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MAGNETOSPHERES OF THE OUTER PLANETS

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1. INTRODUCTION

Anyone who wishes to become properly grounded in magnetospheric physics is well advised to start with three great monographs: Chapman and Bartel's *Geomagnetism* [1940], Alfvén's *Cosmical Electrodynamics* [1950], and Störmer's *The Polar Aurora* [1955].

The subject has acquired its present vigor and broad participation only during the 27 years since 1958, when we found that enormous numbers of energetic charged particles are durably trapped in Earth's external magnetic field.

The magnetosphere of Earth is the prototypical planetary magnetosphere. It has been investigated intensively and may be said to be understood to "first order", though many of its details continue to be baffling and controversial.

Meanwhile, we have been proceeding with the investigation of particle and field phenomena associated with other planetary bodies—the Moon, Mercury, Venus, Mars, Jupiter, and Saturn. There are significant plasma physical effects at the Moon and at Mercury, Venus, and Mars, but only Jupiter and Saturn join Earth in exhibiting fully developed magnetospheres.

The three latter cases have a certain gross similarity but each is distinctively different in detail, thus giving rise to Frank McDonald's [1980] famous remark: "If you've seen one magnetosphere, you haven't seen them all." It is reasonable

to expect that the prospective Voyager 2 investigations of Uranus in 1986 and Neptune in 1989 will add further support to this remark.

Because of the availability of a massive body of literature including several book-length monographs and review papers on the magnetospheres of Earth, Jupiter, and Saturn, I decided not to attempt a twenty-minute digest of this knowledge but rather to review some general considerations of an elementary nature and to present some speculations.

2. CONDITIONS FOR THE EXISTENCE OF A PLANETARY MAGNETOSPHERE

A common statement is that a planet will have a magnetosphere if and only if it: (a) is "sufficiently strongly magnetized" and (b) is subjected to the flow of the solar wind.

Such a statement contains a certain measure of validity but requires further scrutiny.

On the subject of planetary magnetism, the following section is adapted from a paper that I wrote in 1976 [Van Allen, 1977].

There are five qualitatively different types of magnetism that a planetary body can exhibit:

- (a) Remanent ferromagnetism in cool crustal material.
- (b) Electromagnetism caused by currents in an electrically conductive interior, such currents being driven by self-excited dynamo electromotive forces generated by the convective flow of material. This mechanism requires a hot fluid interior and planetary rotation at a "sufficiently rapid rate".
- (c) Electromagnetism of type (b) at some remotely previous epoch, with subsequent resistive-inductive decay of the current systems after the electromotive forces have become negligible.

- (d) Electromagnetism caused by systems of currents induced in the conducting ionosphere of the planet by fluctuating magnetic fields in the solar wind and/or driven by motional electromotive forces caused by the relative motion of magnetic fields in the solar wind. In either case, the electrical circuit may be closed in part through the conductive interplanetary medium.
- (e) Electromagnetism similar to type (d), but with the induced currents in conducting portions of the planetary body itself.

Most of the interiors of the above mentioned seven celestial bodies (with the possible exception of the Moon) are thought to be at temperatures above the Curie temperature of ferromagnetic materials (≈ 1000 K) if, indeed, such materials are present; hence, remanent ferromagnetism, if any, must be confined to the outer crust of the bodies. For a large, rotating planet having a fluid interior, there is no theory of type (b) magnetism that proceeds from first principles to a confident quantitative prediction of the magnetic properties of the planet.

In order that a planetary body have a magnetosphere of durably trapped particles, it is necessary that its dipole moment be sufficiently great that there are closed magnetic shells such that particles can drift in longitude without striking the body (or its appreciable atmosphere) or without escaping from the system.

In the vacuum case, the magnetic field extends to infinity and the criterion for durable trapping of a single test particle is derivable from Störmer theory. The total population of trapped, non-interacting particles is limited by the further criterion that the volume density of kinetic energy of charged particles is less than or of the order of $B^2/8\pi$, where B is the local magnetic field strength. A realistic physical source of particles is, of course, cosmic ray albedo neutron decay. I consider that a full solution of the self-consistent vacuum case would be a worthy theoretical exercise but, to my knowledge, no one has produced such a solution. The lack of interest in the vacuum case stems from the fact that flowing plasma, or at least plasma, appears to be ubiquitous throughout the universe.

