling of Europa's Plasma Interaction

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Europa hosts a periodically changing plasma interaction driven by the spatial variations of Jupiter's magnetic field and magnetospheric plasma. We have developed a multi-fluid magnetohydrodynamic (MHD) model for the plasma interaction to investigate its response to these magnetic field and plasma variations at Europa's orbit. The model solves the multi-fluid MHD equations for electrons and three ion fluids (magnetospheric O+ as well as O+ and O+2 of ionospheric origin) while incorporating sources and losses in the fluid equations due to ionization, recombination, charge exchange and other relevant collisional effects. We first verify the accuracy of our model's representation of the plasma interaction by simulating the Galileo E4 flyby using input parameters constrained by the Galileo MAG and PLS observations. Our model produces 3D magnetic field and plasma bulk parameters that agree with and provide context for the E4 flyby observations. We next present the results of a parameter study of Europa's plasma interaction at three different S-III longitudes within the magnetosphere, for three different global magnetospheric states, comprising 9 steady-state simulations in total. We describe how the self-consistently generated ionosphere varies in response to the external plasma, and we show how the relative strengths of the magnetospheric plasma versus Europa's ionosphere control Europa's interaction with Jupiter's magnetosphere.

Oral presentation

Connecting the Galileo particle, plasma, and field data with ionospheric, exospheric, and MHD models

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The neutral and plasma environments of Ganymede are poorly constrained. We have developed the first 3D test particle model of the ionosphere of Ganymede (Carnielli et al., Icarus, 2019) in order to identify the source and composition of the ion population, to evaluate the ion dynamics, and to characterise the energetic neutral atom population. The test particle model has also been applied to make the first assessment of the ionospheric ion sputtering on Ganymede's surface (Carnielli et al., Icarus, 2020, in press). The ionospheric model is driven by electric and magnetic fields from an MHD model (Jia et al., JGR, 2009) and by neutral number densities from a 3D test particle exospheric model (Leblanc et al., Icarus, 2017). We have compared the simulation outputs with field, plasma, and particle observations from the magnetometer (MAG), Plasma Wave Subsystem (PWS), and Plasma Science (PLS) instruments during the Galileo G2 flyby (Carnielli et al., Icarus, 2020). The agreement between the modelled and observed magnetic field, ion bulk velocity, and ion energy distribution validates the simulated field environment. The underestimations of the modelled ion density and ion spectrogram magnitude compared with the observations impose constraints on the ion production rates, that is, on the exospheric number densities and ionisation source. The combination of the three models is a powerful tool for the analysis of future observations from JUICE in the environment of Ganymede, in particular from J-MAG, RPWI, and PEP.

Oral presentation

Triton Plasma Interactions

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The orbit of Triton is inside the magnetosphere of Neptune. The moon is exposed to a slow and tenuous magnetospheric plasma, consisting mostly of H+ and N+. The ionosphere of Triton is dense and extended. The encounter of this slow and tenuous external plasma with a dense and extended ionosphere makes for a unique interaction.
Here we present hybrid model results for this interaction. The hybrid model treats ions as particles and electrons as a fluid. We present general features of the interaction and in particular the plasma environment that a spacecraft would encounter during a flyby.

Oral presentation

Moon-induced auroral radio emission in the outer solar system

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At Jupiter and Saturn, part of the optical aurorae are controlled by the moons (Io, Europa, Ganymede, Callisto, Enceladus). At Jupiter, a radio counterpart of the atmospheric auroral signatures has been observed for the Galileans moons Io, Europa and Ganymede. Until now, they had only been remotely observed using ground-based radio-telescopes (e.g. NDA, LWA), or electric antennas aboard spacecraft (e.g. Voyager, Cassini) and compared to simulations (e.g. ExPRES). The polar trajectory of the Juno orbiter allowed the spacecraft to cross the magnetic flux tubes connected to these moons, or their tail, and probe in-situ the characteristics of the source region (plasma conditions, source electrons) and the properties of the induced decametric radiated waves (flux density, beaming pattern). Here, we analyze the crossing of the Io and Ganymede flux tube and derive, from Juno/JADE-E (electrons) and Juno/Waves (radio) data, an estimation of the radio-source size, the resonant electron energy and the emission beaming angle, which bring us new constrains on the Cyclotron Maser Instability process that produce these radio emissions. Finally, we present simulations from the ExPRES tools that predict possible radio emission induced by Enceladus at Saturn (comparing to Cassini/RPWS observations), or Ariel at Uranus (comparing to Voyager/PRA observations).

