# Magnetospheric Studies: A requirement for addressing interdisciplinary mysteries in the Ice Giant systems

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## 1. Introduction

We discuss **scientific mysteries in the planetary systems of Uranus and Neptune** and argue that **magnetosphere-related measurements are key to resolve** them.

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. Several reviews have provided comprehensive lists of general science questions related to Uranus and Neptune, the Ice Giant planets[1-2]. Here we highlight a compact set of mysteries (Fig. 1) based on specific observations that illustrate major gaps in our current understanding; more details can be found in our recent review[134].

This paper demonstrates that instrumentation measuring the space environment of these planets will **not only advance mysteries related to space physics** (§2) but **also inform a broad range of other science fields** with similarly pressing mysteries (§3). Landmark examples for the usefulness of space physics measurements to other science disciplines are the discoveries of the plumes of Enceladus[128] and Saturn's G-ring arc. While optical discovery would have been possible, that would have required prior knowledge for targeting that is unnecessary for particle and fields measurements. Similarly, the subsurface ocean on Europa[8] was detected through magnetic induction, which also provides unique constraints for its habitability.

Energetic particles are a sensitive tool for detecting neutral material with densities so low that they are challenging to detect otherwise like Europa's neutral torus[134] or Saturn's corona[138]. The surfaces of giant planet moons show clearly-visible albedo patterns, some of which result from a bombardment of plasma and energetic particles[113].

Radio wave measurements provide a remote-sensing tool for the aurora and deep interior; the latter through constraining the planetary rotation period. Plasma wave instruments are sensitive to the detection of lightning, dust, and thermal plasmas, which support atmospheric, ring, and satellite science.

Such non-magnetospheric mysteries that may be resolved through magnetospheric measurements are discussed in §3.

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|---|---|---|---|---|---|
| **Intense Radiation Belts** | P*^ | R*^ | B°+ | E°+ | |
| **Missing Mass Balance** | P*^ | R* | B+° | E°+ | $L^{u}$ |
| **Plasma Flow Driver** | P*^ | R*^ | B+ | | $L^{ur}$ |
| **Extreme Magnetospheres** | P*^ | R* | B+° | E°+ | $L^{uor}$ |
| **Shock Acceleration** | P*^ | R*^ | B+° | E°+ | |
| **Atmospheric Erosion** | P*^ | | B+ | | $L^{u}$ |
| **Ice-based Dynamos** | P* | R* | B+ | E° | $L^{uoi}$ |
| **Moon Weathering** | P* | R*^ | B+ | | $L^{iv}$ |
| **Ocean World Lifetime** | P* | R*^ | B+ | | $L^{iv}$ |
| **Auroral Processes** | P*^ | R*^ | B+° | E°+ | $L^{uvir}$ |
| **Ring Dynamics** | P*^ | R* | B+ | E+ | $L^{v}$ |

**Fig. 1.** *Measurements traditionally used for magnetospheric studies can contribute to the investigation of several interdisciplinary mysteries at Uranus and Neptune. Every entry is a mystery that is elaborated on in §2-3 below. P=plasma R= radiation; (*ions & electrons; ^incl. ion composition); B=magnetic field, E=electric field (+DC, °AC); L=Light ($^{u}$UV, $^{o}$visible, $^{i}$IR, $^{r}$radio)*

There are also many open questions regarding the magnetospheres of the Ice Giants and on planetary magnetospheres in general. Uranus and Neptune are surrounded by unique magnetospheres generated by highly-complex magnetic fields[4,123] that trap plasma and high energy radiation, and generate a variety of radio and plasma waves. Their uniqueness makes the Ice Giants a critical piece in the puzzle that shows how planetary properties are related to their space environments and how feedback between parts of the planetary system work.

Understanding **how and why planetary magnetospheres differ is required to make valid extrapolations** in support of the rapidly growing and controversial fields of space physics of exoplanets[6], brown dwarfs, and very low-mass stars[108]. One of the few possible observables for the interior structure of an exoplanet is its magnetic field. The unusual magnetic fields of Uranus and Neptune may be a particularly good model for exoplanets because most known exoplanets have sizes just below Neptune[9] and because M dwarfs, the smallest extrasolar bodies with known magnetic fields, also have non-dipolar fields[126].

