



Magnetospheric Studies: A Requirement for Addressing Interdisciplinary Mysteries in the Ice Giant Systems

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Abstract Uranus and Neptune are the least-explored planets in our Solar System. This paper summarizes mysteries about these incredibly intriguing planets and their environments spurred by our limited observations from *Voyager 2* and Earth-based systems. Several of these observations are either inconsistent with our current understanding built from exploring other planetary systems, or indicate such unique characteristics of these Ice Giants that they leave us with more questions than answers. This paper specifically focuses on the value of all aspects of magnetospheric measurements, from the radiation belt structure to plasma dynamics to coupling to the solar wind, through a future mission to either of these planets. Such measurements have large interdisciplinary value, as demonstrated by the large number of mysteries discussed in this paper that cover other non-magnetospheric disciplines, including planetary interiors, atmospheres, rings, and moons.

Keywords Uranus · Neptune · Ice Giant · Future missions · Magnetosphere · Space plasma · Radiation belts · Atmospheric escape · Planetary rings · Habitability · Planetary dynamo

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1 Introduction

Uranus and Neptune represent a distinct class of planets that remains the least investigated in the solar system and marks the frontier for a wide range of scientific areas. While Jupiter and Saturn (the “Gas Giants”) are made mostly of hydrogen, the bulk compositions of Uranus and Neptune (the “Ice Giants”) are dominated by heavier “ices” such as water, methane, and ammonia. Their rotation and magnetic axes are highly inclined, leading to magnetospheric dynamics unlike anywhere else in the solar system. Because these planets have only been visited by flybys of *Voyager 2*, we currently cannot claim to understand the inventory of our solar system. This becomes even more critical given that these Ice Giants may be indicative of planets common throughout the galaxy (Hofstadter et al. 2017). As such, the study of solar system’s Ice Giants is a crucial step for providing ground truths for the understanding of Ice Giant exoplanets (Rymer et al. 2018).

There already have been several reviews on open science questions related to the Ice Giants (Agnor et al. 2009; Rymer et al. 2013; Hess et al. 2013; Arridge et al. 2012, 2014; Turrini et al. 2014). Here, we focus on the magnetospheres of the Ice Giants. In contrast to these works, we do not attempt to provide a complete compilation of science questions. In particular we avoid generic questions that are common to any unexplored planet such as, “What are the relevant processes for X?” Instead, we present a compact set of mysteries that build on concrete observations and follow the theme of “We observed X, but it does not appear to make sense”.

The aim of this work is to underscore the value of magnetospheric measurements not only for the sake of deepening our understanding of magnetospheres within our solar system and beyond (Sects. 1.2 and 3), but to support most other disciplines interested in the Ice Giant systems (e.g., their atmospheres, interiors, moons, and rings; Sects. 1.3 and 3) as well.

1.1 Flyby Missions Are Insufficient

Voyager 2’s brief encounters with the Ice Giants provided only a glimpse at the complexity and uniqueness of these worlds and ultimately supplied many more questions than answers. The current limited understanding of the Ice Giants is analogous to the knowledge of other planets after initial flyby encounters (e.g., the *Mariner* missions at Mercury, Venus, and Mars; the *Pioneer* and *Voyager* missions at Jupiter and Saturn). Just as the understanding of those planets was transformed after sending dedicated orbiter missions (e.g., *MESSENGER*, *Pioneer Venus Orbiter*, *Mars Global Surveyor* and *Mars Express*, *Galileo*, *Cassini*, etc.), so too will our knowledge of the Ice Giants expand from the long-term measurements and investigations afforded by an orbiting mission.

In particular, magnetospheric conditions can change rapidly compared to structures and dynamics in atmospheres or on planetary/satellite surfaces. Because observed changes in in-situ particles and fields conditions may be the result of time-dependent dynamic processes or transition of the spacecraft into a different region of space, flybys are limited to snapshots of a planetary space environment. The only way to address this is with an orbiting spacecraft that provides information on typical conditions of the system, which then enables identification of dynamic events, as demonstrated by the results from orbiter missions such as *Galileo*, *Cassini*, and *Juno*. (Multiple spacecraft are generally better, which justified missions like *Cluster* or *MMS* at the Earth. Similar missions would be useful as a follow-up but are neither needed nor realistic for the first exploration of an Ice Giant.)

Of course, the first orbiters at every other planetary system revealed many surprises that were not expected from the limited information gleaned by the flyby encounters of their

predecessors. For example, one of the greatest discoveries of *Cassini* was the eruption of material (Dougherty et al. 2006; Porco et al. 2006) from the subsurface ocean of Enceladus (Postberg et al. 2009; Thomas et al. 2016), a phenomenon unnoticed by the previous flybys of *Pioneer 11*, *Voyager 1*, and *Voyager 2*, as well as Earth-based observations. The plumes of Enceladus were first discovered in standard magnetic field data (Dougherty et al. 2006), providing an observational target for dedicated visible observations (Porco et al. 2006). Future orbiter missions to the Ice Giants should yield their own surprises, especially given that the flyby measurements may not have been representative.

1.2 Benefits to Space Physics

Planetary magnetospheres are filled with plasma and radiation. Not unlike in a planetary atmosphere, there are varieties of active processes in a magnetosphere that affect transport, heating, and chemistry of material that need to be understood. Particularly Uranus and Neptune have uniquely configured magnetospheres: their internal magnetic field has strong non-dipolar components (Ness et al. 1986, 1989), which makes it unusually complex. There are large angles between rotation and magnetic axis (-58.6° and 46.9° ; Connerney 1993). In combination with the highly tilted rotation axes relative to the orbital plane (97.9° and 29.6° ; Arridge 2015) this results in magnetospheres that point their polar regions at times roughly Sunward, either over the planetary year or planetary rotation. This unusual configuration is thought to be a game changer for several important magnetospheric processes and therefore a critical missing piece for comparative magnetospheres. There are many mysteries on how such magnetospheres work even on a basic level, as we will elaborate on in Sect. 2.

It is important to understand that by studying Uranus or Neptune we will not only learn about these specific planets but also advance our understanding of space physics in general, which can then be applied to other planets in the solar system or other parts of the universe. This is possible because space plasma is not only found in magnetospheres. In fact, it is the most common form of matter in the visible universe. Most of it is found in stars that are mostly observed remotely through telescopes. In-situ measurements through space missions operating directly within magnetospheres of a planet or the heliosphere of our Sun provide ground-truth that applies to the rest of the universe.

The same is true for radiation, the high-energy tail of any plasma population. The acceleration of plasma to higher energies is a universal question that applies over the full measurable energy range and the entire universe, from the solar wind to galactic cosmic rays. Astrophysical particle acceleration is also mostly observed indirectly, for example through associated radio or gamma ray emissions (Hillas 2013; Abramowski et al. 2016). Also using a laboratory or collider on Earth has its limits because the spatial and temporal scales on which these processes occur in space are often far larger than the Earth or human lifetimes (Selesnick et al. 2007). Fortunately, we can leverage in-situ measurements and visit planetary radiation belts and bow shocks, like the ones of Uranus and Neptune, and use them as a natural laboratory to study radiation physics in general.