Oral presentation

Investigating the origin of sulfur-bearing species on the Galilean moon Callisto

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The surface of Callisto hosts a suite of constituents that have unknown origins, including an infrared absorption feature centered near 4 µm that has been attributed to sulfur dioxide (SO2). This feature was first confirmed in spectra collected by the Near Infrared Mapping Spectrometer (NIMS) on the Galileo spacecraft, and it is also observed in prior ground-based telescope observations. However, the often low signal-to-noise and low resolving power of NIMS (R ∼40 – 200) and prior ground-based observations (R ∼200 – 400) has limited our ability to interpret the origin of this 4-µm feature. We will present new near-infrared spectra collected with the SpeX spectrograph on NASA's Infrared Telescope Facility (∼1.9 – 5.3 µm, R ∼2500) that represent a significant improvement over previous observations, providing new information about S-bearing species on Callisto.

Previous work has suggested that the 4-µm feature results from S-rich species that are erupted by volcanic activity on Io, ionized, and subsequently transported by Jupiter's co-rotating plasma to the other Galilean moons. This process can neatly explain the enhanced abundance of an absorption feature centered near 4.05 µm on the trailing (upstream) hemisphere of Europa and Ganymede, which has been attributed to S-bearing species. In contrast, our results show that the 4-µm feature is significantly stronger on Callisto's leading (downstream) hemisphere, suggesting that this feature might have originated from in-falling dust grains from Jupiter's retrograde irregular satellites. Alternatively, S-bearing species could be native to Callisto and are exposed in the large Asgard and Valhalla impact basins on Callisto's leading side. The central wavelength of this feature is shifted to 4.02 µm, casting doubt on SO2 as the primary contributing constituent. Our results are more consistent with other S-bearing species like H2S2 or HS2, which could be formed by charged particle radiolysis of hydrogen sulfide (H2S).

Oral presentation

Plasma flow around a satellite with an ionosphere: Theoretical models of the moon-magnetosphere interaction

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Key aspect of moon-magnetosphere interactions are dependent on the diversion of the flow around the conducting body of the moon and the acceleration of the flow along the flanks of the moon. Analytic solutions for the magnetic field perturbations [Neubauer, 1980; Saur et al., 2004 and references therein] have been derived assuming the moon's conductance is constant within a specified radius and zero outside that radius. Solutions also exist [Simon, 2015] for a conductivity which varies as a power law of the radius. Simon, 2015, applied this solution to analysis of *Cassini* magnetometer data from Enceladus encounters. But these solutions can be used to calculate the flow field as well. Numerical models can also be used to calculate the flow field, but they are sensitive to boundary condition applied at the surface of the moon and may have limited fidelity within a fraction of a body radius. Numerical models are also computationally expensive, and often impractical to run for a wide variety of parameters. Here we present an analytic solution similar to those of Simon et al., but for an exponential conductivity profile which is more applicable to the ionospheres of moons like Io and Europa. We then describe the effects the resulting of flow field would have on the interaction between the moon's ionosphere and the plasma, the production of charge exchange ions and the energy the resulting fast neutral atoms.

Oral presentation

Investigating the energy inputs to Triton's enigmatic ionosphere

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In 1989, Voyager 2 carried out the first, and thus far only, in-situ exploration of the Neptune system. This included a distant flyby of Neptune's only major moon Triton – a large icy moon that may possibly be a captured Kuiper Belt Object. Based on radio occultation measurements during the flyby, Triton was found to have an intense ionosphere with peak electron densities on the order of 10ˆ4 cm^{-3} (Tyler et al., 1989). This was surprising, as Neptune's orbital location at 30 AU from the Sun means that the flux of ionizing solar UV photons is relatively low. It was therefore suggested that magnetospheric electron precipitation may be an important, and possibly dominant, energy input to Triton's ionosphere (e.g. Majeed et al., 1990; Strobel et al., 1990; Yung and Lyons, 1990). However, subsequent modelling efforts were never able to fully explain the structure of Triton's ionosphere from either solar photoionization or magnetospheric electron input (Krasnopolsky and Cruikshank, 1995; Sittler and Hartle, 1996).

We have revisited the question of the energy input to Triton's ionosphere using modern particle transport and ionospheric chemistry models. Our modelling effort is based on the available data on Triton's magnetospheric environment and atmosphere, and is informed by recent advances in our understanding of cold nitrogen-dominated atmospheres from the exploration of Titan by Cassini (e.g. Mandt et al., 2012; Westlake et al., 2012) and Pluto by New Horizons (e.g. Luspay-Kuti et al., 2017; Mandt et al., 2017). Here we will present preliminary results of the modelling, as well as discuss possible implications for future missions to Triton and the Neptune system.

Oral presentation

Impact of using a collisional plume model on detecting Europa's water plumes from a flyby.