Before we can reliably predict magnetospheres of exoplanets and their interaction with their parent stars, we need to further improve our understanding of the magnetospheres within our own solar system. Stepping stones towards this are finding answers to the space physics related mysteries listed in §2.

## 2. Magnetospheric studies

### 2.1 *How can Uranus have such intense radiation belts when it lacks a strong source population?*

According to our current understanding, a planet with strong radiation belts needs to have a large reservoir of particles that can be accelerated, an efficient acceleration process, and/or weak loss processes for radiation. Uranus challenges this understanding because its electron radiation belts are similar in intensity to those of Earth and Jupiter[18] (Fig. 2) up to energies as high as 1 MeV. These intensities exist despite *Voyager 2* measurements that suggest a "vacuum magnetosphere" with only a weak source of low energy plasma[19], slow acceleration through radial diffusion[20], and very strong whistler-mode hiss and chorus waves that can efficiently remove electrons without accelerating them[105]. 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 surprisingly intense, its ion radiation belts are not[22] despite the particles sharing several relevant physical processes.

Until we can determine how representative the *Voyager 2* flyby was for the magnetospheric state, we have to seriously consider that we still have not achieved a universal understanding of radiation belts. One explanation for Uranus' high intensities might be significant contributions from processes that are negligible at other planets, for example efficient acceleration of ionospheric material. It is also possible that we will find new processes like charged cosmic ray secondaries produced in the atmosphere and surviving, different to other planets, because they scatter in the higher-order magnetic fields into the equatorial plane.

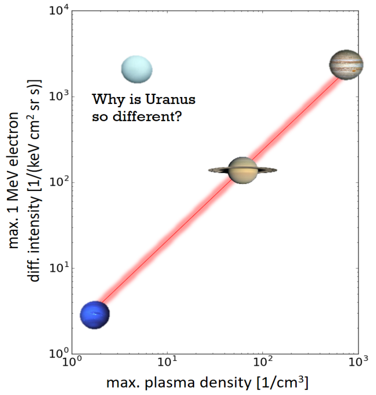

**Fig. 2.** *Maximum observed electron intensity over maximum observed plasma density[134]. It remains unclear how Uranus can sustain electron radiation belts comparable to Jupiter's, even though it has less material available to be energized.*

### 2.2 *Neptune's magnetosphere was not observed to shed Triton plasma. How do magnetospheres far from their host stars balance their mass budgets?*

Neptune's magnetosphere largely comprises $H^+$ and $N^+$ sourced from Triton[23]. These ions are trapped by Neptune's magnetic field and therefore should accumulate over time, similar to the situation with Io at Jupiter. However, *Voyager 2* measured surprisingly low ion densities at Neptune[25]. Magnetospheres shed new plasma over time, either through a cycle of reconnection with the solar wind[26] or the release of plasmoids[27], to maintain a quasi-steady state of the total mass content. Surprisingly, no signatures of plasma loss through the magnetotail were observed[28].

Recent work[5] highlights that the main mass loss mechanism at any planet far from its host star, like Neptune, may happen via a different mechanism than discussed above, namely the

Kelvin-Helmholtz instability (Fig. 3). Understanding how material leaves a magnetosphere is intrinsically important to gain the full picture of magnetospheric mass transport and balance.

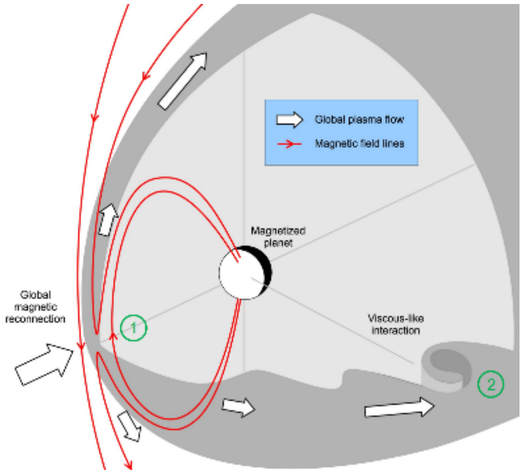

**Fig. 3.** *It is unknown how Neptune sheds potential mass from Triton, whether its*[5]*: 1) reconfiguration of magnetic field by reconnection (red), or . 2) mixing of plasma* from the magnetosphere (light gray) with the solar wind (dark gray) *via Kelvin-Helmholtz vortices.*