In the presence of flowing plasma, the approximate criterion for the existence of a magnetosphere is that the magnetohydrodynamic stagnation distance r on the upstream side of the planet exceeds the radius of its surface or appreciable atmosphere. In the case that plasma within the magnetosphere exerts a negligible pressure, the magnitude of r is given by

$$nmv^2 = \frac{M^2}{2\pi r^6} \quad (1)$$

wherein n , m , and v are the number density, atomic mass, and relative bulk velocity of the ions in the plasma and M is the body's magnetic dipole moment. The plasma in question may be the solar wind out to the heliopause or the interstellar wind beyond the heliopause. For planetary satellites within a planet's magnetosphere, the flowing plasma may be that co-rotating with the planet.

Inside the heliosphere, v for the solar wind is independent of the distance R from the sun and n is inversely proportional to R^2 . Hence by Equation (1)

$$\frac{r_P}{r_E} = \left(\frac{M_P R_P}{M_E R_E} \right)^{1/3} \quad (2)$$

where the subscripts E and P refer to Earth and to any other planet, respectively.

It is seen from Equation (2) that Earth would have the same size magnetosphere as it now does if it were at a heliocentric distance of 50 AU and its magnetic moment were reduced by a factor of 50. This statement assumes, of course, that the heliopause lies beyond 50 AU, as now seems likely.

By Equation (1), it is noted that if Earth were placed outside the heliopause in the nearby interstellar medium ($n \sim 0.05 \text{ cm}^{-3}$, $v \sim 20 \text{ km s}^{-1}$), r would be unchanged if the planet's magnetic moment were only 1/200 of its present value. This example illustrates the fact that the solar wind is not essential for producing a magnetosphere.

A further case of general interest contemplates a magnetized planet immersed in a stationary plasma. If the planet were not rotating, it would be simply a large Langmuir probe with no magnetospheric properties. But if the planet is rotating, however slowly, there is a corresponding unipolar electric field and the nearby plasma will co-rotate with the planet out to the radius at which the co-rotational speed is equal to the Alfvén speed. At the outer boundary of the co-rotating plasma, there are presumably instability effects that result in the generation of waves and acceleration of particles. Hence, even in the case of nonflowing plasma a magnetosphere will exist. Cases of this nature are treated in the theory of pulsars, though for rotational rates far greater than those of planets.

The foregoing remarks suggest the great variety of magnetospheres that may, and probably do, exist.

3. SOURCE OF MAGNETOSPHERIC PARTICLES

Potential sources of energetic particles in a planet's magnetosphere are as follows:

- (a) The solar wind
- (b) Solar energetic particles
- (c) Primary cosmic rays
- (d) Secondary particles from cosmic-ray interactions in the planet's atmosphere, rings, and satellites
- (e) Ionized gas from the planet's ionosphere
- (f) Gas sputtered from rings and satellites by particle and photon bombardment
- (g) Gas emitted volcanically or outgassed from rings and satellites

Plasma physical phenomena associated with the Moon, Mercury, Venus, and Mars are attributed principally to particles from source (a), with perhaps an admixture of particles from source (e).

The quasi-thermal plasma and low energy particles within Earth's magnetosphere are also primarily from source (a) and secondarily from source (e), as judged by elemental composition and energy spectra. However, higher energy ($E \gtrsim 0.2$ MeV) particles come primarily from source (d), with some admixture of particles from source (b).

The quasi-thermal plasma and low energy particles in Jupiter's magnetosphere are identified as dominantly from source (g), the volcanically active satellite Io being the principal contributor, but there are also (probably) significant contributions from sources (a), (e), and (f). Sources (b) and (d) of very energetic particles are presumed to be operative but particles from these sources have not been identified conclusively.

The various potential sources of particles in Saturn's magnetosphere have been assessed as follows: Very energetic protons ($E_p \gtrsim 10$ MeV) are from source (d). Protons having $E_p \lesssim 1$ MeV and electrons having $0.035 < E_e < \text{a few MeV}$ are principally from the solar wind, source (a), and to a lesser extent from source (b). Electrons and protons of lesser energies are apparently from sources (e), (f), and (g) as well as from the ionosphere of Titan.