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H2O molecules from Europa's water plumes may be detected by the 2031 flyby of the JUICE mission spacecraft. Previous work on the feasibility of these detections has assumed a collisionless model of the plume particles (Huybrighs et al., 2017). More sophisticated models of the plumes including particle collisions have shown that a shock could develop in the plume interior as rising particles collide with particles falling back to the moon's surface, limiting the plume's altitude. We investigate to what extent the limited altitude of the shocked plumes reduces the ability of the JUICE spacecraft to detect plume H2O molecules, by comparing the density of H2O molecules at altitudes above the shock region with those indicated by a collisionless model. We compare the feasibility of detecting putative plume sources (e.g. Roth et al. 2014, Jia et al. 2018, and Arnold 2019) given by the two models. By comparison with previous work we predict the effect of plume temperature and initial velocity on the size and reach of the plume and hence its likelihood of detection. We will also investigate whether a lower altitude flyby would significantly improve the area on Europa's surface over which the spacecraft could detect plumes.

Oral presentation

The variable energetic charged particle environment of outer planet moons

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The process by which surfaces in the Solar System are modified by external agents such as micrometeoroid bombardment, solar photons and charged particles is called "weathering". Examples of weathering of the jovian and saturnian moons include the numerous leading-trailing hemisphere differences, the lens-shaped modifications by energetic electrons on the inner satellites and the variable exospheres that surround the planets' icy moons, partially due to sputtering of their surfaces by supra-thermal ions and electrons. Energetic charged particles are among the most important drivers of weathering as they penetrate materials deeper than other weathering agents. They also release large amounts of secondary neutral and charged particles into the moons' exospheres and ionospheres or the surrounding magnetosphere. Quantifying the level of weathering for any of these objects requires a detailed description of the ambient energetic particle environment, including its composition and flux at different energies. Earlier studies used spacecraft observations to derive long-term averages or instantaneous values of these parameters. Describing the parameters' range and typical time variations, however, is also critical as some weathering processes can be responsive to changes in the local environment (e.g. variable sputtering creates transient satellite exospheres). The challenges in doing this kind of work include making sense of spatial versus magnetospheric time variations, a difficult task due to single point, in-situ measurements that are currently available from the outer planets. However, following several decades of highly complementary energetic observations at Jupiter and Saturn, we now begin to understand what may be the drivers of such variability, as well as their characteristic time scales. In this presentation we will review these observations and our current understanding of the dynamics of the moons' energetic particle environments and we will discuss how these may guide observations by future missions to the jovian satellites.

Oral presentation

Determining the Io volcanic source with Hisaki neutral oxygen observations and 3D modeling

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The Jovian system is very intriguing with extremely different particle sources ranging from the volcanic Io to the frozen world of Europa with both existing within Jupiter's relatively high radiation magnetospheric environment. While Voyager, Galileo and Cassini provided historic observations of this unique environment, they also raised numerous questions. As the dominant source of particles to Jupiter's magnetosphere, Io is of particular importance. However, this source is not well understood with total rate estimates varying from 700-2400 kg/sec and even the specific source mechanisms (ex. volcanic vs. sublimation) are under debate. Thus, characterizing the Io source is required to understand Jupiter's magnetosphere as well as enabling understanding of the minor (but extremely important) source, Since its launch in 2013, the JAXA Hisaki (SPRINT-A) mission offers the potential to answer some of these questions and help make future missions more successful.

The JAXA Hisaki mission has provided unprecedented observations of the Jovian system with its extreme ultraviolet (EUV) spectroscope (EXCEED) instrument. In particular, it's UV neutral oxygen line of sight observations provide the best glimpse so far of Jovian neutral particle populations. This is exciting in that for the first time, the neutral tori can be directly observed on time scales that constrain satellite sources. The current Hisaki oxygen UV line of sight (LOS) observations are already revealing an intriguing amount of spatial and temporal. This data can also shed unprecedented insight into neutral torus distributions which could subsequently provide essential information about the sources and mechanisms from Io. However, 3-D modeling is required to interpret the complex and dynamic observational geometries. Thus, for this presentation, we show preliminary research that combines Hisaki neutral oxygen LOS observations with computational modeling to identify and characterize Io's source of particles to Jupiter's magnetosphere.

Oral presentation

The Langmuir probe observations of the dust and plasma at Enceladus plume and the E-ring

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The Enceladus is known as a significant plasma source of the Kronian magnetosphere. The cryovolcanic activities on its south pole explode the water vapour and the ice grains into the surrounding space, forming the several moon radii large plume. It is evident from the image that the small icy moon located at the centre of Saturn's E ring replenishes the significant amount of dust particles to the ring and the neutral torus. The strong coupling between the dust particle and the plasma has been confirmed by the several plasma and particle instruments onboard Cassini. With the Langmuir Probe, it is mainly detected as a substantial depletion of the electron density as a result of the electron attachment to the charged dust grains. The dusty plasma can result in a different type of moon-magnetosphere interaction. With the Cassini/LP, the dusty plasma has been detected near the Enceladus plume as well as the E ring.
The plume activity has also been detected at the Jupiter's icy moon Europa, and its associated neutral torus is also indicated. We will show the structure and characteristics of the dusty plasma region near the Enceladus and the E ring obtained by the Cassini/LP and discuss the possible dust plasma interaction that can be observed by the RPWI instrument onboard JUICE.

