WHITE PAPER FOR THE
HELIOPHYSICS SCIENCE DECADAL SURVEY, 2013-2023.

The Case for Exploring Uranus' Magnetosphere.

This White Paper is endorsed by 66 scientists (listed at the end) from the USA and Europe, many of whom are early career scientists representing the driving force of the heliophysics community in the decades to come.

Motivation.

In order to further our understanding of how life and the platforms for life exist in the wide variety of magnetic environments in the Universe it is vital that we make comprehensive measurements in the widest possible variety of environments. **Our Solar System provides the only local laboratory in which we can perform experiments that are helping us to understand the nature of planetary magnetospheres in general.**

A White Paper submitted to the Planetary Science Decadal Survey 2013-2023 [*Hofstadter et al*.] provides a persuasive case for a Uranus orbiter to investigate the composition, structure, atmosphere and internal dynamo of the planet and the nature and stability of its moon and ring system. They advocate a New Frontiers type mission with 2020-2022 being a particularly efficient launch window. The proposed mission is exciting, exploratory and timely given that the 'ice giants' are the only major category of Solar System object never to have had a dedicated mission. In that plan, powerful arguments for a magnetospheric element to such a mission were overlooked. Here we outline the science case for a dedicated magnetospheric mission to Uranus, one that could go in tandem with, or be combined with, the proposed planetary orbiter.

We also note that a "Uranus Pathfinder" mission, which does include strong magnetospheric elements, is being proposed by *Arridge et al.* to the European Space Agency. Given the cost of these missions and the evident excitement across the planetary and heliophysics communities for such a mission, it seems sensible to coordinate our efforts over the coming decade, both within NASA and between NASA and ESA. We the undersigned advocate strong support in the Heliophysics Decadal Survey for the magnetospheric science opportunities associated with a Uranus (or Neptune) orbital mission.

Background.

The Uranian system has a unique configuration among the planets because its axis of rotation lies nearly in the ecliptic plane. Its north and south poles lie where most planets have their equators, and its tenuous rings are almost perpendicular to its orbital plane. In addition to the unconventional spin orientation, the Uranian magnetic dipole axis is tilted at the unusually large angle ~ 60° from its spin axis. Figure 1 illustrates the configuration that exists near Uranian solstice, appropriate to the Voyager 2 encounter in 1986. The next Uranian solstice occurs in 2028, a few years before the earliest feasible arrival time for a Uranus orbital mission.