4. IN SITU ENERGIZATION OF PARTICLES

Particles that are injected into a magnetosphere, from whatever source and in whatever manner, are energized and diffused spatially by fluctuating magnetic and electric fields (including those in plasma waves) and convected and energized by quasi-steady electric fields. These very complex processes are essential to the overall character of the particle population but they also tend to confuse the process of identification of the sources and sinks of the particles.

Irrespective of detailed processes for the generation of plasma waves and electromagnetic radiation and for the acceleration and diffusion of particles, it

appears that all such magnetospheric processes derive their power from three basic sources:

- (a) The kinetic energy of flowing plasma (e.g., the solar wind)
- (b) The rotational energy of the planet
- (c) The orbital energy of satellites

Sunlight contributes to establishing the conditions for energy transfer by ionizing atmospheric gases and by photon sputtering and ionization of solid surface material but apparently contributes little to gross energetics.

The coupling between any one of the three sources of energy and the particle population must be such as to generate electric fields since, apart from gravitational fields, acceleration of a charged particle can be accomplished only by an electric field.

The power flux of the solar wind at 1 AU is typically $0.4 \text{ erg (cm}^2\text{s)}^{-1}$. The cross-sectional area of Earth's magnetosphere perpendicular to the solar wind flow is that of a circle of approximate radius 14 planetary radii or $2.5 \times 10^{20} \text{ cm}^2$. Hence, the total power that is potentially available from the solar wind is of the order of $1 \times 10^{20} \text{ erg s}^{-1}$, on an average day. During days of high solar activity the power flux increases by as much as an order of magnitude.

The solar wind power exceeds that required for all dissipative processes in Earth's magnetosphere by a factor of the order of 100. The coupling of this power into the magnetosphere apparently occurs by way of the motional electromotive force induced in the magnetosheath.

The total rotational kinetic energy of Earth is $2 \times 10^{36} \text{ erg}$, an enormous amount relative to all magnetospheric requirements. The coupling here is exhibited by co-rotation of plasma and the maintenance of the corresponding system of electrical currents in the plasma and in the ionosphere. The best present estimates are that the power extracted from Earth's rotational energy is much less than that extracted from the solar wind flow.

At Jupiter, the situation is the reverse of that at Earth, and it appears that most of the power for magnetospheric processes comes from the rotational energy of the planet and the orbital energy of the innermost Galilean satellite, Io. The gas emitted volcanically from Io plays a central role in Jupiter's magnetosphere. Nonetheless, the long magnetotail (several AU in length) of Jupiter certifies the importance of the solar wind flow in establishing the topology of its outer magnetosphere.

Saturn also exhibits a long magnetotail but the energetics of its magnetosphere lie between those of Earth and Jupiter, with perhaps comparable contributions from the solar wind and the planet's rotation. Titan with its dense atmosphere lies in the outer fringes of Saturn's magnetosphere and hence has a less significant role in the physics of Saturn's magnetosphere than does Io in Jupiter's.

5. THE MAGNETOSPHERE OF URANUS

One of the most exciting near-term prospects for magnetospheric physicists is the encounter of Voyager 2 with Uranus during the period around closest approach on January 24, 1986.

It has been established by Pioneer 10 that the radial flow of the solar wind extends to and far beyond the orbits of Uranus and also Neptune [Barnes and Gazis, 1984].

There is, as yet, little quantitative evidence on the magnetic moment of Uranus. However, it is reasonable to expect that the value of its moment is of the order of 4×10^{27} gauss cm³ or about 0.2 gauss a_U^3 where a_U is the planet's equatorial radius.

