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The magnetospheres of Uranus and Neptune: what we know and what we don't know

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Abstract

The complex and highly non-symmetric internal magnetic fields of Uranus and Neptune, coupled with the relatively fast rotation and the unusual inclination of the rotation axes to the orbital planes imply that their magnetospheres are subject to drastic geometrical variations during a rotation period, the nature of which can change significantly during the orbital revolution. The two short stretches of available in situ observations have been interpreted mostly in terms of quasi-equilibrium models developed for other magnetospheres, with some attempted adaptation "by hand" to the changing geometries. Many unresolved questions remain concerning the proper description of the dynamical processes, particularly magnetic topology, magnetotail configuration, and coupling to the ionosphere.

1. Introduction

Almost all we know about the magnetospheres of Uranus and Neptune is derived from observations during the single flyby ($\sim$ 2 days inside the magnetosphere) of each of the two planets by Voyager 2 (Uranus in January 1986, Neptune in August 1989), supplemented by a limited amount of remote sensing and a great deal of theoretical speculation.

2. Overview of Voyager results

See [1, 3] for reviews of the Voyager results, with references to the original publications, also [2, 7] for more recent summaries and discussions.

2.1. Magnetic field geometry

Both planets were found to have intrinsic magnetic fields, sufficiently strong to hold off the ambient solar wind at distances of some 25 R_P (planetary radii). Totally unexpected is the large tilt of the magnetic dipole moment from the rotation axis, about $50°$ to $60°$ (compared to $< 12°$ for all other known planetary magnetic fields), as well as the large dipole offsets $\sim 0.35\ \mathrm{R}_P$ to $0.48\ \mathrm{R}_P$ (compared to $< 0.12\ \mathrm{R}_P$ for all others).

2.2. Magnetospheric configuration

The overall morphology of the magnetosphere, as inferred from the observations, is consistent with the generic model: an inner magnetosphere populated by energetic radiation-belt particles and a low-energy plasmasphere, connecting to an inflated outer magnetosphere and then to a magnetotail with plasma/current sheet, the structure of the latter being considerably more complicated and time-varying than in previously observed magnetospheres, presumably as a consequence of the rotating highly tilted dipole field.

2.3. Plasma distribution

The plasma in the magnetosphere of Uranus has a relatively low density and is thought to be primarily of solar-wind origin. At Neptune, the distribution of plasma is generally interpreted as indicating that Triton is a major source.

3. Some outstanding problems

3.1. Magnetospheric variability and its time scales

Table 1 (calculated from numerical values given in [2]) lists some time scales at Uranus and Neptune and, for

Table 1: Time scales.

	Jupiter	Saturn	Uranus	Neptune
τ_{rot} (h)	9.8	10.6	17	16
τ_{sw} (h)	210	80	44	41
τ_{sw}/τ_{rot}	21	7.5	2.6	2.6

comparison, also at Jupiter and Saturn: the planetary rotation period and the time τ_{sw} of solar wind flow past the effective length of the magnetotail, empirically estimated as $100 \times \mathrm{R}_{CF}$ (distance at which the planetary dipole field pressure equals the solar-wind dynamic pressure). It can be shown that τ_{sw} gives the order of magnitude of magnetospheric convection time. The large dipole tilt implies that its geometry relative to the solar wing changes drastically during the planet's rotation. Since $\tau_{sw} > \tau_{rot}$ but not by much, there can be no quasi-steady magnetospheric plasma flow (except during the small fraction of the orbital revolution of Uranus when its rotation axis is nearly aligned with the solar wind flow [11, 9], which happens to have been the case during the Voyager epoch).

3.2. Magnetic topology and magnetotail dynamics

The large tilt implies that a relative orientation of magnetospheric and interplanetary fields favorable for reconnection will (for most epochs of orbital revolution) always occur at some time during the rotation. The changing geometry allows for complex changes of magnetic reconnection, with accompanying changes of the magnetic topology. Even without reconnection, the configuration of the magnetotail may oscillate between different states during a rotation (e.g. [10]).

3.3. Magnetospheric convection and magnetosphere/ionosphere coupling

In addition to the time-scale problem (section 3.1), studies of magnetospheric convection (e.g., [5, 8, 4]) need to deal with variable Pedersen conductance, due to the large variation of surface magnetic field strength (factor of $\sim$ 10, compared to $\sim$ 4 for Jupiter and Saturn, $\sim$ 3 for Earth, 2 for a centered dipole).

3.4. Plasma sources and transport

Radial transport at Uranus and Neptune is generally assumed to be fast (in some not precisely defined sense). Although not implausible in such an asymmetric and dynamic magnetosphere, the process is not easily described by detailed theory. Particular complexities arise in relation to a plasma source from Triton (e.g. [6]).

4. Conclusion

Much of the work on the magnetospheres of Uranus and Neptune has been based on the principle "... the first step in trying to understand a magnetosphere that is being observed for the first time has always been to invoke analogies from the terrestrial magnetosphere and see how far they can be pushed" [12]. Clearly, the analogies have been pushed to the limit and beyond. A time-varying quasi-equilibrium approach is no longer adequate; fully dynamical theories are needed to describe these highly complex magnetospheres.

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