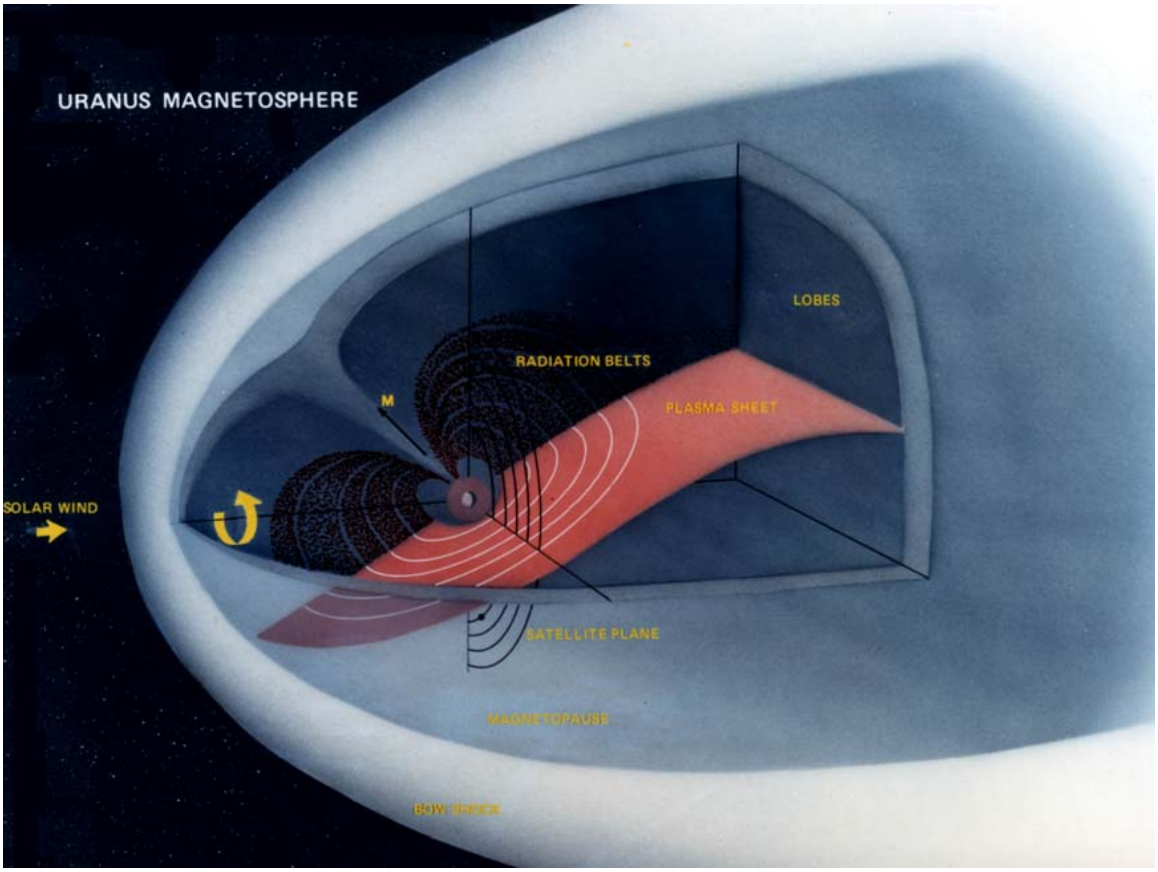

Figure 1. Overview sketch of the Uranian magnetosphere showing bow shock and magnetopause, boundary layer, dayside cusp, satellite plane, plasma sheet (shaded), radiation belts, and extended hydrogen atmosphere around Uranus. The magnetic and rotation axes are marked. From *Krimigis et al*., 1986.

Given the strength of the magnetic field at Uranus and the fairly rapid rotation rate, one might expect to find that the Uranian magnetosphere is rotation-driven like those of Jupiter and Saturn [*e.g*., *Bagenal*, 1992; *Vasyliūnas*, 2004]. In fact, **Voyager 2 observations were more nearly consistent with a classic solar-wind-driven magnetospheric convection system like that of Earth.** This can be explained by the fact that, near solstice, a solar-wind-driven magnetospheric convection system would be orthogonal to, and thus unimpeded by, planetary rotation [*Vasyliūnas*, 1986; *Hill*, 1986; *Selesnick and Richardson*, 1986]. Because its flyby trajectory was close to the ecliptic plane, the Voyager spacecraft was unable to observe the plasma properties in the ring plane (or in the magnetic equatorial plane) inside an *L* value of about 12.

The unique magnetospheric configuration at Uranus provides the opportunity to investigate several aspects of plasma production, energization, transport, and satellite interactions that, despite several decades of study, are still not fully understood. These include the following specific top-level questions:

1. Magnetospheric transport.

The peculiar combination of magnetic and spin axes means that the plasma sheet is twisted as the planet rotates. Voyager measured the magnetotail to ~400 Uranus radii behind the planet. The extreme tilt of the magnetic axis, combined with the tilt of the rotational axis, causes the field lines in the roughly cylindrical magnetotail to be wound into a helical (corkscrew) shape [*Hill et* *al*., 1983]. Otherwise well understood mechanisms for plasma transport and diffusion have never been studied in this type of geometry. **How does plasma move radially in this type of configuration?**

The unique feature of the Voyager 2 encounter was the fact that the spin axis of Uranus was aligned nearly along the planet-sun line. This led to the condition that a solar-wind-driven magnetospheric convection system was effectively decoupled from corotation, as noted above. Stated another way, the flow system rotational electric field, which ordinarily would have "shielded" the middle magnetosphere from the solar wind, was oriented in such a way that solar wind effects could penetrate deeply into the magnetosphere. The consequences included:

a) Convection patterns similar to Earth's with a well defined plasma pause.
b) Strong dynamics including Earthlike injection phenomena;
c) An electron radiation belt that was as intense as the most intense seen at Earth; and
d) The strongest whistler-mode emissions seen at any of the outer planets.

By the time that a new Uranus orbiter mission might reach Uranus, this pole-on configuration would no longer prevail exactly, and would become less applicable as the mission progresses. The mission could thus address the following fundamental questions: **When the solar-wind-induced and rotational motions become less decoupled, will Uranus' magnetosphere become more quiescent, like that of Neptune, or will it become more rotation-driven, like those of Jupiter and Saturn? Will it show injections as were seen during the Voyager encounter? Will the radiation belts be equally intense? What will convection look like?**

2. Energetic particle trapping.
One might expect that the configuration at Uranus would lead to less efficient particle trapping and heating required to form radiation belts. In fact, Voyager 2 found electron radiation belts at Uranus of intensity similar to those at Earth and much more intense than those at Saturn. The ion radiation belts are similar between Uranus and Saturn, although they differ in composition. **How stable are the Uranian radiation belts? Are they always present? Are they devoid of heavy ions, and if so, why? What are the relative roles of moon sweeping and wave-particle interactions in limiting the radiation belt fluxes? How far inward do these belts extend towards the rings and upper atmosphere of Uranus?**

3. Neutral particle dynamics
Neutral gas and dust are critical components of magnetospheres as currently shown with recent Cassini research of the Saturnian system. Such particles not only provide sources of magnetospheric material but also modify magnetospheric dynamics though interactions with charged particles and the planetary magnetic field. No other planetary system allows for neutral particles, rings and moons (rotating around the planetary spin axis) to interact with magnetic fields and plasma at such large oblique angles (60 degrees). This should create highly dynamic and previously unobserved types of particle interactions. Additionally, ring particles can retain an electric charge and interaction with an offset magnetic field should hinder ring stability and yet these rings exist at Uranus. **With the high inclination of the Keplerian plane versus the magnetic equator at Uranus the dynamics of neutral gas and dust as they are formed and redistributed throughout the magnetosphere are likely to be complex and provide insight**

into sources and magnetospheric evolution as well as providing critical insight in magnetospheric stability and dynamics.