Testing our space physics theories is especially important because they are now extrapolated and applied to exoplanets and brown dwarfs outside of our solar system (Schrijver 2009; Nichols et al. 2012; Kislyakova et al. 2014; Hallinan et al. 2015). However, before we can move on to reliably make such predictions, we first need to further improve our models. Current magnetospheric physics is built upon measurements obtained at the planets we studied in detail, which does not include Uranus or Neptune. This gap may be critical: For example, it has been suggested that the nature of the interaction of a magnetized planet with the surrounding solar wind changes with increasing distance to the Sun (Sect. 2.3, Masters 2018), making it important to test this hypothesis, which is best done at the Ice Giants.

Similarly, acceleration at bow shocks becomes increasingly similar to supersonic shocks, again making Uranus and Neptune ideal to find ground truth on the mechanisms involved (Sulaiman et al. 2015).

1.3 Magnetospheric Measurements Benefit Broad Systems Science

Planetary moons, rings, and the planets themselves interact with the planetary magnetospheres in which they are embedded. Exploring planetary magnetospheres is relevant not only to understanding magnetospheric dynamics and space physics, but is also critical for other disciplines within planetary science.

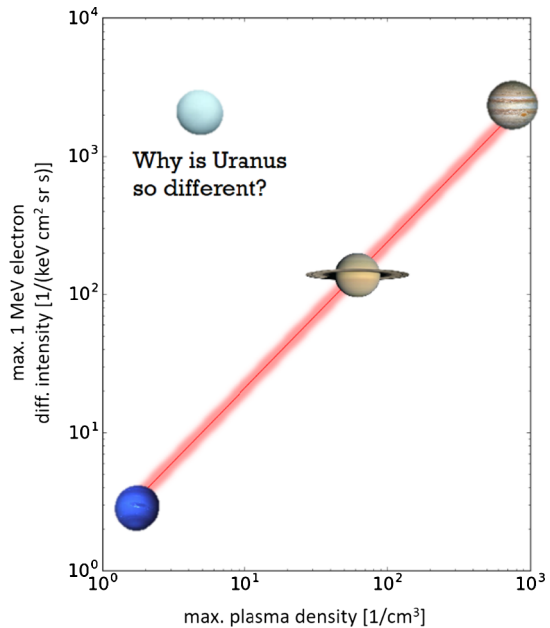
The surfaces of giant planet satellites show clearly-visible large-scale albedo patterns at various wavelengths (Schenk et al. 2011; Patterson et al. 2012). Some of these patterns can only be understood in context with the magnetospheric environment, as they result from a bombardment of corotating plasma and bouncing energetic particles that affect the thermal inertia, composition, crystallinity, etc. of the moon surfaces (Lane et al. 1981; Hendrix et al. 2012; Paranicas et al. 2014; Howett et al. 2011, 2012).

Furthermore, previous orbiting missions at other planets provide examples of how comprehensive magnetospheric measurements can supplement and even serve as indicators for processes important to non-magnetospheric science. One landmark example is the discovery of a sub-surface salt-water ocean on Europa that arose from observations of odd magnetic field perturbations due to currents induced from the motions of the sub-surface liquid within the satellite (Kivelson et al. 2000; Saur et al. 2010). Magnetic field measurements also have been used to infer internal and ionospheric structure of Io and Callisto (Jia et al. 2010; Hartkorn and Saur 2017; Blöcker et al. 2018), and the permanent dipole field of Ganymede (Gurnett et al. 1996; Kivelson et al. 1997). Magnetic measurements were also used to constrain the internal dynamos of Jupiter, Ganymede, and Saturn (Kivelson et al. 1997; Dougherty et al. 2018; Connerney et al. 2018). As geologically active moons can supply material to magnetospheres, magnetospheric observations (like UV emissions of the Io plasma torus) are a proxy of the responsible geologic activity (preceding volcanic eruption; Yoshikawa et al. 2017).

Since a planet's magnetic field can force charged particles to continuously interact with neutral material (i.e. from a ring or gas torus), the neutral material more significantly affects charged particle intensities than it affects light, which only passes once through the material. The measurement of energetic particles is therefore a very sensitive tool for detecting neutral material that might originate from an active moon or from an unknown ring. Initial detection of Saturn's G-ring arc (Hedman et al. 2007), Saturn's Methone ring (Roussos et al. 2008), and Europa's neutral torus (Lagg et al. 2003; Mauk et al. 2003) were first made through energetic particle observations. The latter provided the first hint that Europa might have plumes, which were not observed optically until much later (Roth et al. 2014).

For these reasons, it is important that future large-scale Ice Giant missions carry comprehensive instrument suites that support research from multiple disciplines, including magnetospheric physics. In order to set requirements for such a comprehensive payload, we discuss in Sect. 3 how magnetospheric measurements can support the science of other disciplines, including planetary and moon interiors, atmospheric evolution and structure, and moon geology.

Fig. 1 Correlation between observed 1 MeV electron intensities (Mauk and Fox 2010) and the maximum magnetospheric bulk plasma densities of the Giant planets (Selesnick et al. 1987; Richardson et al. 1991; Thomsen et al. 2010; Bagenal et al. 2016). It can be seen that Uranus' electron radiation belts stand out since they are comparable to Jupiter's in intensity (both in the absolute sense below 1 MeV and in the relative sense compared to the Kennel-Petschek limit, Mauk and Fox 2010), even though Uranus has over one hundred times less material available to be energized



2 Magnetospheric Science

2.1 Unexpectedly Intense Radiation Belts at Uranus

The mystery discussed in this section can be summarized as: How can Uranus have such intense radiation belts (Mauk 2014) when it lacks a strong source population (McNutt et al. 1987)?

According to our current understanding, in order for a planet to have strong radiation belts it needs to have a large reservoir for particles that can be accelerated, an efficient acceleration process, and/or weak loss processes that might remove the accelerated particles. Similar to other radiation in the universe, radiation belt particles start at relatively low energies in the eV and keV range and are subsequently accelerated over several orders of magnitude to MeV and even GeV energies. This acceleration can happen, for example, because electromagnetic waves in a planet's magnetosphere can transfer part of the free energy to the charged particles trapped in the magnetic field. However, Uranus challenges our understanding of radiation physics because it has electron radiation belts that are similar in intensity to those of Earth and Jupiter (Mauk and Fox 2010; our Fig. 1) up to energies as high as 1 MeV, despite having of what was deemed a "vacuum magnetosphere" with only a weak source population of low energy plasma (McNutt et al. 1987), slow acceleration through radial diffusion (Cheng et al. 1987), and the strongest whistler mode hiss and chorus waves observed by the *Voyager* spacecraft (Kurth and Gurnett 1991). The presence of these waves are noteworthy because they can efficiently remove electrons through scattering into the atmosphere (Coroniti et al. 1987) without accelerating them (Tripathi and Singhal 2008). Intensities of Jupiter and Uranus start to differ in the high MeV range, which means that no Jupiter-grade radiation shielding is required for Uranus. While the electron radiation belts are relatively intense, its ion radiation belts are within our expectations (Mauk 2014) even though ions share several relevant physical processes with the electrons.

With only the limited observations from the *Voyager 2* flyby, it remains unclear how representative these measurements are. More observations might reveal that there is no mystery. But until such observations are available we have to seriously consider that despite everything we have learned about radiation belts at Earth, Jupiter, and Saturn, we still have not achieved a universal understanding, as highlighted by our inability to explain those of Uranus. If we want to build a solid basis to apply radiation belt physics to more extreme objects like Brown Dwarfs or data-starved targets like exoplanets, then we need to study the Ice Giant radiation belts. Given that Neptune is the planet most similar to Uranus, studying Neptune might also be helpful to solve the Uranus radiation mystery described here.