The basis for this empirical expectation is shown in Table I and Figure 1, which summarize existing knowledge of the magnetic moments of planets as a function of their rotational angular momenta. The two line segments labeled Uranus and Neptune are drawn vertically at the approximately known values of their respective angular momenta and the lengths of the segments

Table I
Angular Momenta and Magnetic
Moments of Planets

	$I\omega$	M	$\frac{M}{I\omega} \times 10^{15}$
	$\text{g cm}^2 \text{ s}^{-1}$	gauss cm^3	gauss cm s g^{-1}
Mercury	9.74 E 36	2.4 E 22	2.5
Venus	1.82 E 38	< 3 E 21	< 0.02
Earth	5.859 E 40	7.92 E 25	1.35
Mars	1.98 E 39	1.4 E 22	0.007
Jupiter	4.19 E 45	1.53 E 30	0.37
Saturn	7.03 E 44	4.32 E 28	0.061
Uranus	1.52 E 43	—	—
Neptune	2.07 E 43	—	—
Pluto	~ 3 E 36	—	—
Moon	2.36 E 36	< 4 E 20	< 0.2

Note: $a \text{ E } b = a \times 10^b$

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suggest ranges of values of their magnetic moments within which actual values will not be astonishing.

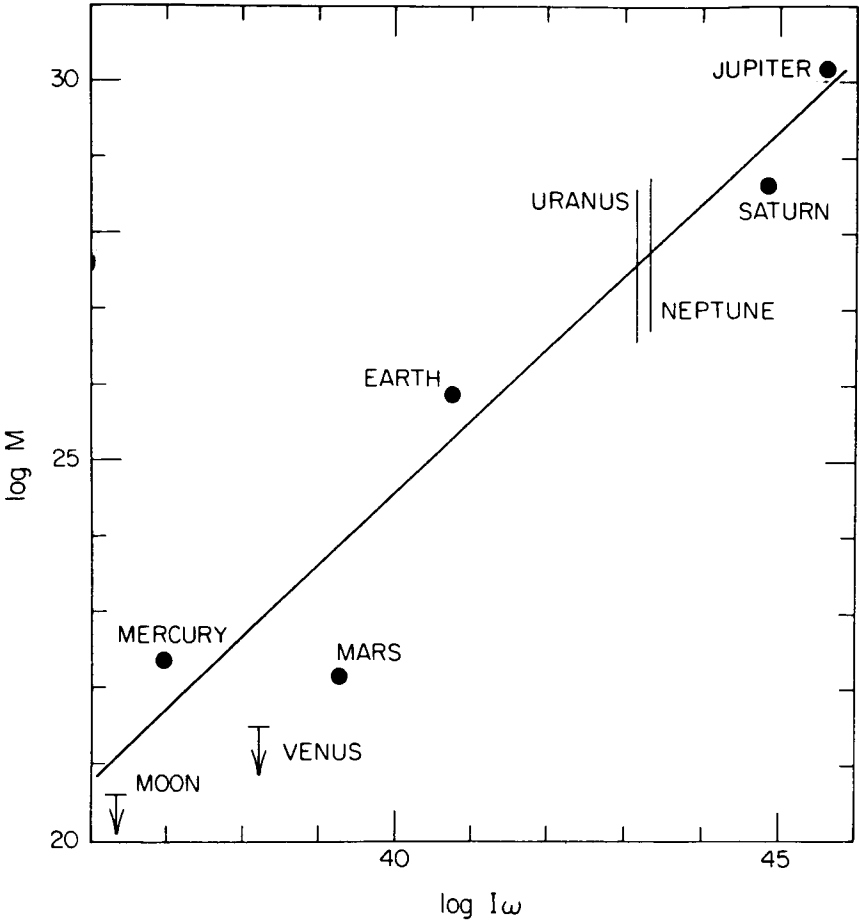


Figure 1. The empirical relationship between magnetic dipole moments M of planets and their rotational angular momenta $I\omega$. The line segments labeled *Uranus* and *Neptune* are drawn vertically at the approximately known magnitudes of their angular momenta. The lengths of the segments span ranges of M within which it would not be astonishing to find their actual values.

Based on Equation (1) and the above guess as to the magnitude of the magnetic moment of Uranus, one calculates a stand-off distance of 26 planetary radii, a value that is proportional to the cube root of the assumed moment.