4. Satellite weathering.

The radiation belts of Uranus appear to be dominated by hydrogen ions, without any evidence of heavier ions that might have been released from the surfaces of the moons. Uranus' radiation belts are so intense that proton irradiation would quickly darken (within 100,000 years) any methane trapped in the icy surfaces of the inner moons and ring particles. This may have contributed to the darkened surfaces of the moons and ring particles.

Only limited information has been available about the weathering of the Uranian satellites. At the time of the Voyager 2 encounter, there was discussion about the nature of the dark material on these bodies and the possible role that charged-particle weathering has in darkening the ice. One proposal was that, if a small fraction of methane were present in the ice, weathering by charged particles could darken ice grains by the creation of carbonaceous material (*Cheng and Lanzerotti* 1978). However, *Veverka et al*. (1991) pointed out that, despite the absolute albedoes, the only surface constituent that was observed spectrally was water ice which should produce a bighter albedo. This seemed to call into question the presence of methane. *Cheng et al.* (1991) later argued that heavy processing of the top layer by ions would alter the surface so much that it would not have methane ice spectral features. While this remains an open question, other lines of thinking have suggested that the darkening is purely due to geology, and that weathering is a secondary effect. *Grundy et al.* (2003) recently identified leading/trailing differences on the surfaces of the Uranian satellites. **Leading/trailing asymmetries are suggestive of processing by grains, plasma, or energetic charged particles. The relative importance of these effects are yet to be resolved, and in situ observations of magnetospheric particles and plasma are necessary to unravel the causes of the observed surface differences.**

5. Daily variability.

Overall configuration and stability of the Uranian magnetosphere: What are the 3D magnetic and plasma properties of the main regions and their boundaries of the asymmetric magnetosphere of Uranus? Do these regions contain quasi-steady or transient particle populations**? How does this exotic magnetosphere reconfigure during a Uranian day?**

6. Seasonal variability.

The Uranian seasonal changes are completely unlike those of the other major planets. Near Uranian solstices, one pole faces the Sun continuously while the other pole faces away (this was the case during the Voyage encounter). Only a narrow strip around the equator experiences a rapid day-night cycle, but with the Sun very low over the horizon as in the Earth's polar regions. At the opposite side of its orbit, the orientation of the poles is reversed, so that each pole gets around 42 years of continuous sunlight, followed by 42 years of darkness. Near equinox, the Sun faces the equator of Uranus, giving a period of day-night cycles (on the order of 17 hours) similar to those seen on most of the other planets. Uranus reached its most recent equinox in 2007. The next solstice will happen in 2028, and the next equinox in 2049. An orbital mission launched around 2020 would reach Uranus shortly after its 2028 solstice and could be expected to observe it during the approach to its 2049 equinox. **The effect of the equinox geometry at Uranus on magnetospheric configuration and stability is entirely unknown.**

Measurement requirements.

In their White Paper *Hofstadter et al.* describe the science drivers for several measurements including high resolution magnetometery, microwave sounding, multi-wavelength imaging and spectroscopy, along with laboratory and ground based support measurements. They note that a single spacecraft would be more cost effective (based on a high-level study done at JPL) and that significant science payloads could be inserted into orbit around Uranus using chemical propulsion alone using relatively modest launch vehicles. Thus cost is the single biggest factor limiting instrument payload size making cost sharing across disciplines and internationally a very attractive option in producing a feasible cost-effective mission.

We advocate the inclusion of a dedicated magnetospheric element, ideally on a spinning platform, to be included on, or go in tandem with, a planetary mission to Uranus and ideally in collaboration with ESA. Additional instrumentation would ideally include:

Ion plasma composition and full electron pitch angle distributions across the widest possible dynamic range (a combination sensor akin to the JEDI-JADE plasma suite on the Juno spacecraft might be most appropriate).

Radio and plasma wave package with similar capabilities to those onboard the Cassini (RPWS) and Juno (WAVES) spacecraft.

Neutral particles and dust detectors (something like the Cassini INMS and CDA instruments).

An additional high resolution **magnetometer** (like the Cassini MAG) would be required if the magnetospheric platform is a separate platform.

A companion White Paper by *Hess et al.* outlines how a dedicated magnetospheric mission can fit under a New Frontiers type costing. We add our support to that White Paper and further endorse that the community endeavour to perform such a mission in collaboration with the Planetary Science and international (ESA) community.

A final note, while the science outlined here is motivated by our desire to make un-paralelled magnetospheric measurements at Uranus, the tour phase out to 20 AU will afford a rare opportunity to make solar wind observations in the outer heliosphere and as such appeal to an even broader section of the heliophysics community.

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