The mystery of Uranus' radiation belts also results in a potential "energy crisis" in the planet's magnetosphere since the energy content of the radiation belts is larger than can be explained using our current knowledge from the limited measurements. Because radiation belts exist as a permanent interplay between physical processes that produce and remove radiation (e.g., Kollmann et al. 2013; Nénon et al. 2017), there is a variety of possible explanations for the intensity of the Uranian radiation belts. One explanation might be that the Ice Giant radiation belts have more significant contributions from processes that have been observed to play lesser or negligible roles at other planets. For example, the observed high intensities might be possible to due particularly efficient acceleration of ionospheric material.

It is also possible that we will find new processes to be important that are unique to Uranus or both Ice Giants, such as galactic cosmic ray impacts producing secondary charged particles in the atmosphere. Planets with near-dipolar magnetic fields force the charged secondary particles created in the atmosphere to magnetically mirror within that atmosphere where they are quickly lost. However, under the influence of the higher-order magnetic fields of the Ice Giants, the particles might be able to scatter fast enough to become trapped in the equatorial plane and accumulate over time in the radiation belts. All theories require comprehensive measurements of the magnetospheric conditions to be supported or ruled out.

Observables and Required Measurements

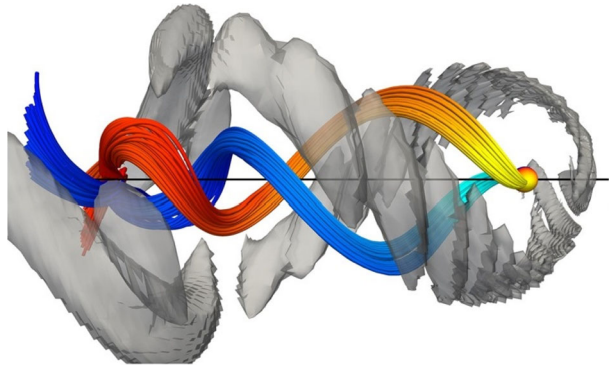
- Radiation belt populations – 1) energetic (tens of keV to tens MeV) ions and electrons and 2) vector magnetic field
- Potential seed populations – 1) thermal plasma (few to tens of eV to few keV) ions and electrons and 2) vector magnetic field
- Potential source, loss, and acceleration mechanisms 1) vector magnetic field; 2) DC electric field; 3) high-frequency electric and magnetic field (up to several MHz and tens of kHz respectively); and 4) cosmic rays (GeV protons)

2.2 Contradicting Signatures for Uranian Plasma Flow Drivers

Uranus magnetosphere has solar wind drivers (Selesnick et al. 1987; discussion below), yet it shows no evidence for solar wind particles (Mauk et al. 1987). What drives plasma flows in Uranus' unique magnetic configuration?

Planetary magnetospheres are as diverse as the planets they encompass. There are magnetospheres that can be considered archetypes where a single mechanism is dominating its dynamics. For example, Jupiter is the archetype of a corotation-dominated magnetosphere, where magnetospheric plasma is roughly following the planetary rotation (Vasyliunas 1983) and the theoretically expected plasmopause is beyond the actual dayside magnetopause (Mauk et al. 2009). Earth is usually considered as an archetype for solar wind-driven

Fig. 2 The nonalignment of Uranus' rotation and magnetic axes forces its open magnetic field lines (red to blue) to follow a helical path. (The simulation from Griton et al. (2018) shown here assumes an idealized Uranus where the relevant axes are exactly perpendicular and the planet rotates ten times faster than reality. Grey areas show likely areas of magnetic reconnection)



convection where most plasma near the magnetotail is convected sunward (Dungey 1961; Wolf 1995). However, Earth still possess a plasmasphere with corotating plasma and therefore in that respect resembling Jupiter. Because Uranus did not have a plasmasphere at the time of the *Voyager 2* flyby (Selesnick and Richardson 1986), it may actually be considered as a better archetype for having solar wind-driven plasma flows than Earth. The assertion that Uranus has strong solar wind drivers is supported by the observation of magnetotail reconnection signatures (Mauk et al. 1987). In addition, an abrupt drop of keV plasma densities when approaching the planet ($\lesssim 5$ Uranus radii) has been interpreted as plasma convected by the solar wind being deflected around the depleted region (Selesnick et al. 1987) while still flowing mostly sunward (Selesnick 1988).

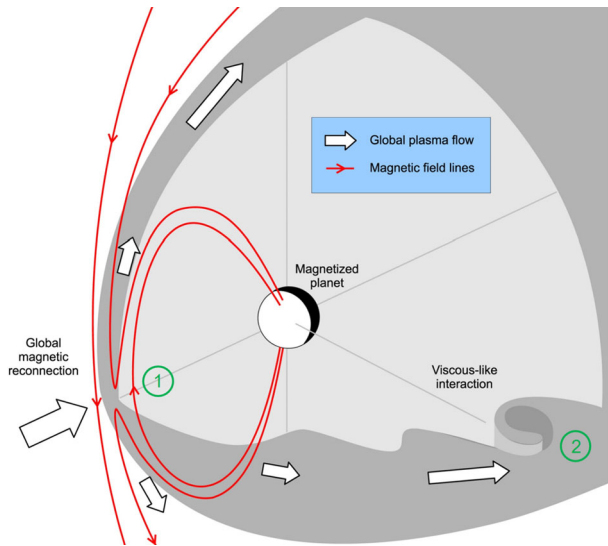
Despite this support for the importance of the solar wind at Uranus, no alpha particles accelerated from the solar wind were found (Cheng et al. 1987; Mauk et al. 1987), which is curiously different from all of the other planets visited by the *Voyager* spacecraft. Because Uranus is a fast rotator and the magnetosphere changes between being open and closed to the solar wind throughout a Uranian day (Cao and Paty 2017), planetary rotation must also play some role, though its importance is not understood.

Independent of the answer of this question, Uranus' unique magnetospheric configuration and dynamics can serve as a prime laboratory in which to understand plasma flows in a magnetosphere. This is because Uranus' corotational electric field (perpendicular to rotation and magnetic axes) can seasonally become perpendicular to the convection electric field (perpendicular to the solar wind speed and magnetic axis). This configuration forces the open magnetic field lines in the Uranian magnetotail to follow a helical motion near solstices (Fig. 2) and prevents the formation of a plasmopause (Selesnick and Richardson 1986; Griton et al. 2018). Depending on season, the field configuration can also lead to a complex multi-lobe structure during equinoxes (Cowley 2013). For all of the other planets that have been studied in detail, the solar wind-driven and rotational electric fields are roughly in the same plane, which makes it difficult to disentangle for example whether flows result from tail reconnection or centrifugally-driven interchange instabilities (Mitchell et al. 2015). At Uranus' magnetosphere, this issue does not exist, making it ideal to study plasma flow drivers and how they feed back on each other.

Required Observables and Measurements

- Magnetospheric plasma – thermal plasma energy spectra and ion composition (eV to keV)
- Magnetospheric configuration – vector magnetic field
- Other signatures of magnetospheric dynamics (energetic particles, aurora, waves)

Fig. 3 Sketch (Masters 2018) of the two main processes through which a magnetosphere can shed plasma: 1) Magnetic reconnection reconfigures the magnetic field lines (red) first on the dayside of planet, as shown, which eventually creates plasmoids on the nightside that carry plasma away down the tail. This process is observed at the inner magnetized planets. 2) Kelvin-Helmholtz vortices mix plasma from the magnetosphere (light gray) with the surrounding environment (dark gray). This process was suggested to be dominant at the outer magnetized planets (Masters 2018), as well as exoplanets far from their host star, but observational confirmation is still pending



2.3 No Obvious Mass Balance at Neptune

As we will discuss in this section, Neptune's magnetosphere has not been observed to shed the plasma (Mauk et al. 1991) that its moon Triton is continuously producing (Richardson et al. 1991). This mystery leads to the question: How do magnetospheres far from their host stars balance their mass budgets?