Oral presentation

Remote Detection of Surface Charging at Saturn's Icy Moons

Authors: Geraint Jones[1]; Andrew Coates[1]; The Cassini CAPS Team

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Almost all of Saturn's large icy moons reside within the planet's magnetosphere, and are continuously exposed to the magnetospheric plasma population. This plasma flow gives rise to the surface charging of these moons, the level of which is balanced by photoemission. The first detection of a charged surface, at Hyperion, was reported by Nordheim+ (2014). Here we report on Cassini Plasma Spectrometer (CAPS) observations made during the Cassini spacecraft's close encounters with Rhea and Dione that also demonstrate the remote detection of charged surfaces at Saturn's icy moons. At Rhea, Cassini passed a few tens of kilometres of the north and south polar regions of the satellite, respectively. The CAPS Electron Spectrometer, ELS, had good pitch angle coverage during the encounters, with its 8 anodes covering directions from towards, to away from the moon. CAPS-ELS observed the expected decrease in the high energy electron population caused by their absorption by Rhea, but also observed an enhancement in the population of electrons at energies below a few hundred eV. We present our interpretation of this population as being associated with the surface charging of Rhea. At the time of these encounters, the moon's surface was negatively charged, meaning it could reflect certain incoming electrons before they struck the ground, and could also accelerate low energy electrons liberated near the surface. We also present less direct evidence of this process occurring at Dione. Finally, we discuss the implications of these observations, and their relevance for missions to the other Outer Planets.

Oral presentation

Pickup ions in the outer solar system

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Ion pickup provides the key mechanism by which comets interact with the solar wind. Following ionization of neutral particles, the new-born ions are accelerated in the convection electric field and gyrate around the magnetic field – forming a cycloid in real space and an unstable ring in velocity space. Pickup is present at most other planetary objects, and in the outer solar system there are recent data from Titan, Enceladus, Rhea, Dione and Saturn's neutral-dominated magnetosphere. Here, we briefly review the pickup process and present examples of pickup ions at all these objects. We look forward to future missions where pickup will play a key role such as JUICE.

Oral presentation

Detectability of subsurface oceans and their flows by JUICE

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We present work on the electromagnetic interactions of liquid water oceans on Ganymede and Europa with Jupiter's magnetic field. Both moons have surface water ice crusts several hundred kilometers thick, with layers of the crust thought to be in liquid form under higher pressure and temperature. In our study we examine the detectability of Ganymede and Europa liquid oceans by the JUICE RPWI and MAG instruments. To simulate these environments, we have developed the necessary framework describing ocean induction and furthermore adapted the MIT-GCM to conditions at the subsurface oceans of both Galilean moons to investigate the liquid flows developing in response to gravitational tides and subsurface heat vents. We aim to develop techniques to separate these components of ocean flow from the induction taking place already due to the motion itself of the moons on their orbits within a locally changing Jovian magnetic field linked mostly to Jupiter's rapid rotation and the inclination of its magnetic field.

Poster presentation

Io plasma torus and Jovian aurora activities seen by Hisaki: Recent result, current status, and future plan

Authors: Fuminori Tsuchiya[1]; Ichiro Yoshikawa[2]; Atsushi Yamazaki[3]; Kazuo Yoshioka; Tomoki Kimura; Go Murakami; Hajime Kita; Masaki Kuwabara; Chihiro Tao; Ryoichi Koga; Reina Hikida; Kei Masunaga; Masato Kagitani; Takeshi Sakanoi; Hiroaki Misawa; Yasumasa Kasaba

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Hisaki has carried out unprecedented continuous observation of Io plasma torus and Jovian aurora since December 2013 and found responses of the Jovian magnetosphere to volcanic activities of Io and the solar wind. Hisaki detected a major volcanic enhancement of Io in the spring of 2015. Koga et al. (2019) examined production and loss of oxygen based on the first simultaneous observation of oxygen neutral cloud around Io and plasma torus. Hikida et al. (2019) found unexpected hot electron population in dusk side of Io plasma torus, suggesting that the mass increase in the torus enhanced the plasma transport from the outside within a specific region or via a local heating process. The unresolved rotational modulation, so called System IV period, was investigated by Tsuchiya et al. (2019). They found that the rotation became close to rigid corotation during the volcanic active period, which was contrary to theoretical predictions. Since the autumn of 2016, the Juno spacecraft was in the orbit around Jupiter. Hisaki monitored activities of Jovian aurora and the plasma torus (Yao et al. 2019, Roth et al. 2020). While major volcanic activities such like that occurred in 2015 have not be found in the Juno mission period yet, Hisaki see moderate long-term changes in the plasma torus, which could be caused by the volcanic eruption. Hisaki also see some aurora brightening which may be caused by internal magnetospheric process and/or the solar wind. These datasets will provide opportunities to compare in-situ observation by Juno with the global view by Hisaki. JAXA approved extension of Hisaki mission period by the end of March 2022. During the extended mission period, Hisaki will continue long-term monitoring of Io plasma torus and Mars. We will also mention about post-Hisaki mission, the next UV telescope we started feasibility studies.

