Collaborative document for the Outer planet moon - magnetosphere interaction workshop 2020

The Outer planet moon - magnetosphere interaction workshop 2020 took place on November 5 - 6, 2020. This year's meeting was held online due to the global COVID-19 outbreak. The workshop was attended by 67 participants from all over the world, spanning a range of 19 different time zones. The workshop contained 43 talks and poster presentations.

This document covers open questions that were raised during the workshop and key points from the presentations.

For any further questions contact the organisers: Lina Hadid (lina.hadid@lpp.polytechnique.fr), Mika Holmberg (mika.holmberg@esa.int) and Hans Huybrighs (hans.huybrighs@esa.int)

Open questions

Which open questions have been identified during the meeting?

General

- What is the effect of the variable energetic charged particle environment on the moon-magnetosphere interaction?
- Do energetic charged particles associated with interchange events cause transient exospheres?
- What is the role of waves in the energetic ion depletions near the Galilean moons?
- Which ion pick up species are present in the outer planet magnetospheres and what are their dynamics?
- What is the charge state of the outer planet moon's surfaces?
- What are the sputtering rates at the outer planet moons?
- What are the atmospheric density profiles and 3D structure of the outer planet moon's exospheres and tenuous atmospheres?
- Are the ionospheres of the icy moons dusty plasma environments?

Europa

- Are there water plumes on Europa? How often are they active and where do they occur?
- Why are the different Europa plume observations not consistent in terms of density and location?
- What is the rate of ionization in Europa's wake?
- Why are energetic protons depleted in Europa's wake?
- Is there dusty plasma in the plumes of Europa?

Io

- What is the coupling between volcanoes, the atmosphere, the neutral clouds and the plasma torus?
- Are there SO_2 derived neutral clouds, gigantic Mendillo-disc, jets and streamers originating from Io?
- Is Io the source of the S and O ions detected in the equatorial regions of Jupiter by Juno?
- What is the effect of the SO_2 neutral losses on the neutral cloud models?
- Is the Io torus a dusty plasma environment?
- Why don't we cross a radio source every time we pass through the Io flux tube? Is the electron density too low/too high? Is the plasma not energetic enough?

Callisto

- Is there sulfur on Callisto's surface?

Saturn and Enceladus

- What is the cause of the difference in the electron densities measured by the Cassini Langmuir probe (LP) and the RPWS electric field antennas?
- Are there asymmetries, dawn/dusk or day/night, in the plasma disk of Saturn?
- How does the photoelectrons from the spacecraft and from the LP itself affect the Cassini LP measurements?
- How is the high plasma density in the plume of Enceladus created? Known ionization sources can not explain the high plasma density measured by the Cassini LP.

Triton

- How do the extreme variations between Neptune's magnetic field axis and the solar wind affect the magnetospheric interactions?
- What is the role of haze clouds and plumes on the magnetospheric interaction?

Lessons for JUICE

What lessons should be passed on to the JUICE team?

Europa

- Detecting Europa's plumes during JUICE flyby proves to be more difficult when neutral on neutral collisions are considered in the plume modelling. A shock forming between the upgoing and falling particles reduces the extent of the plume. Reducing the JUICE flyby altitude can improve the detectable area for plumes on the surface by ~30% for 100km reduction.
- Energetic proton depletions could be used as a proxy to study atmospheric charge exchange, water plumes and other aspects of the magnetospheric interaction (field perturbations in the wake, Alfvén wing)
- Spacecraft surface charging in Europa's ionosphere, in plumes of Europa and in dense plasma environments occasionally detected at the orbit of Europa far from the moon, will impact cold electron measurements
- Large differential charging detected in dense plasma environments occasionally detected at the orbit of Europa, but far from the moon, might create large

contaminating electric fields and currents that can interfere with electric field measurements
- The orientation of the solar panels with respect to the plasma flow and the solar radiation can be used to alter the spacecraft surface potential

Ganymede
- The exospheric O2 densities may be underestimated by a factor of 10 (based on MAG/PWS/PLS analysis of G2 flyby)

Io
- The main processes of SO2 neutral losses are: electron-impact dissociation, cascade of resonant charge exchanges, SO2+ recombination ,... They could produce features comparable to those detected in Na: extended neutral clouds, gigantic Mendillo-disc, jets and streamers and perhaps be the source of S and O ions detected in the equatorial regions of Jupiter by Juno.