Plasma inside of the magnetosphere of Neptune is largely composed of H^+ and what is assumed to be N^+ (e.g., Richardson and McNutt 1990). The N^+ is thought to be from the interaction of magnetospheric plasma with the atmosphere of the moon Triton (Yung and Lyons 1990), which provides 10^{25} ions/s (Richardson et al. 1991), similar to O^+ escaping from Earth's magnetosphere (Seki et al. 2001). This plasma becomes trapped by the magnetic field of Neptune and therefore should accumulate over time, as in other planetary magnetospheres (e.g., Io supplying Jupiter's magnetosphere). However, the magnetosphere of Neptune was found to have surprisingly low ion densities during the *Voyager 2* encounter (Belcher et al. 1989).

Other known magnetospheres shed their plasma over time to maintain a quasi-steady state of the total mass content instead of it rising to infinity. One mechanism to shed plasma is through a cycle initiated by magnetic reconnection between the interplanetary magnetic field (IMF) and the planet's magnetic field at the dayside magnetopause (Fig. 3, left). This eventually leads to magnetic reconnection in the nightside magnetosphere, allowing for some of the magnetospheric plasma to be carried away, as the reconnected magnetic field lines in the planet's magnetotail are now only connected to the IMF (Dungey 1961). Nightside reconnection and plasmoid release can also be caused by a combination of internal plasma sources and fast magnetospheric rotation. In such systems magnetic field lines stretch over time until they become unstable and form plasmoids (Vasyliunas 1983). However, during the brief *Voyager 2* flyby, it was noted that, unlike Uranus, there were no signatures observed at Neptune that resembled effects due to magnetotail reconnection (Mauk et al. 1991).

While it is possible that the lack of such observations means that *Voyager 2* missed them during the brief encounter, it is also possible that the main mass loss mechanism at Neptune,

and any other planet far from its host star, happens via a different pathway. The Kelvin-Helmholtz instability is able to mix solar wind and magnetospheric plasma or even lead to a net outward transport (Ma et al. 2017). The instability arises when plasma velocity shear leads to surface waves along the magnetopause that can mature into rolled up vortices. Recent work by Masters (2018) highlighted that we should expect solar wind parameters in the outer solar system (decreased plasma density and IMF magnitude) to be more conducive of a viscous-like interaction (e.g., the Kelvin-Helmholtz instability) than for reconnection. This would be in stark contrast with magnetospheres closer to the Sun, like that of the Earth, where an interaction through large-scale reconnection is dominant. If a viscous-like interaction is dominant instead at the ice giants, this could promote plasma escape through complex, rolled-up Kelvin-Helmholtz vortices (Fig. 3, right). Further understanding of how plasma is lost, and what that means for the mass and energy budget of the Neptunian system, is intrinsically important for understanding the fundamental ways planetary magnetospheres can accumulate and lose plasma.

Observables and Required Measurements

- Magnetospheric plasma – energy, angular, and compositional distributions of thermal (few to tens of eV to few keV) ions and electrons
- Signatures of plasma loss from the magnetosphere – vector magnetic field, aurora
- Signatures of plasma production (EMIC waves)

2.4 Extreme Magnetospheric Dynamics at Neptune

The orientation of the rotation and magnetic axes of Neptune are a game changer for magnetospheric dynamics. Does this reveal gaps in our basic understanding of magnetospheric physics?

All planets that have been studied in detail have roughly axially-symmetric magnetospheres with plasma and current sheets approximately along the magnetic equatorial plane. Neptune's magnetosphere shows a similar configuration during its planetary rotation but drastically changes every ~ 8 h to a unique configuration, where the plasma sheet becomes cylindrical (Fig. 4). Plasma sheets are associated with electric currents. A planar current sheet closes through the magnetopause. A cylindrical current sheet could, in theory, close on itself (Voigt 1981; Schulz et al. 1995), but it is unclear how it would transition from closure through the magnetopause into a potentially self-closing current loop. Furthermore, the outward diffusion of plasma on the dayside predicted by convection models (Selesnick 1990; Hill and Dessler 1990) are inconsistent with the observed strong inward diffusion (Richardson et al. 1991). While recent MHD simulations of the Neptunian magnetosphere (Mejnertsen et al. 2016) have gotten closer to the *Voyager 2* observations, they still miss key properties of the observed ion populations. Before we can move on to reliably predict magnetospheres of exoplanets and their interaction with their parent stars, we first need to further improve our models and understanding of the magnetospheres within our own solar system.

Required Observables and Measurements

- Magnetospheric plasma flows – thermal plasma energy spectra (eV to keV ions)
- Magnetospheric current carriers: plasma and energetic ions and electrons (few eV to 100's of keV)
- Electromagnetic fields – 1) vector magnetic field and 2) DC electric field
- Other signatures of magnetospheric dynamics (energetic particles, aurora, waves)

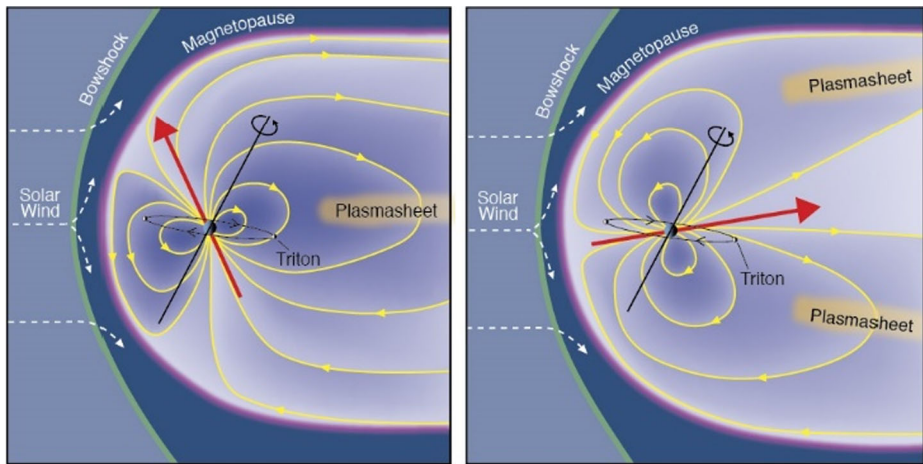


Fig. 4 Neptune's magnetosphere changes each planetary rotation between a configuration similar to other magnetized planets with a planar plasma disk in the equatorial plane (left) to a unique configuration with a cylindrical plasma sheet (right). The black line and red arrow indicate the rotation and magnetic axes, respectively. Different shades of blue distinguish the solar wind, magnetosheath, and magnetosphere regions. Magnetic field lines are shown in yellow. Image Credit: Fran Bagenal and Steve Bartlett

3 Magnetospheric Contributions to Interdisciplinary Studies

3.1 Atmospheric Evolution

The magnetic fields of Ice Giants resemble Earth's during reorientation of its magnetic field (Glassmeier and Vogt 2010). Do such magnetic fields, or planetary fields in general, affect atmospheric escape?