Poster presentation

Variability in the energetic electron bombardment of Ganymede

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Co-authors: Andrew R. Poppe [2]; Christopher Paranicas [3]; Quentin Nénon [1]; Shahab Fatemi [4]; Sven Simon [5]

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This study examines the bombardment of energetic magnetospheric electrons onto Ganymede as a function of Jovian magnetic latitude. We use the output from a hybrid model to constrain features of the electromagnetic environment during the G1, G8, and G28 Galileo encounters when Ganymede was far above, within, or far below Jupiter's magnetospheric current sheet, respectively. To quantify electron fluxes, we use a test-particle model and trace electrons at discrete energies between 4.5 keV E 100 MeV while exposed to these fields. For each location with respect to Jupiter's current sheet, electrons of all energies bombard Ganymede's poles with average number and energy fluxes of 1e8 cmˆ-2 sˆ-1 and 3e9 keV cmˆ-2 sˆ-1, respectively. However, precipitation is inhomogeneous: poleward of the open-closed field line boundary, fluxes are enhanced in the trailing (but reduced in the leading) hemisphere. Within the Jovian current sheet, closed field lines of Ganymede's mini-magnetosphere shield electrons below 40 MeV from accessing the equator. Above these energies, equatorial fluxes are longitudinally inhomogeneous between the sub- and anti-Jovian hemispheres, but the averaged number flux (4e3 cmˆ-2 sˆ-1) is comparable to the flux deposited by each of the dominant energetic ion species near Ganymede. When outside of the Jovian current sheet, electrons below 100 keV enter Ganymede's mini-magnetosphere via the downstream reconnection region and bombard the leading apex, while electrons of all energies are shielded from the trailing apex. Averaged over a synodic rotation, electron flux patterns agree with brightness features observed across Ganymede's polar and equatorial surface.

Poster presentation

Ganymede Book

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We are currently working on a book on Ganymede, which shall be publihed with Cambridge University Press. A group of various authors are working on a total of 21 chapters reviewing the science done at Ganymede. This book is considered to become a reference book for scientists on e.g. the JUICE mission and an introduction book for young scientists deciding to join the Jovian research community.

Poster presentation

Energetic proton depletions near Europa: the effect of plumes, atmospheric charge exchange, Alfvén wings and the wake

Authors: Hans Huybrighs[1]; Aljona Bloecker[2]; Elias Roussos[3]; Christiaan van Buchem[4]; Norbert Krupp[3]; Yoshifumi Futaana[5]; Stas Barabash[5]; Mika Holmberg[1]; Olivier Witasse[1]

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The flux of energetic protons (80 keV-1.04 MeV) near the Galilean moons was measured by the Energetic Particle Detector (EPD) on the Galileo mission (1995 - 2003). Near Galilean moons (such as Io and Europa) depletions of the energetic ion flux, of several orders of magnitude, were observed.

Such energetic ion depletions can be caused by the precipitation of these particles onto the moon's surface or charge exchange with the neutral atmosphere. In addition, a magnetic field gradient can restrict access of the ions to certain regions, creating a "forbidden region." To interpret the depletion features in the EPD data, a Monte Carlo particle tracing code has been developed. The expected flux of the energetic ions is simulated under different scenarios including those with and without an atmosphere, plume or inhomogeneous electromagnetic field. By comparing the simulated distribution to the EPD data, the cause of the depletion features can be investigated.

We identify the following causes of energetic proton depletions near Europa:

- Depletions are consistent with plumes during the flybys E12 and E26. These plumes coincide with the source location of Jia et al., 2018 and Arnold et al., 2019.
- Depletions are consistent with atmospheric charge exchange during the flyby E26
- Depletions coincide with Europa's Alfvén wing during the flybys E17 and E25A The Alfvén wings are two cylindrical regions extending to the north and south of Europa in which the low-energy plasma and the magnetic field are modified compared to the upstream conditions.
- Depletions coincide with Europa's geometrical wake (in the plasma downstream direction) during flyby E11 Furthermore, we investigate the effect of varying the atmospheric properties (scale height, density, presence of a sputtered component) and plume properties (density, location) on the depletions.

Poster presentation

Survey of the Nançay Decameter Array's extended catalog for the possible control of Jupiter's decametric radio emissions by Europa.