Key points per contribution

What are the key points of the contributions?

Orals

Roussos *et al*., The variable energetic charged particle environment of outer planet moons (invited)

Key points
- variations of energetic particle environment impact various aspects of moon-magnetosphere interaction
- Problem: long term average of energetic ion/electron flux are often used but can be very misleading -> dynamics can vary strongly from the average case
- Even for moon/magnetosphere interaction aspects developing over geological time scales, we should re-think how to construct the average electron/ion spectra to which the moons are exposed.

Variability time scales
- <u>Short</u> (<= week): planetary period variations of the spectra are described by models, but not used! Typically average spectra (e.g. Cooper et al., 2001) are used, e.g. for surface sputtering estimations. There is sufficient data to move away from this!
- Examples of short time scale variations: Interchange events of <15 min (undispersed) & > 15 min (dispersed) (Krupp et al, 2020, Azari et al. 2018), may cause transient exospheres. This has yet to be investigated. Exposure to interchange events is regular for both jovian & saturnina moons
- <u>Intermediate</u> (weeks-months): Variability of noon-midnight electric field (Saturn), dawn-dusk electric field (Jupiter) has been resolved at such scales, electron belts are

typically more responsive to such electric field changes. For protons/ions, ICMEs have been identified as drivers of mid-term variability (transient belts) at Saturn. Transient ion belt extensions have also been observed at Jupiter (>15-20 Rj), but origin is still unclear.
- <u>Long term (>> months)</u>

Regoli *et al*., Effects of Titan's magnetospheric environment on its atmosphere

Key Points
- Energetic proton environment at Titan's orbit is highly variable.
- Organization according to distance to the center of the plasma sheet possible, with higher fluxes at the center and decreasing fluxes towards the lobes.
- Kappa distribution provides a good description of the fluxes.
- Energy deposition at Titan's orbit by energetic ions (H+ and W+) is highly dependent on energy and species.
- Finite gyroradius creates asymmetries that only depend on electromagnetic field configuration around the moon.
- Local heating and ionization by ions needs to be analyzed on a flyby-to-flyby basis.

Achilleos, Modelling ambient field and plasma conditions at moon orbits

- Current sheets / plasma sheets have structure which can be complex, but diagnostic of solar wind and internal influences
- Modelling approaches include 'transforming' simplified field models – or time-dependent MHD codes
- Such approaches help quantify the 'response' of the plasma sheet to the relevant influences
- At Jupiter and Saturn the field produced by the current sheet itself has a significant influence on particle dynamics in the 'middle magnetosphere'

Kaweeyanun *et al*., Modelling of Energy-Transfer Processes at Ganymede's Upstream Magnetopause

Goal: characterize rates for magnetic reconnection and Kevin-Helmholtz instability
- This is the first analytical assessment for both interactions
- Reconnection can occur throughout closed-field magnetopause
- The average reconnection rate is driven by Jupiter's rotation
- K-H instability viable along all-latitude magnetopause flanks.
- K-H growth rate suggests vortices are viable, but vortex growth will likely be suppressed by MR effects.