It is a long-standing hypothesis that a planetary magnetic field protects the planet's atmosphere from erosion through the solar wind that picks up ionospheric material and sputters the atmosphere (McElroy 1968; Lundin et al. 2007). This is the canonical explanation why the weakly magnetized planets Mars and Venus, which are without a currently operating dynamo and are believed to have been similar to Earth in the past, have lost their atmosphere (Jakosky et al. 2017) or at least its water (Barabash et al. 2007) or hydrogen content into space (Lammer et al. 2003). If this is the case, Earth's atmosphere may be more vulnerable during magnetic field reversals (Wei et al. 2014) when the field weakens and reorients in a fashion that allows easier entry of solar particles into the atmosphere, i.e. through polar cap expansion when the magnetic field decreases as it reconfigures into a new dominant polarity (Glassmeier and Vogt 2010).

However, modeling and observations of the total present-day atmospheric escape rates of Earth and planets with no active dynamo (Mars and Venus) are of the same order of magnitude, challenging this long-standing theory of the role of a magnetosphere (e.g., Gunell et al. 2018; our Fig. 5). Atmospheric escape, for example through polar wind, occurs also for magnetized planets (Axford 1968; Glocer et al. 2007). Recent modeling work suggests that planetary magnetospheres may actually enhance polar ion outflow by efficiently collecting and funneling energy from the solar wind into the atmosphere (Blackman and Tarduno 2018; Glocer et al. 2018).

It remains to be investigated how to compare the escape rates of different planets in a meaningful way. The escape yield from magnetized and unmagnetized bodies may still

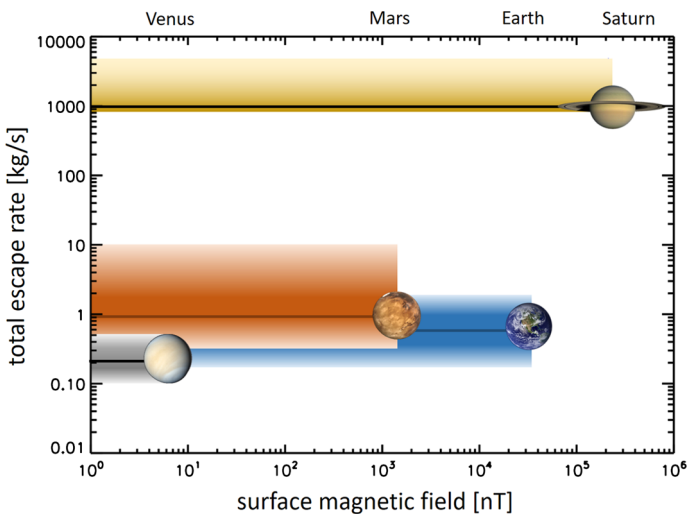


Fig. 5 Total present-day atmospheric escape rates (Lammer et al. 2008; Borovsky and Denton 2008; Jakosky et al. 2018; Tseng et al. 2013) and their relative variability (Lundin et al. 2013; Masunaga et al. 2019) or uncertainty (Engwall et al. 2008; Tseng et al. 2013), shown as a function of surface magnetic fields (estimated for weakly magnetized planets: Zhang et al. 2016; Acuna et al. 1999; equatorial for magnetized planets). The zeroth-order expectation is that planetary atmospheres are eroded more easily in the presence of weak magnetic fields. As it can be seen here, this expectation is not met. Additional observations from the Ice Giants will help determine how escape efficiencies should be normalized to planetary parameters and reveal what role the magnetic field in fact plays in atmospheric evolution

differ, which could show when normalizing the total escape rates (e.g., to account for the different atmospheric masses or interacting cross sections). However, it currently remains unclear what normalization (e.g., which cross section to use – that of the planet itself, its magnetosphere, its cusp, etc.) would offer a fair comparison. Because the terrestrial planets are all relatively similar both in their properties and escape rates, it can be informative to compare them to planets with very different parameters, like the Giant Planets. For example, an escape rate three orders of magnitude larger than the terrestrial planets has been inferred for Saturn (Tseng et al. 2013) even though it has a strong magnetic field.

The Gas Giants may not be the best test case for atmospheric escape because it is difficult to disentangle the escape of atmospheric mass from the material escaping their moons. The high escape rate at Saturn may be enhanced by ring dust spiraling into the atmosphere (Mitchell et al. 2018). The Ice Giants on the other hand have only weakly active moons and tenuous rings compared to Saturn. In fact, Uranus' magnetosphere is thought to almost exclusively contain atmospheric material with little solar wind plasma (Cheng et al. 1987; Mauk et al. 1987), which is ideal to study atmospheric escape.

The Ice Giants in general can be considered intermediate cases between Earth and a weakly magnetized planet because their unique magnetospheric configurations result in relatively easy access for the solar wind to their magnetospheres at times despite the presence of their magnetic fields (Cao and Paty 2017). Furthermore, when the magnetic polarity of a planetary dipole changes (i.e. the magnetic north and south poles flip), the magnetic field orientation tilts and the contribution of higher-order magnetic moments becomes more important (Leonhardt and Fabian 2007). Geological evidence shows that the terrestrial geomagnetic field undergoes such changes roughly every several hundred thousand years, but this reorientation has never been observed directly. The present-day magnetic field config-

urations of Uranus and Neptune are likely similar to what Earth's may be like during parts of its field reversal: highly tilted and of higher order (e.g., Stanley and Bloxham 2004); this may reveal the nature of terrestrial atmospheric dynamics during these reversal periods.

So far, no dedicated instrumentation to measure atmospheric escape has been sent to any of the Giant Planets. While atmospheric escape generally occurs in the form of both neutral and ionized particles, neutral particles are gravitationally well confined at massive planets so that at the Ice Giants it is likely sufficient to only observe ion escape. The energy of the outflowing ions can be used to distinguish planetary ions from solar wind plasma; for example, solar wind protons have a nominal energy of 1 keV while atmospheric ion outflow is found at lower energies (Nordström et al. 2013; Ramstad et al. 2017). The Earth was found to predominantly lose hydrogen with energies orders of magnitude lower (a few eV) (Engwall et al. 2006, 2008). Likewise, the plasma flow direction relative to the magnetic field can be used to identify atmospheric escape since large parts of Earth's atmospheric escape occurs through the polar cap via polar wind or ion beams (e.g., Yau and Andre 1997) and similar could be expected for the Ice Giants under favorable configurations on seasonal or diurnal timescales.

Observables and Required Measurements

- Atmospheric escape – 1) density and bulk velocity vector of cold and thermal plasma (few to tens of eV, even during times of positive spacecraft potential, up to tens of keV) ions and electrons, 2) vector magnetic field
- Particle precipitation into atmosphere (keV to MeV ions and electrons, magnetic field, aurora)

3.2 Mechanics of Ice-Based Dynamos

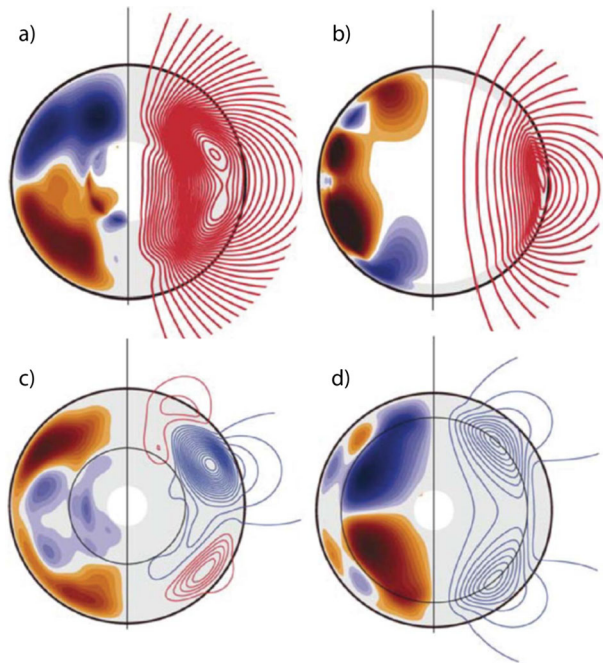
The magnetic fields of the Ice Giants are unlike those of the other planets in the solar system (Ness et al. 1986, 1989). Can this be explained with a planetary dynamo driven by ionically conducting ices (Stanley and Bloxham 2004) and, if so, how do they work?