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Jupiter is an intense source of Auroral Radio Emissions (AREs). Such emissions are produced by a resonance between non-relativistic electrons gyrating along Jupiter's magnetic field lines and electromagnetic waves, known as the Cyclotron-maser instability. The Jovian AREs in the Decametric (DAM) wavelength range can be detected from ground-based radiotelescopes above the cut-off frequency of the Earth's ionosphere. The occurrence of Jovian DAM is partially controlled by the Jovian satellites Io, Europa and Ganymede. The satellite control of the Jovian DAM consists of radio emissions induced by field-aligned electric currents resulting from the interaction between the satellites and the magnetospheric magnetic field along their orbit. An evidence of this control is the nonuniform occurrence of the jovian DAM emissions as a function of the satellites' orbital phase and the observer's longitude. Such evidence was firstly observed for Io and have been found also for Ganymede. The continuous observation of Jupiter's radio emissions by the Nançay Decameter Array (NDA) along the years has enabled the gathering of an extensive digital data catalog with 29 years of daily observations. This catalog has already provided statistical evidences of control of the Jovian DAM emissions by Io and Ganymede, as well as the possibility of further selection and analysis of various jovian radio components. This work aimed at analyzing this NDA's extended catalog to track any Jovian DAM emissions induced by the satellite Europa. We were able to detect 2 types of Europa DAM emissions, namely Eu-A and Eu-C (termed by analogy with the Io DAM reference). We have then identified their average parameters, such as the median, mean and standard deviation of the maximum frequency, duration and intensity.

Poster presentation

Simulations of UV Emission from the Io Plasma Torus using the Colorado Io Torus Emission Package 2 (CITEP 2)

Author: Edward Nerney[1]

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In anticipation of the upcoming missions JUICE and Europa Clipper, we have built a 3D Io plasma torus emission model in order to simulate what we would expect to see from both UVS instruments looking at the Io plasma torus. The Colorado Io Torus Emission Package 2 (CITEP 2) calculates the line of sight given the position of each spatial pixel and pointing of the spacecraft and produces a synthetic spectrum given plasma densities and temperatures along the line of sight using the CHIANTI atomic database to compute volume emission rates. We compare our model with Cassini UVIS and Hisaki UV observations of the Io plasma torus. Further, we use the output from our 3D physical chemistry model for a 3D distribution of plasma to compare with observations and predict what we expect to see when JUICE and Europa Clipper arrive at Jupiter.

Poster presentation

Io's Loss of Neutral Material: Numerical Simulations

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Io losses ∼ 1 ton/sec of neutral material through the interaction of the plasma of the torus and its atmosphere.
This canonical loss rate is based on estimates of the ion supply to the torus provided by electron impact ionization of neutrals and is used as a source rate for the simulations of the large neutral clouds (S and O) extending along Io's orbit.
But the actual processes causing the ejection of these neutrals are poorly understood and rarely addressed by numerical simulations.
We estimate Io's SO2 neutral loss from two important processes: 1) the resonant charge exchange of SO2+ ions in the atmosphere and corona of Io and 2) the dissociative recombination of SO2+ ions in Io's dense wake.
We combine an MHD simulation of the plasma flow in Io's atmosphere with a multi-species chemistry calculation of the reaction rates to estimate Io's neutral loss rate.

Poster presentation

Spectroscopic observations of Io Neutral Clouds: constraints on Na-bearing dust grains ejected from Io

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We report the results of model simulations performed to explain the nature of a recently detected sodium emission feature in Io Neutral Clouds via high resolution spectroscopic observations from the Telescopio Nazionale Galileo (TNG) Italian telescope. The emission feature is blueshifted compared to the main emission (the banana-shaped Neutral Cloud) by a few tens of km/s, and it is most prominent when Io's orbital longitude is a few tens of degrees from opposition (before eclipse behind Jupiter's shadow). The feature changes morphology with time, indicative of a geometry effect. We constrained its direction, velocity, and brightness (i.e. column density) with a model of sodium atom trajectories under the influence of Io and Jupiter gravity and solar radiation pressure. The model that best explains this emission feature has the atoms injected into the exosphere from the leading/sub-Jovian hemisphere of Io, with a range of velocities from 10 to 70 km/s. These trajectories are consistent with those of negatively charged dust grains (grain size ~10 nm) which follow the co-rotational electric field of Jupiter's magnetosphere. Both modeling and observational constraints provide an order-of-magnitude estimate of the sodium production rate (via transport of dust) of ~10^{26} s^{-1}. Our findings are consistent with previous in situ dust detection by, e.g., Galileo showing that Io is the source of dust in the Jovian system, and provide another method to monitor the amount of material that Io is supplying to its plasma torus.