Within this radial distance from the center of the planet, it is reasonable to expect a well-developed magnetosphere, albeit one of extraordinary properties because of the approximately axial alignment of the rotational axis with the planet-sun line in 1986 as shown in Figure 2 [Van Allen, 1977]. If the magnetic axis of the planet is approximately parallel to its rotational axis, then the co-rotational equipotential surfaces are turned by 90° relative to the

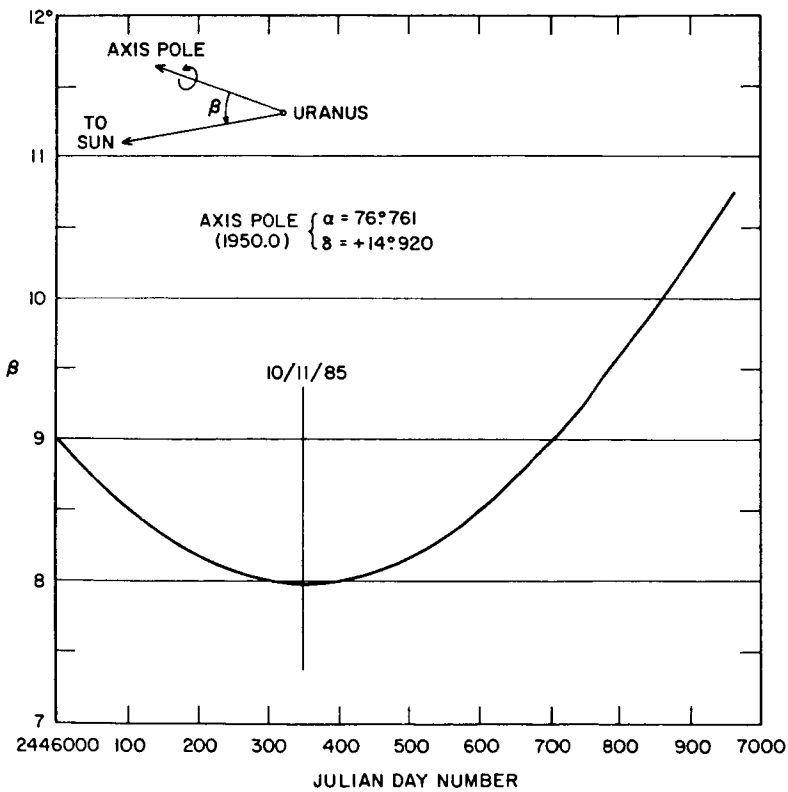
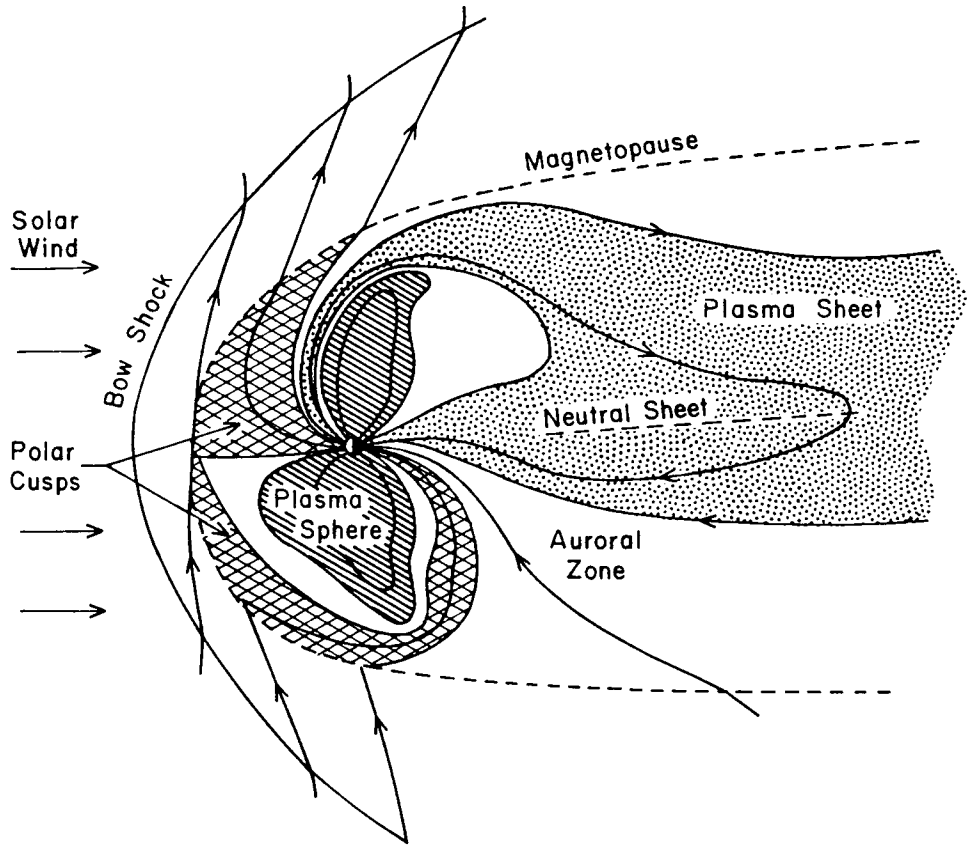