### 2.3 *Uranus may have solar wind-driven plasma flows, yet it shows no solar wind plasma. What drives its plasma flows?*

Planetary magnetospheres are as diverse as the planets they encompass. Jupiter is the archetype of a corotation-dominated magnetosphere, where magnetospheric plasma roughly follows the planetary rotation. Earth is considered the archetype for solar wind-driven convection. However, Earth shares features with Jupiter because it does possess a plasmasphere with corotating plasma. *Voyager 2* observed magnetotail reconnection signatures[31] and no plasmasphere[32] at Uranus, suggesting that it may also represent a good archetype for solar wind-driven plasma flows. However, despite this evidence for solar wind-driving, no solar wind alpha particles were found at Uranus[20,31]. In parallel to the solar wind driver we also find that rotation drives some of the magnetospheric dynamics[33,129]. The balance between the drivers is currently not understood yet Uranus is an ideal laboratory to disentangle them because its corotational electric field (orthogonal to rotation and magnetic axes) seasonally becomes perpendicular to the convection electric field (orthogonal to the solar wind flow and magnetic axis). All other planets in our solar system have the solar wind-driven and rotational electric fields in roughly the same plane, making it difficult to disentangle flow drivers.

### 2.4 *We lack a "standard model" for magnetospheres. How are planetary properties related to its space environment?*

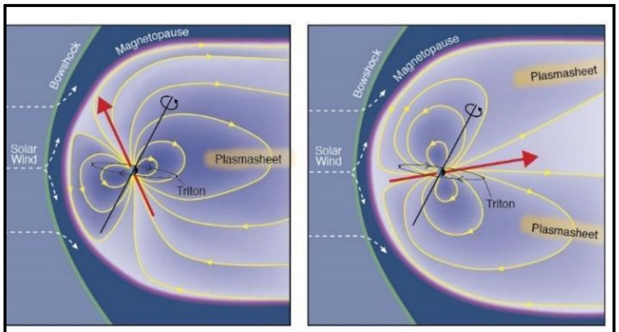

**Fig. 4.** *Neptune's magnetosphere*[96] *changes drastically each planetary rotation between a configuration similar to other magnetized planets (left) to a configuration with a cylindrical plasma sheet (right) that is unique and not understood.*

Many studies over the past decades focused on understanding the magnetospheres of particular planets in isolation. Like nuclear physics before the development of its standard model, we currently only have limited understanding on why magnetospheres differ. Uranus and Neptune are ideal test cases to develop such an understanding and test theories "outside the fitting range" of the planets where they were developed. For example, all other magnetized planets have roughly axially-symmetric magnetospheres with plasma and current sheets approximately along the magnetic equatorial plane. Neptune's magnetosphere shows the other extreme because every ~8h the axes become almost perpendicular leading to a cylindrical plasma sheet (Fig. 4). Similarly, we are used to magnetotails that extend with a well-defined structure on the night side. Again, we can study physics under extremes because the deep nightside magnetosphere of Uranus is extremely dynamic and shows an otherwise unobserved helical structure[129].

### *2.5 The bow shocks of the Ice Giants are analogues to supernova remnants. Can we use them to understand cosmic ray acceleration?*

Supernova remnants are ultra-high Mach number shocks that can accelerate particles to cosmic ray energies. How particles are initially accelerated so that this mechanism can kick in remains an open question. Some shocks can be sampled in-situ with spacecraft, but supernovas are inaccessible. Bow shocks of our solar system's inner planets are similar in principle, but have such low Mach numbers that these physical processes are unlikely to occur. This is different for the outer planets because Mach numbers increase with heliocentric distance. From Saturn's high-Mach number bow shock we have already found evidence that parallel shock acceleration is much more important than predicted[131]. Such measurements even further out in the heliosphere will enable us to better understand what controls the acceleration process and may reveal previously unknown or underappreciated processes, as demonstrated earlier[132].

## 3. Contributions to interdisciplinary studies

### *3.1 Do planetary magnetic fields reduce atmospheric escape?*

It is a long-standing hypothesis that a magnetic field protects an atmosphere from erosion. This is the canonical explanation for why Mars and Venus, which are believed to have been similar to Earth in the past but do not have active dynamos, have lost their atmosphere[43] and/or water[44] into space.