Poster presentation

An Alfvénic source for suprathermal electrons in the Io torus

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The Io-Jupiter interaction is a large source of Alfvénic wave energy that propagates to high latitudes and results in auroral emissions. We use a self-consistent two-dimensional hybrid gyrofluid-kinetic electron (GKE) model in a dipolar topology to simulate this wave energy propagation along the Io flux tube and examine the resulting wave-electron interactions. At high latitudes the interaction of electrons with inertial Alfvén waves are manifest as highly field-aligned broadband electron distributions (e.g. Damiano et al., 2019) that are consistent with recent Juno observations. Post-energization, the distribution functions maintain an elongated tail suggesting that energization of trapped electrons via dispersive scale Alfvén waves can be a source of suprathermal electrons critical to the torus energy balance (Bagenal and Delamere, 2011) and the Io torus physical chemistry (Coffin et al, 2020). The post-energization appearance of electron beams close to the Io torus also suggests that Alfvén-wave energized electrons could be a source of the observed trans-hemispheric beams (as proposed by Bonfond et al., 2008).

Poster presentation

The RADiation hard Electron Monitor (RADEM) for the JUICE mission

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The JUpiter ICy moons Explorer (JUICE) is the European Space Agency (ESA) next large class mission to the Jovian system. The mission, scheduled to launch in 2022, will investigate Jupiter and characterize its icy moons, Callisto, Europa and Ganymede for a period of 3.5 years after a 7.5-year cruise to the planet.
Previous missions to the planet already revealed a harsh radiation environment with a large population of energetic electrons. For this reason, the JUICE mission will include the RADiation hard Electron Monitor (RADEM), a low power, low mass radiation monitor, that will increase the range of long-term spectral measurements acquired by the Energetic Particle Detector (EPD) aboard the Galileo spacecraft, up from 11 to 40 MeV for electrons and up from 55 to 250 MeV for protons. RADEM consists of three detector heads based on traditional silicon stack detector technologies: the Electron Detector Head (EDH), the Proton Detector Head (PDH), and the Heavy Ion Detector Head (HIDH), that will measure electrons from 0.3 MeV to 40 MeV, protons from 5 MeV to 250 MeV and Heavy Ions from Helium to Oxygen with energies from 8 to 670 MeV, respectively. Because the detectors have limited Field-Of-View, a fourth detector, the Directionality Detector Head (DDH) will measure electron angular distributions which can vary greatly in the Jovian System as observed by the Galileo spacecraft.
RADEM will be fully operated during the cruise of the Solar System offering broad scientific opportunities outside of the main mission. In this work, we will present RADEM from a technical point-of-view, as well as the scientific opportunities that will be addressed by the radiation monitor during the JUICE mission.

Poster presentation

The JUICE Radio & Plasma Wave Investigation (RPWI) of the Jovian moon-magnetosphere interactions

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The Radio & Plasma Wave Investigation (RPWI) of the JUICE mission will investigate the dynamics, structure and energy/momentum exchange processes of the Jovian and Ganymede magnetospheres and how the Jovian magnetosphere interacts with the Galilean moons. The RPWI investigation provides a complete set of electric (DC - 45 MHz), magnetic (0.1 Hz - 20 kHz) and plasma sensors to monitor electric currents, acceleration structures, electromagnetic and plasma waves (e.g., Radio, Alfvén & Whistler waves), thermal plasma characterisation, plasma convection, dust particle distributions and their charge state. Among its many science objectives RPWI will focus on the characterisation of the ionosphere-magnetosphere-subsurface ocean electrodynamic coupling processes near the Galilean moons.

Poster presentation

Europa-UVS and JUICE-UVS Plans for Auroral and Airglow Observations of Moon-Magnetosphere Interactions

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Ultraviolet Spectrograph (UVS) investigations of moon-magnetosphere interactions in the Jupiter system use auroral and airglow emission line spectral imaging to constrain several properties. These properties include atmospheric densities for various constituents and imaging of plume or other regional density enhancements, while revealing the flow of plasma and magnetospheric electron energy throughout the interaction region. Io's equatorial spot aurora "rocks" in latitude with Jupiter's magnetic field. Europa's polar aurora generally alternates in brightness from pole to pole relative to the plasma sheet location. Ganymede's auroral oval locations in contrast are more fixed in location than Jupiter's changing magnetic field orientation would explain alone, with inductive currents generated in a subsurface ocean compensating for this influence. Callisto's higher ionospheric conductivity results in dimmer auroral emissions (relative to airglow processes), and while its emission morphology is less diagnostic the constraints to atmospheric constituents that UV observations provide are key to photochemical modeling of ion production rates. Neutral cloud and torus UV emission observations are a key measure of processes linking local interactions to multiple aspects of the Jupiter system. At the time of this meeting the Jupiter Icy Moons Explorer (JUICE) UVS instrument has been delivered to ESA for integration on the spacecraft, and the similar Europa-UVS instrument on NASA's Europa Clipper mission is being built. These UVS instruments closely follow the Juno-UVS design in terms of using a modern microchannel plate (MCP) detector, including robust shielding from intense MeV electron radiation and higher count rate dynamic range. Photons in the 50-210 nm wavelength range (slightly expanded relative to Juno-UVS's 70-200 nm range) are observed at moderate spectral and spatial resolution along a 7.5° slit. We describe the UVS science plans and basic concepts of operations with respect to moon-magnetosphere interaction related goals.