Figure 2. The time dependence of the angle β between the rotational axis of Uranus and the planet-sun line [Van Allen, 1977].

transverse potential surfaces that are attributed to solar wind flow—as compared to the situations at Earth, Jupiter, and Saturn. This case has been discussed in a preliminary way by Siscoe [1971, 1975] (Figure 3) and by Olson. If the magnetic axis is inclined markedly to the rotational axis, an even more exotic magnetosphere may be expected because of the large diurnal variation that will occur in this case.



HYPOTHETICAL MAGNETOSPHERE OF URANUS
(AFTER SISCOE)

Figure 3. Hypothetical topology of a Uranian magnetosphere during the epoch of pole-on presentation to the solar wind [Siscoe, 1975].

Recent observations by the International Ultraviolet Explorer of auroral optical emissions from Uranus provide the principal observational evidence thus far for the existence of a well-developed magnetosphere [Durrance and Moos, 1982; Clarke, 1982; and Caldwell, Wagener, and Owen, 1983]. Less direct evidence depends on the suggestion of Chang and Lanzerotti [1978] that the low optical albedos of the satellites and rings of Uranus are the result of trapped particle bombardment and consequent carbonization of methane ice on their surfaces.

An important feature of the Uranian magnetosphere is the presence therein of five satellites, in close regular orbits (Table II) [Dermott, 1984], and nine thin rings which lie between 1.59 and 1.96 planetary radii [Elliot, 1984]. As at Jupiter and Saturn, these elements of the Uranian system doubtless have profound effects on the absorption and possibly the emission and acceleration of charged particles.

Table II
Satellites of Uranus

<u>Satellite</u>	<u>Orbital Radius (a_U)</u>	<u>Body Radius (km)</u>
V Miranda	5.0	220
I Ariel	7.3	660
II Umbriel	10.2	560
III Titania	16.7	800
IV Oberon	21.7	815

During the Voyager 2 encounter with Uranus, Pioneer 11 will be relatively nearby as shown by Figure 4. Hence, Pioneer 11 will be able to provide valuable

observations of the solar wind, the magnetic field, and energetic particle intensity in the nearby interplanetary medium before, during, and after that encounter [Van Allen, 1984]. All of these quantities are significant in determining the state of Uranus' magnetosphere and fluctuations thereof.