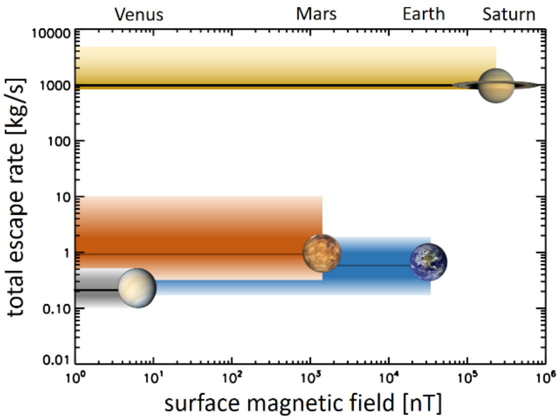

**Fig. 5.** *Estimates of total present-day atmospheric escape rates vs. magnetic fields*[134]*. The expectation that planetary atmospheres are eroded more easily for weak magnetic fields is not met.*

However, observations of the total current atmospheric escape rates of Earth, Mars, and Venus are of the same magnitude (Fig. 5), challenging this theory[48]. Recent modeling suggests that intrinsic magnetic fields may actually enhance ion outflow[50].

The escape efficiency from magnetized and unmagnetized bodies may still differ, which could be revealed when normalizing the total escape rates (e.g., to account for different atmospheric masses or interaction cross sections). However, it currently remains unclear what normalization scheme would offer a fair comparison. Because the terrestrial planets are thought to have been similar in the past, it can be informative to compare them to planets with a fundamentally different history, like the Giant Planets. However, the Gas Giants may not be the best test cases for atmospheric escape because it is difficult to disentangle the escape of atmospheric mass from moon material. Conversely, Uranus and Neptune are thought to have comparatively weakly active moons. Uranus' magnetosphere with little solar wind plasma, in particular, is ideal to study atmospheric escape.

### 3.2 *Do the Ice Giants really have planetary dynamos that are driven by ionic instead of metallic conductance?*

All planetary dynamos that generate intrinsic magnetic fields are believed to be driven by the convection of electrically conductive fluids in their interiors. For the Ice Giants, the fluid has been suggested to be ionized "ice" compounds[58] very different from other planets, which may explain their unusual highly non-dipolar magnetic fields[4,123], as well as gravity and thermal emission measurements[58].

Besides the conducting material, features like the existence of superionic layers, the location and vertical extent of the active dynamo, and/or the depth of the zonal winds influence the magnetic field[59]. This structure can be modeled, but these models remain poorly constrained for Uranus and Neptune. In contrast, recent magnetometer data constrained the inner structure of Saturn[10] and Jupiter[11]. Energetic particle[124] and auroral[123] measurements complement local measurements by probing the global field structure as well as gravity and thermal emission measurements[59].

The time evolution of the intrinsic field may offer additional information. While Earth's axial dipole component changes on millennial time scales, its higher order moments vary over centuries or less[61]. Jupiter's field even changes as fast as over decades[62]. Fast evolution can also be expected for the complex fields of the Ice Giants. Short-term changes can be observed in-situ or through signatures on moon surfaces and rings. These results can then used to infer flows near the top of the dynamo region[62], providing information on the field generation processes.

### 3.4 *Why are the Ice Giants' moons so dark?*

Many of the Ice Giant moons (Fig. 6) are unusual relative to other similarly-sized icy satellites in the solar system because of their low albedos[2]. 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 are not necessarily representative of their pristine surface compositions.

It has been suggested that irradiation by keV protons may be responsible for the darkening of the Ice Giant satellites[63] and that leading/trailing compositional asymmetries[65] are likely due to surface alterations by magnetospheric plasma. Modeling of the asymmetries is complicated by the large dipole tilt, such that each moon is irradiated over a large range of L values and magnetic latitudes.

Inversion of reflectance spectra to determine surface properties is challenging. Because the spectra depend also on the grain size and mixing regime of surface constituents[68], models provide non-unique fits. Measurements of the variation in radiation and plasma are needed to provide additional constraints.

Similarly, 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.