Hongyang Zhou *et al.*, Reconnection-driven dynamics at Ganymede's upstream magnetosphere: 3D global Hall MHD and MHD-EPIC simulations

- Flux ropes of about 1 R_G in length form on the magnetopause at a rate about 3/minute and produce spatiotemporal variations in plasma and field properties
- MHD-EPIC model can resolve both electron and ion kinetics at the magnetopause and show localized non-gyrotropic behavior inside the diffusion region

Harris *et al*., Multi-fluid MHD Modeling of Europa's Plasma Interaction

Multi-fluid MHD modelling of Europa's plasma interaction

Developed 3-ion-fluid MHD model for the plasma interaction
- steady-state multi-fluid MHD based on BATS-R-US
- 3 ion fluids
    - Ambient, thermal magnetospheric O^+
    - ionospheric O_2^+
    - ionospheric O^+
- ionospheric fluids generated by source/loss terms such as electron impact ionization (and others)
- plasma fluids coupled to the electromagnetic fields through MHD equations

E4 flyby
- x-y components of field are dipole dominated
- z component is dominated by plasma interaction
- good data-model comparison indicates model is an accurate representation of the plasma interaction

Parameter study of the effects of changing magnetospheric conditions
- 9 simulations spanning anticipated conditions of the magnetosphere at Europa's orbit
- Measured precipitation of thermal plasma for each simulation
- Precipitation increases with ambient plasma density

Publication has been submitted to JGR, hopefully forthcoming early in 2021.

Roth *et al*., Europa plume studies

Philips et al., 2000 -> no evidence for geological activities on Europa
17 yrs later: 6+ studies claiming evidence for Europa's plumes

Main message: the case for plumes is not closed yet!

Problems
- inconsistencies in location, density, detection rate between different methods
- Sparks et al studies: plume features could be explained by random noise (Giono et al., 2020)

- Non detections with certain methods (e.g. HST spectroscopy De Kleer and Brown 2018)

Dayton-Oxland *et al*., Impact of using a collisional plume model on detecting Europa's water plumes from a flyby

Main message: detecting plumes using an in-situ instrument becomes harder when we consider particle collisions between the neutral plume particles. The collisions in the plume cause a shock which creates a more confined plume compared to a non-collisional case.

Bagenal *et al*., Variability of the Galilean moon plasma environment and implications for moon-magnetosphere interactions (invited)

Io

- the big issue: the coupling between volcanoes, the atmosphere, the neutral clouds and the plasma torus is not clear yet!

Schmidt *et al.,* The Io-torus interaction as seen through a telescope

- Io’s sodium jets can reach Europa (~10^22 Na atoms/s)

Smith *et al*., Determining the Io volcanic source with Hisaki neutral oxygen observations and 3D modeling

- Applied 3D MOnte Carlo modeling with Hisaki (neutral oxygen) observations to determine Io source to Jovian magnetosphere
- Two distinct Io volcanic source populations (during quiet activity period)
    - 290 kg/s O (& S) preferentially from Jupiter facing side
    - 270 kg/s SO2 (source location not unique)
- Dominant neutral species throughout Io’s orbit is oxygen

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

- An analytic solution for the flow field is convenient
    - Easily incorporated into other models of the ionosphere, e.g. atmospheric sputtering, charge exchange, fast neutral production and particle access to the surface
- This presentation described assolution for an exponentially decreasing conductance outside the body
- Plasma is excluded from the lower ionosphere
    - Reducing production of fast neutrals and atmospheric sputtering
- Flow along flanks is slower than predicted by standard model

- This flow field can be incorporated into other calculations of the interaction

Coates *et al*., Pickup ions in the outer solar system

- At Saturn's moons, Cassini CAPS sees early stages of ion pickup (implantation, nongyrotropic, ring), and both positive & negative ions - Rhea, Dione, Titan
- In Saturn's magnetosphere, ring distributions seen near Enceladus, water group ions
- Pickup a key process at moons and for populating outer planet magnetospheres
- Particle distribution function measurements (positive and negative ions with enough field of view, energy coverage & resolution) essential to follow development of distributions and determine composition
- Waves indicative, but not enough to uniquely determine species and dynamics

Xystouris *et al*., Low-energy electrons in Saturn's inner magnetosphere from the Cassini Langmuir Probe