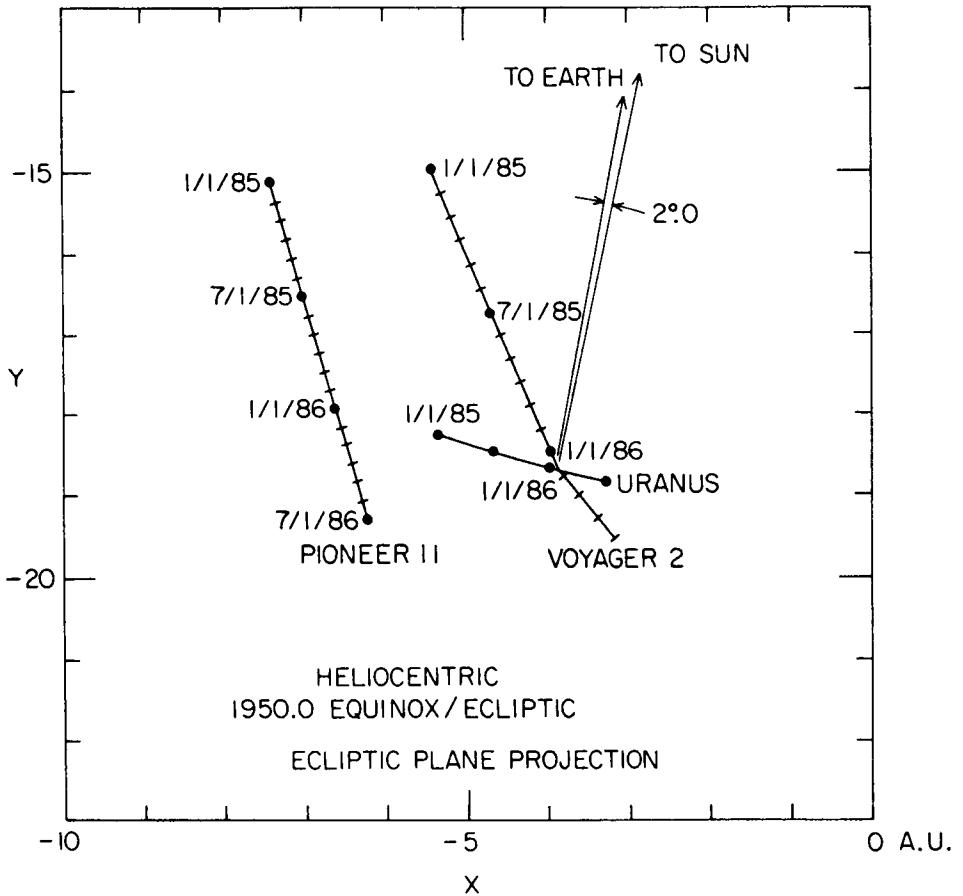


Figure 4. Ecliptic plane projection of the trajectories of Pioneer 11, Voyager 2, and Uranus during 1985-1986. The latter two bodies are close to the ecliptic plane and hence their relationship is well represented by this diagram. However, Pioneer 11 is substantially north of the ecliptic plane, having a Z-coordinate of 5.753 AU on January 24, 1986 [Van Allen, 1984].

Desch and Kaiser [1984] and Hill and Dessler [1985] have considered, from different points of view, the prospects for detection of non-thermal radio emission with the planetary radio astronomy (PRA) instrument on Voyager 2 as it approaches Uranus. To my knowledge, no such emission has been identified as of the date of this writing.

6. THE MAGNETOSPHERE OF NEPTUNE

As previously mentioned, Pioneer 10 has established the flow of the solar wind out to and beyond the orbit of Neptune. By Figure 1, an empirically reasonable guess for the magnetic moment of Neptune is 6×10^{27} gauss cm³ or 0.4 gauss a_N³ and the corresponding stand-off distance is some 32 planetary radii.

Relevant comments are as follows:

- (a) It seems probable that Neptune has a well developed magnetosphere.
- (b) The rotational axis of Neptune is inclined at only 29° to the pole of its orbital plane. Hence, its magnetosphere may be expected to be more nearly "normal" than that of Uranus, perhaps most nearly resembling that of Saturn, except for the apparent absence of dense rings and close satellites.
- (c) Of the two well-known satellites of Neptune—Triton and Nereid—only Triton is both close enough (14.6 planetary radii) and large enough (radius = 1750 km) to have a significant role in the planet's magnetosphere. But in contrast to Titan, Triton has, at most, a very tenuous atmosphere according to present evidence. (The tentatively identified satellite or partial ring, at ~ 3 planetary radii [Reitsema et al., 1982], may also qualify as an object of magnetospheric significance.)
- (d) Very energetic particles from the cosmic ray albedo neutron source may be expected to dominate the inner magnetosphere as they do at Saturn.
- (e) There is little prospect of substantial evidence on the magnetospheric properties of Neptune before the Voyager 2 encounter in August 1989.

7. CONCLUSION

Let me conclude by again recalling Frank McDonald's implicit admonition to be skeptical of any forecasts of magnetospheric properties, including those that I have just made.

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