**Fig. 6.** *Uranus' moons are unusually dark in visible light. Could this be because of space weathering from the local radiation environment?*

### 3.5. *The subsurface oceans at the Ice Giant moons may have frozen out. What is the timeline for habitability of Ocean Worlds?*

In order to understand icy moons and dwarf planets with subsurface oceans, we need to study the life cycle of their oceans. The higher the surface-area-to-volume ratio of an ocean world, the faster that ocean freezes. Both modeling[75] and observations[73] suggest that Charon, a moon of Pluto, has a frozen subsurface ocean. Charon is of similar size to several of the Ice Giants' moons. 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 thus ocean lifetimes, which determine the window of opportunity for life to evolve, or the "habitability lifetime."

Properties of oceans and other conducting parts of a moon can be determined through magnetic induction responding to the rotating magnetospheric field. This will be far easier to determine in the Ice Giant systems than at other moons (e.g., Europa) because the Uranus' and Neptune's off-center and inclined dipole moments produce a rich power spectrum of driving frequencies[139].

### 3.6. *The temperature in Uranus' upper atmosphere is not understood. What role do auroral processes play?*

Uranus' upper atmosphere[133] and ionosphere are hotter than expected from solar irradiation and cools for years after equinox[78], which cannot be explained by geometric season alone. High temperatures are remarkable especially given that Uranus barely releases heat compared to other gas planets[107].

Aurora and its driving magnetospheric processes are good candidates to explain the temperature observations: aurora are known to inject energy into the upper atmosphere and ionosphere. As the vernal and autumnal equinoxes are different from the magnetic perspective at Uranus[80], this may explain why the observed temperatures are not symmetric about the equinox.

However, we do not understand the aurora of the Ice Giants. Unlike other planets, where aurora tends to be steady and/or of similar duration as the driving interplanetary conditions, Uranus' aurora appears highly variable, indicating fundamentally different drivers[82]. At Neptune it is unclear if the aurora is driven by injection of plasma from Triton's orbit[135] or by interaction with the solar wind[136]. To understand the underlying drivers that determine the energy and duration of the aurora, we need in-situ measurements of the charged particles and magnetic field.

### 3.7 *What role does the magnetosphere have in unusual ring structure and dynamics?*

The rings of Uranus and Neptune are very different from those around the Gas Giants, and appear to vary on much shorter timescales (years to decades), making them critical for understanding planetary rings in general.

Charged particles, including ring particles, in a magnetic field are subject to the Lorentz force. For small ring grains (on the order and below a micrometer in size), this force can be significant[90], meaning that the ring dynamics cannot be fully understood when ignoring the fields, plasma, and energetic particles that surround it. This is especially important for Uranus's mysterious $\mu$-ring (Fig. 7), which is dominated by such (sub)micron-sized grains[86].

Generally, the ring systems of Uranus and Neptune show unusual dynamics. Uranus' $\mu$-ring shows large brightness variations with longitude that cannot be explained by gravity alone[91]. The most surprising discovery about Neptune's ring system was the detection of 4-5 ring arcs in the Adams ring and the change of their relative positions[93]. The role of electromagnetic forces needs to be considered to understand the time dependence of ring dynamics.

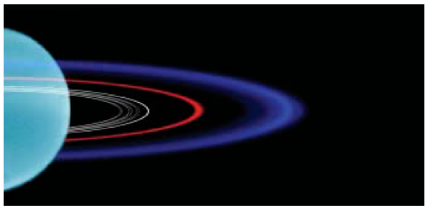

***Fig. 7.*** *It is unclear how Uranus' blue $\mu$-ring is sustained without a geologically-active moon.*

## 4. Flybys are insufficient

In order to address these mysteries, detailed studies of the Uranus and Neptune systems are required. Both planets have unique mysteries. An orbiter would enable multiple flybys of the satellites, rings, and planet allowing for long-term observations and comprehensive mapping. An **orbiter is critical** for magnetospheric measurements and their broader science use because the magnetosphere is asymmetric and highly dynamic. Changes in in-situ measurements may indicate true time variability or the spacecraft entering a different region. Experience on typical conditions gained by an orbiter are the first step to resolve this ambiguity.

## 5. Summary

Here we outline various magnetospheric and interdisciplinary mysteries at Uranus and Neptune, where our current understanding of physics and/or planetary systems is incomplete. In order to resolve these mysteries we must include magnetospheric science in missions to these planets to gain insights into these systems as a whole, including structure, dynamics, and origins of the magnetosphere, radiation belts, and aurora.

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