Planetary dynamos that generate the intrinsic magnetic field of planets are believed to be driven by electrically conductive fluids that convect within planetary interiors. In the case of the terrestrial planets, this fluid is liquid iron; for the Gas Giants it is liquid metallic hydrogen; for the Ice Giants it is thought to be C, N, and/or O “ice” compounds that become electrically conductive under high pressure (Mitchell and Nellis 1982).

While the other planetary magnetic fields in the solar system are dominated by the dipole component and show a clear preference for axisymmetry and equatorial antisymmetry, this is not true for Uranus or Neptune (Fig. 6). The *Voyager 2* encounters of Neptune and Uranus revealed that the Ice Giants' magnetic fields are rather unique, lacking any predominant symmetry. Most recently, *Cassini* and *Juno* magnetometer data proved indispensable in constraining the inner structure and dynamics of Saturn and Jupiter (Connerney et al. 2018; Dougherty et al. 2018; Moore et al. 2018). Key interior features like the existence of a superionic water and/or stratified layers, the location and vertical extent of the active dynamo region, and/or the depth of the zonal wind system all influence the magnetic field and are hence constrainable by in-situ magnetometer measurements (e.g., Nettelmann et al. 2013).

Though many attempts have been made to model the interior structure and magnetic field of the Ice Giants (e.g., Stanley and Bloxham 2004, 2006; Helled et al. 2010), these remain poorly constrained because all the in-situ data were gathered during fly-bys. Additional measurements, preferentially from orbiting spacecraft, are desperately needed to unveil the

Fig. 6 In-situ magnetic field measurements are essential to constrain the interior structure. The results from Stanley and Bloxham (2006) demonstrate that dynamo simulations without a stable stratified layer (panel **a** and **b**) tend to show a dipole-dominated field independent of the convective shell geometry (outer grey region). When adding a stable stratified layer to the deeper super-ionic region underneath the convective shell (inner grey region, panel **c** and **d**), non-dipole dominated solutions are preferred when the convective shell is not too thin. The plots show the axisymmetric toroidal field in the left halves and the poloidal field lines on the right



complex structure and dynamics of the Ice Giants' internal magnetic fields. Geomagnetic observations show that, while the axial dipole component changes on millennial time scales, the higher order moments vary on advective time-scales of centuries to decades (Hulot et al. 2010). We expect the magnetic fields of Uranus and Neptune to have significantly evolved since the *Voyager 2* era, as such evidence of secular variation on decadal timescales has been seen at Jupiter from comparison of observations taken over 45 years from *Voyager*, *Pioneer*, *Ulysses*, and *Juno* (Moore et al. 2019).

Observables and Required Measurements

- Total (internal/external) local magnetic field configuration – 1) vector magnetic field and 2) thermal and energetic particles (few tens of eV to hundreds of keV) ions and electrons (which may locally disturb the internal magnetic field)
- Global field configuration (UV to IR aurora)

3.3 Space Weathering of Icy Moons

Most of the Ice Giants' moons have dark, spectrally neutral or reddish surfaces (Brown and Cruikshank 1983). How is the weathered uppermost surface layer of these satellites related to their pristine composition?

What makes many of the Ice Giant moons unusual when compared to other similar-sized icy satellites in the solar system are their low albedos and relatively weak H₂O ice bands (e.g., Brown and Cruikshank 1983; Veverka et al. 1991; Karkoschka 1997; Arridge et al. 2014; Cartwright et al. 2018; our Fig. 7). Optical observations are only sensitive to the uppermost (top ~ 1 mm) layer of their ice-rich surfaces, which can be heavily altered due to space weathering and therefore is not necessarily representative of their pristine surface

compositions. This leads to questions of how the observed dark surfaces of these satellites are related to the primordial material that crystallized at their surfaces.

It has been suggested that irradiation of substrates made of CH₄-H₂O mixtures by keV protons may be responsible for the darkening of the Ice Giant satellites (Lanzerotti et al. 1987). Grundy et al. (2006) and Cartwright et al. (2015) both concluded that the leading/trailing compositional asymmetries on the Uranian satellites Ariel, Umbriel, Titania, and Oberon are likely due to surface alterations by magnetospheric plasma populations, possibly forming CO₂.

Studies of the satellites of the Gas Giants have provided significant evidence of similar surface modifications by the surrounding space environment. For example, Schenk et al. (2011) and Howett et al. (2011) found detectable patterns on both the leading and trailing hemispheres of the Saturnian satellites from magnetospheric plasma/particles, the latter determining that the thermal properties of the satellites were influenced by the impinging plasma/particles. Hansen and McCord (2004) determined the water ice on Europa, while crystalline at depth, pervasively contain a veneer of amorphous H₂O ice, most likely formed via radiolytic damage of the otherwise crystalline H₂O ice.

Inversion of these reflectance spectra to determine surface properties and trace the origin of surface darkening using radiative transfer models is still challenging. Because the spectra depend not only on the surface composition but also on the grain size and mixing regime of surface constituents (e.g., Brown 1983; Hapke 2012), spectral models provide useful but non-unique fits. To determine the importance of various candidate processes for observed surface features, a comprehensive and quantitative understanding of the moons' space environment is needed, including measurements of the average and extreme radiation populations, as has been done for the satellites of the Gas Giants.

Also, Triton's substantial N₂-rich atmosphere and ionosphere (e.g., Broadfoot et al. 1989) are affected by the surrounding magnetospheric environment. Large parts of the chemistry in the N₂-rich atmospheres of Titan and Pluto are driven by the ionization and dissociation of N₂ and the reactions that follow (Cravens et al. 2009). Ionization, especially in the deeper layers of the atmosphere, is not due to EUV light but due to precipitating magnetospheric ions and electrons (Ip 1990) as well as cosmic rays (Gronoff et al. 2009). If we want to understand the structure and dynamics of Triton's atmosphere and ionosphere, we need to know its average space environment, as well as the probability of extreme irradiation events.

Observables and Required Measurements

- Geologic activity and surface composition – 1) visible and infrared spectra and maps
- Potential weathering agents – 1) energetic (keV, MeV respectively) ions and electrons; 2) dust particles; and 3) thermal plasma (few to tens of eV to tens of keV) ions and electrons

3.4 Timeline for Habitability of Ocean Worlds

In this section, we suggest that the Icy Moons of the Ice Giants may be at a different “stage in life” than many Jovian or Saturnian moons. What is the lifetime of subsurface oceans and therefore timeline for habitability?