Motivation: (i) study plasma sources, (ii) instruments comparison
Data: r<8Rs, |Z|< 0.5, used only Langmuir Probe's electron density
Results:

- The electron density measured by the Cassini LP follows a hybrid power-law model, suggested by Persoon et al., 2013
- However, the Cassini LP electron densities differs to the electron density from RPWS/f_{UHR} (Persoon et al., 2015):
  – ne, R(ne), m-gradient → still into investigation
- Looking for further structures → spatial analysis → LT asymmetries
  – Hints of dusk-dawn asymmetry – not present in ions
  – No day-night asymmetry – present in ions (Holmberg et al., 2014)

Current work: LP heavily affected by sunlight → photoelectrons impact → study shadowing and shading factors based on Cassini 3D model
→ Vector-Spacecraft interaction: Simple method that can be used on any instrument, on any mission (e.g. JUNO)

Morooka *et al.*, The Langmuir probe observations of the dust and plasma at Enceladus plume and the E-ring

- The Cassini LP have found many regions with dusty plasma in Saturn's magnetosphere: in the plume of Enceladus, E ring, F ring, Saturn's ionosphere, Titan's ionosphere
- Cassini LP can be used to characterise the dusty plasma environments
- Similar dust-plasma environments can be expected in the Jovian system: in the Europa plumes, Europa torus, Ganymede ionosphere

Haythornthwaite *et al*., Fast and Slow Water Ion Populations in the Enceladus Plume

- In the Cassini CAPS data a low energy positive ion peak occurs in two north-south Enceladus flybys during transit of plume
- This peak has been previously associated with O+
- New interpretation is that the peaks are associated with (high velocity) jets than are also seen in the neutral gas emissions
- This feature is not seen in later horizontal flybys of the plume, indicating it is not a compositional feature
- The new interpretation also resolves the lack of O+ seen in the INMS data as well why the feature is not seen in later flybys
- Velocities of the jets are resolved along the track of Cassini

Jones *et al*., Remote Detection of Surface Charging at Saturn's Icy Moons

- Rhea's surface is negatively charged
- Estimated surface potential of Rhea range from a few V positive at the subsolar point to below -100 V at the antisolar point
- Surface charging of small bodies with weaker gravitational field could make loose surface materials more mobile

Sulaiman *et al.*, Moon-magnetosphere interactions of Io and Enceladus: A high-resolution, in-situ parametric study (invited)

- Studying the flux tube of Io reveals fields and particles signatures characteristic of auroral processes, such as:
    - Alfvénic turbulence and broadband electrons consistent with stochastic acceleration
    - Intense ion cyclotron heating associated with upward proton conics
    - Electron beams unstable to the generation of whistler-mode auroral hiss
- Io's interaction with Jupiter is significantly more powerful than Enceladus' interaction with Saturn

Louis *et al*., Moon-induced auroral radio emission in the outer solar system

In-situ measurements of Jovian moon-induced decametric radio emission:

- crossings of Io's (x2), Europa's (x1) and Ganymede's (x1) radio sources.
- decametric radio emission produced by a loss-cone electron distribution function driven the Cyclotron Maser Instability (CMI), sustained by Alfvénic acceleration process;
- CMI needs minimal dense, hot, energetic plasma to occurs;

- measured electron energy: 1-20 keV & measured beaming angle aperture: 74°-86°
- radio emission associated with down-tail UV emission (likely reflected Alfvén wing spots).