Poster presentation

JUICE spacecraft charging in the variable Jovian magnetosphere, plumes of Europa and the auroral zone of Ganymede: Implications for future particle and fields measurements

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Spacecraft Plasma Interaction Software (SPIS) surface charging simulations for JUICE show that surface charging during typical Jovian magnetospheric conditions will likely not cause substantial disturbances for the particle and fields instrumentation. However, a few specific environments might. We have studied three different environments that may cause larger disturbances.

1. The variable magnetosphere. Typical plasma densities in the plasma sheet at 9.5 R_J are around 30-80 cm^{-3}. However, Galileo/PWS have detected plasma densities of up to 760 cm^{-3}. Such high densities could be due to activity on Europa, such as plumes, or a local disturbance of cold and dense iogenic plasma.

2. The plumes of Europa. Several Galileo Europa flybys and ground based observations have indicated that Europa is an active moon with plumes. If JUICE encounters one of the stronger plumes, surface potentials could charge down to around 10 V lower than the potential commonly obtained in the ionosphere of Europa, assuming a cold plume electron temperature of 5 eV.

3. The auroral zones of Ganymede. HST observations of the aurora of Ganymede shows localized regions of bright spots superimposed on a continuous background emission. In order to produce bright auroras, the electron population would need to be accelerated up to hundreds of eV.

Preliminary simulation results for all of the above environments show surface potentials of tens of volts or more, which could cause significant disturbances in both particle and electric fields measurements. Even though the occurrence rate for the above environments are low and JUICE will only spend a fraction of its time in them, it is important to prepare for disturbances that might occur during such encounters since all of the above environments are of particular scientific interest.

Poster presentation

Large density spikes in Titan's upper ionosphere

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Titan, the largest moon of Saturn, has a dense and nitrogen-rich atmosphere, which is similar to that of early Earth before lived evolved. Solar EUV radiation and energetic particles ionizes the atmosphere and thereby forming a layer of plasma, the ionosphere, in the uppermost part of the atmosphere. The Cassini spacecraft flew past the moon Titan 127 times during its 14-year mission in the Saturn system. During most of these close flybys Cassini entered the ionosphere and some reached the ionospheric peak, located at some 1400 km above the moon surface. With the Langmuir probe instrument, we could study the plasma properties, e.g. ion and electron density, temperature etc., and a very dynamic ionospheric structure was found. In particular, significant and apparently sporadic density spikes in the upper ionosphere were found. These density peaks are manifested as a sudden increase in the measured density by some 10-100 cm^{-3} over a time period of roughly minutes. These have so far been left unattended in our studies of Titan. We will present some statistics on their appearance and initial result on the mechanism forming them.

Poster presentation

Polarization electrostatic field in the presence of negatively charged dust: implications for dust confinement near Saturn's F ring

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It is well known that in the magnetosphere of the outer planets (eg. Saturn, Jupiter, Neptune), even in the absence of an electric current, a polarization electric field develops as a consequence of charge separation in a plasma, providing a restoring force to maintain charge neutrality. It is also well established that certain regions of these planetary systems (ionosphere, icy moons, rings) are populated by significant amount of charged dust that play an important role in the physical and chemical processes in the surrounding plasma environment.
In the present work, we study the effect of the charged dust grains on the polarization electric field using Saturn's F-ring region as a case study. We derive a general expression for E parallel to the magnetic field ($\mathbf{E}\|$) and then using the Cassini RPWS/LP measurements we estimate for the first time in situ **E**—— close to Janus/Epimetheus ring during the F ring grazing orbits. We further demonstrate that the presence of charged dust close to the ring plane (—Z—¡0.1 Rs) amplifies $\mathbf{E}\|$ by at least one order of magnitude, and reverses its direction. Such a reversal implies a confinement of the electrons towards the equatorial plane. This work shows that the presence of the charged dust, as small as nanometers in size, can significantly influence the plasma transport processes, in particular the ambipolar diffusion along the magnetic field lines.

Poster presentation

Jupiter's unusual swirly storms

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Swirl's structure on the planetary surfaces stays a mystery for researchers. Swirly structures visible on Jupiter's surface are the results of storms' movement due to its larger magnetic field. However, the resemblance of these features to the look-alike features on Lunar and Earth's surface makes them interesting.This work discusses the possible relatable reasons behind the swirly storms on Jupiter by utilizing the images from Juno Camera, a "push frame" imager, from the NASA's Jupiter Orbiter Mission. Many storms forming swirly structures are observed on Jupiter's surface apart from the giant red spot. In this work, a joint analysis of swirls on Jupiter, Lunar swirls, and their correlation with Eddies on Earth has been discussed, indicating that these swirls structures may have similar origin features.