Icy moons and dwarf planets with diameters on the order of 400 km or larger can plausibly have subsurface oceans (Beyer et al. 2019) and are therefore commonly referred to as Ocean Worlds. Evidence for past or present liquid water interiors exist on a variety of such worlds, including Neptune's moon Triton and the large moons of Uranus (Beyer et al. 2017;

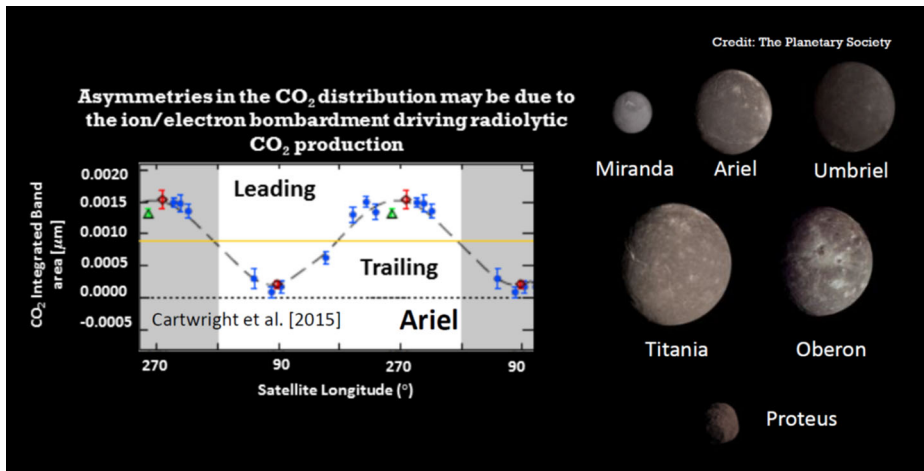


Fig. 7 Uranus' moons are unusually dark in visible light (right) and their surfaces are asymmetric in the infrared (left), likely because magnetospheric charged particles produce CO₂ ice at the locations where they interact with their surfaces. (Left: Cartwright et al. 2015; right: NASA/JPL, Planetary Society)

Beyer et al. 2019). The extent of internal differentiation of the Ice Giant moons is unknown, though liquid water oceans in contact with a hot, rocky core cannot be ruled out (Hussmann et al. 2006; Sohl et al. 2010; Castillo-Rogez and Lunine 2012).

Current research and future NASA missions (Europa Clipper, Dragonfly) focus on worlds with existing subsurface oceans. In order to understand Ocean Worlds throughout the universe, we need to study the life cycle of their oceans. The higher surface-area-to-volume ratios of smaller ocean worlds compared to larger bodies, the faster that ocean freezes out. Both modeling (Bierson et al. 2018) and observations (Beyer et al. 2019) suggest that Charon, a moon of Pluto, plausibly once hosted a subsurface ocean, but that it has since frozen. Charon is of similar size (1,212 km diameter) to several of the Ice Giants' moons, thus serving as a potentially useful analog. While the Gas Giants have several moons that are confirmed or candidate Ocean Worlds, the Ice Giants offer the opportunity to study frozen oceans and therefore ocean lifetime, which determines the window of opportunity for life to evolve, or the "habitability lifetime."

The presence or absence of oceans will be far easier to determine with a magnetometer in the Ice Giant system than at other moons (e.g., Jupiter's moon Europa). This is because the off-center and inclined dipole moments relative to the rotation axis of the Ice Giants, especially Uranus, exposes the moon to strongly-varying fields that produce a strong induction response (e.g., Saur et al. 2010). Analyzing a magnetic induction signature requires additional measurement of the plasma and energetic particle populations. This is because not only the induced field from the moon but also plasma and energetic particles are affecting the observed total magnetic field. Periods of high energetic particle intensities will need to be excluded from analysis because they can dominate the pressure (Bagenal and Delamere 2011; Sergis et al. 2011) but cannot be properly represented by numerical models.

Observables and Required Measurements

- Satellite internal structure – 1) vector magnetic field, plasma, radiation (\leq MeV ions); 2) gravitational harmonics

- Satellite surface geomorphology, tectonics, and composition – 1) multispectral surface imaging

3.5 Auroral Effects on Exospheric Temperatures

Neither the temperature of Uranus' ionosphere nor its trend can be understood based solely on solar illumination. What role does auroral heating, an important process at other planets but one poorly understood at the Ice Giants, play?

Uranus' ionosphere is hotter than expected from solar irradiation (Melin et al. 2011). It cools in a way that cannot be easily explained through geometric season because the cooling was observed to continue years after equinox (Melin et al. 2013, 2019). Other Giant Planets also have hotter exospheres than predicted and/or poorly understood latitudinal temperature profiles (Waite et al. 1997; Clarke 1988; Smith et al. 2007).

Aurora at other planetary magnetospheres are known to abruptly heat the upper atmosphere and ionosphere through energy input in the form of Joule heating. For example, energetic particle precipitation within auroras leads to alterations in Earth's atmospheric heating and cooling rates as well as in the chemical composition – e.g., the NO_x budget (Sinnhuber et al. 2012). In the case of Uranus, it was pointed out that the vernal and autumnal equinoxes are different from the magnetic perspective (Melin et al. 2013), which may explain why cooling continued across the last equinox. The difference arises because the magnetic poles differ in strength (Ness et al. 1986) and the rotation direction is opposite to the solar wind magnetic field (Cowley 2013) for both equinoxes. Auroral properties may vary over magnetic season, e.g. by changing the characteristic energy of precipitating electrons (Melin et al. 2013).

Aurora and the magnetospheric processes leading to it are therefore a good candidate to explain the temperature observations and possibly other changes in the upper atmosphere. Aurora are a nearly universal planetary phenomenon (e.g., Mauk and Bagenal 2013) that have been observed on all planets in the solar system (with the exception of Mercury, due to its lack of an atmosphere) and even on brown dwarfs (Hallinan et al. 2015). However, we do not understand aurora at the Ice Giants. The combination of ion loss to the atmosphere, peculiar solar wind-magnetic dipole configurations, unique magnetotail current systems, and the prominence of higher-order magnetic field moments all lead to unique auroral signatures at both Uranus and Neptune. The most intense auroral emissions at Uranus (Fig. 8; Lamy et al. 2017) were found around the passage of an interplanetary shock. Different to other planets, where aurora tends to be steady and of similar duration as the driving shock, Uranus' aurora appears highly variable, indicating fundamentally different drivers (Lamy et al. 2012). Ice Giant aurora at kilometric wavelengths was found to have a unique time-stationary source, as well as complex radio signals (Zarka 1998). What generates such auroral signatures at Uranus remains unknown. The drivers are similarly unclear at Neptune where it is unclear if the aurora is driven by injection of plasma from Triton's orbit (Sandel et al. 1990) or by interaction with the solar wind (Cheng 1990).

Remote auroral observations alone will not be able to answer this question. In order to understand the impact of aurora, we will also need in-situ measurements of the particle spectra and to understand the underlying drivers that determine energy and duration of the aurora.