Holmstrom *et al*., Triton Plasma Interactions

Triton plasma interactions

Interesting interaction due to

- the extreme variations between Neptune's magnetic field axis and the solar wind (varies from parallel to perpendicular)
- haze clouds and plumes

Galand *et al*., Invited presentation: Connecting the Galileo particle, plasma, and field data with ionospheric, exospheric, and MHD models (invited)

- 3D ion test particle model applied to the environment of Ganymede:
  - Application to ionospheric ions, jovian ions, and hot O2
  - Comparison with Galileo G2 dataset (Carnielli et al., Icarus, 2019, 2020a)
  - Used to assess sputtering rate on Ganymede's surface (Carnielli et al., Icarus, 2020b)
- **Model of relevance to JUICE**:
  - RPWI (e.g., MIME → ionospheric model has been used for optimising the operating modes and advising on operability) and 3GM [total plasma density]
  - PEP [energetic ion and O2 energy distribution]
  - NIM [would measure only a limited part of the ion population as measurements < 5 eV and most ions have higher energies, but relevance to constrain neutral densities]
  - Estimation of ion radiation dose
  - J-MAG (ultimately for analysis of B field by providing info on ion dynamics)
- **Lesson for JUICE:**
  - Comparison with Galileo G2 shows that exospheric O2 densities may be underestimated by a factor of 10

Mueller-Wodarg *et al.*, Detectability of subsurface oceans and their flows by JUICE

- Predicted induced E- & B-field perturbations at Ganymede and Europa are detectable by JUICE instrumentation (RPWI & MAG)
- Our model allows us to detangle the contributions from Jovian B-field and ocean motion
- Will potentially allow us to constrain:
  - Ocean depth
  - Ocean conductance

- Characteristics of internal heat sources

Cartwright *et al*., Investigating the origin of sulfur-bearing species on the Galilean moon Callisto

Question: is sulfur on Callisto?

- spectral signature (4 micrometer) consistent with S bearing species (but not SO2)

Posters

Dols *et al*., Io's Loss of Neutral Material: Numerical Simulations

- Sources of neutral from Io's atmosphere are very large:several tons/s of either S, O or SO2
- The main processes of SO2 neutral losses are: electron-impact dissociation, cascade of resonant charge exchanges, SO2+ recombination ,...
- They could produce features comparable to those detected in Na: extended neutral clouds, gigantic Mendillo-disc, jets and streamers and perhaps be the source of S and O ions detected in the equatorial regions of Jupiter by Juno
- Need to include these sources of neutrals in Neutral CLoud Models like H.Smith+2019

Huybrighs *et al*., Energetic proton depletions near Europa: the effect of plumes, atmospheric charge exchange, Alfvén wings and the wake

Energetic protons can be used to probe the moon-magnetosphere interaction

Energetic proton depletions near Europa are caused by

- protons impacting the surface
- atmospheric charge exchange (flyby E26)
- potential water plumes through charge exchange (80-220 keV) and field perturbations (80-1040 keV)
- field perturbations (wake/Alfvén wing)

Hadid *et al*., Polarization electrostatic field in the presence of negatively charged nm grains: implications for electrons and dust levitation near Saturn's F ring

The effect of the negatively charged dust on the magnetic field aligned ambipolar electrostatic field $E_{||}$ using the Cassini RPWS/LP during the F-ring grazing orbits.

- A general expression for $E_{||}$ and estimate $E_{||}$ near Janus and Epimetheus rings.
- $E_{||}$ is asymmetric with respect to the magnetic equator.
- The charged dust amplifies $E_{||}$ x10 & reverses its direction (ring plane +/-0.1 Rs).
- Implications on electrons and dust levitation from the Kronographic equator.

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

The spacecraft surface charging of JUICE is studied using the Spacecraft Plasma Interaction Software (SPIS)

- Surface charging in typical plasma sheet environments will not cause substantial perturbations to particle and fields measurements
- A few plasma environments with high electron densities and/or temperatures are likely to cause substantial surface charging and differential charging
- These environment includes dense plasma environments near Europa, caused by plume activity on Europa or cold and dense iogenic plasma, the ionosphere + plume of Europa and the auroral zone of Ganymede
- Large negative surface potentials values will prevent cold electrons from reaching the particle instrumentation on the spacecraft and will therefore not be measured
- Large differential charging will create large contaminating electric fields and currents that can interfere with electric field measurements