Observables and Required Measurements

- Auroral emissions: 1) EUV to FUV wide-angle imaging, 2) Near-IR spectra, 3) radio and other waves

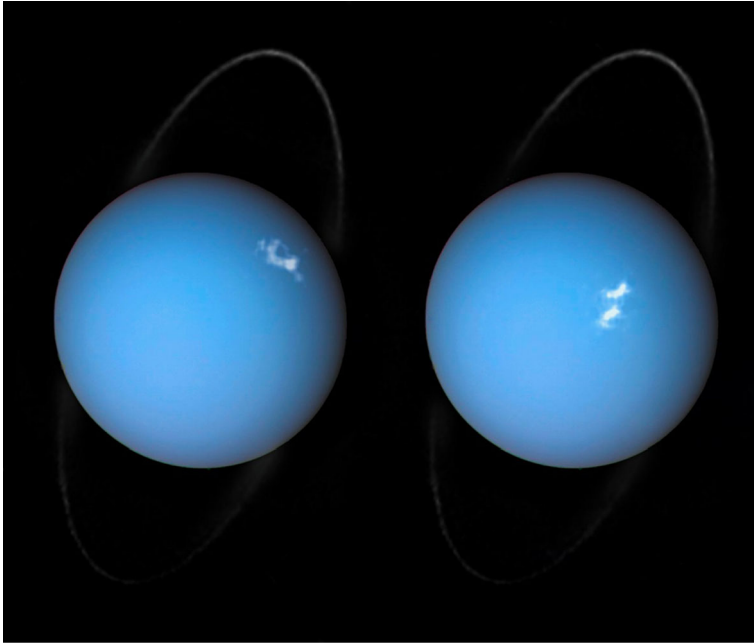


Fig. 8 *Hubble* and *Voyager 2* composite images of bright auroral spots seen on Uranus. Credit: ESA/Hubble & NASA, L. Lamy/Observatoire de Paris

- Auroral precipitation: 1) vector magnetic field; 2) DC electric field; and 3) thermal and energetic (few to tens of eV to a few MeV) ions and electrons

3.6 Magnetospheric Influencing of Ring Structure and Dynamics

Several Ice Giant rings show strong time dependence (Showalter et al. 2008) and unusual grain size distributions (de Pater et al. 2006). Is that related to ring charging and/or highly varying magnetic field?

The rings of Uranus and Neptune are very different from those around Jupiter and Saturn, and appear to vary on short timescales (years to decades), which makes them critical to study if we really want to understand planetary rings in general.

Ring material can charge up due to interaction with the space environment. Dense, low energy plasma can build up charge on the grain surface, while high-energy particles can deposit charge deep within the grain. Charged particles, including ring particles, in a magnetic field are subject to the Lorentz force. A prime example of this are Jupiter's rings, which clearly show the effect of Lorentz resonances in the ring structure, including the formation of the halo (e.g., Burns et al. 1999; de Pater et al. 2008). For small ring grains (on the order and below a micrometer in size), this force can be significant, meaning that the ring dynamics cannot be understood when ignoring the fields, plasma, and energetic particles that surround it. This is especially important for Uranus's mysterious μ -ring, because this ring is dominated by (sub)micron-sized grains (de Pater et al. 2006). Previous studies of the charged dust populations within Saturn's magnetosphere and around comets point to the importance of the surrounding plasma environment, rather than just particle mass and gravity, in the dynamics of sub-micron to micron scale charged dust (e.g., Jones et al. 2009; Horányi and Mendis 1991).



Fig. 9 Schematic illustration of Uranus' μ -ring (lower panel, blue) has a similar color as Saturn's E-ring (upper panel, blue), indicating micron-sized ring grains. It is not clear how Uranus can have such a ring without a geologically-active moon. Understanding formation and stability of this ring requires knowledge of grain charging due to plasma and radiation that make the grain susceptible to electromagnetic forces. Figure from de Pater et al. (2006)

The μ -ring is mysterious because it is blue (Fig. 9 bottom), a quite odd color for a dusty ring (de Pater et al. 2006). Dusty rings typically have a reddish color, due to sunlight reflected off a population of dust particles. A ring could only be blue if Rayleigh scattering occurred off of grains with an extremely steep size distribution (i.e. the ring is dominated by (sub)micron-sized grains). Saturn's E-ring also has such blue color (Fig. 9 top), but is a special case in that it is sourced by geysers on the moon Enceladus. In the case of Uranus, there is a moonlet, Mab, at the location of the μ -ring (Showalter and Lissauer 2006). However, Mab's radius is no more than 6 km (Paradis et al. 2019), making geologic activity implausible. de Pater et al. (2006) therefore suggested that the Uranian μ -ring may originate from micrometeorite impacts on Mab. In analogy to older models for Saturn's E-ring (Horanyi et al. 1992; Juhász and Horányi 2002), the orbits of the dust grains in Uranus's μ -ring may evolve due to the planet's oblateness, electromagnetic forces, and solar radiation pressure. Knowledge of Uranus magnetic and electric fields, plasma, radiation, and neutral particles may thus help constrain the origin of the μ -ring, as well as provide further insight into charged dust and dusty plasma dynamics.

Generally, several rings of the Ice Giant systems show unusual dynamics. At Uranus, another baffling observation was that the μ -ring shows large, persistent variations in brightness with longitude. This cannot be understood through Uranus' gravity alone because Kepler shear should erase these variations within 1 month (Showalter et al. 2008). On much longer timescales, it was surprisingly observed that the radial distribution of Uranus's innermost, ζ -ring, had changed drastically between 1986 and 2007 (de Pater et al. 2007). The most surprising discovery about Neptune's ring system was the detection of 4–5 ring arcs in the Adams ring by *Voyager 2*. Although at the time it was assumed these arcs were stable features, later observations showed that the two leading arcs slowly faded away, and one of them (the leading arc) had jumped forward relative to the trailing arcs (de Pater et al. 2005, 2018). The stability of the two trailing arcs may be caused by a three-body mean motion resonance, involving the two nearest moons, Galatea and Larissa (Showalter et al. 2017). All these observations, together with changes in other dusty rings (e.g., Saturn's D-ring; Hedman et al. 2007), show that changes in dusty rings may be common on timescales of 20 years or less. The role of electrodynamic forces need to be considered to understand these observations and the ultimate time dependence of ring dynamics.

Observables and Required Measurements

- Non-gravitational forces: DC electric and magnetic fields
- Charging processes: plasma and energetic particles (eV to hundreds of keV)
- In-situ dust measurement
- Remote measurement of ring structure (visible to IR)

4 Summary

This paper outlines the various means in which incorporating magnetospheric measurements on dedicated orbital missions to Uranus and/or Neptune will provide unprecedented advancement on a multidisciplinary front. Both Uranus and Neptune are unlike any of the other planets in our solar system and provide a vantage point to better understand exoplanets (see also Rymer et al. 2018). While exploring either planet with a dedicated orbiter would aid in our understanding of the Ice Giant class of planets as a whole, both Uranus and Neptune serve as unique laboratories in their own right. Their uniqueness motivates our community to strive to explore both of these worlds, for as we have demonstrated, an exploration of one will not be able to fully answer all of the mysteries of the other.

In addition to the fundamental need to explore these planets and their systems, we have provided evidence for the value of equipping future missions with a suite of instruments traditionally attributed to magnetospheric investigations to better understand outstanding multidisciplinary scientific mysteries such as: magnetospheric convection for planetary magnetospheres with non-aligned magnetic and rotation axes; the formation of planetary radiation belts; the mass loss of planetary magnetospheres; the space weathering and evolution of potential subsurface oceans of icy satellites; the dynamics of planetary dynamos of Ice Giant-class planets and exoplanets; the role magnetic fields and aurora may play in atmospheric structure, loss, and habitability, and ring-magnetosphere interactions.

Acknowledgements A White Paper with broader scope but less detail than this paper will be submitted to the Planetary Science and Astrobiology Decadal Survey 2023–2032.

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