ON THE MAGNETOSPHERES OF JUPITER, SATURN, AND URANUS

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ABSTRACT

Part A. JUPITER
A brief descriptive summary of Jupiter's magnetosphere is based on in situ observations with the spacecraft Pioneer 10 and Pioneer 11 in November-December 1973 and November-December 1974, respectively. Current interpretative work emphasizes particle acceleration and loss mechanisms, the determination of diffusion coefficients by satellite effects, the topology of the outer magnetosphere, the possible recirculation of energetic particles, and the controversial evidence for an extended magnetotail.

Part B. SATURN
Available evidence on non-thermal radio emissions of the planet and on the solar wind flow at 10 AU is invoked to suggest that Saturn very likely has a large, well developed magnetosphere resembling that of Jupiter but with the important difference that a radiation belt can not exist interior to the outer edge of the A ring of particulate matter. The first in situ observations will be made by Pioneer 11 in August-September 1979.

Part C. URANUS
In the context of present knowledge it is speculated that Uranus also has a large, well developed magnetosphere and one of unique interest during epochs when its rotational axis is approximately along the planet-sun line as in mid-1985. One of the two planned Mariner Jupiter Saturn missions may be targeted so as to fly by Uranus in 1986.

Part A. JUPITER

1. Introduction

The magnetosphere of Jupiter is one of the major physical phenomena of the solar system. In retrospect, its existence was presaged by the 1955 observations of sporadic bursts of radio noise from the planet

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at 22.2 MHz (Burke and Franklin 1955). But it was only following the discovery of the radiation belt of Earth and following the discovery of Jovian non-thermal radiation in the decimetric range that it was suggested (Drake and Hvatum 1959) that Jupiter has a radiation belt of magnetically trapped particles as does Earth, but with a much greater population of relativistic electrons.

Major advances in knowledge of the magnetic properties of the planet and of its magnetosphere have been made by a wide variety of observations on the fly-bys of the two instrumented spacecraft Pioneers 10 and 11 in late 1973 and late 1974, respectively, despite the limited spatial and temporal coverage that the fly-by technique provides. Reliable knowledge is now available on the absolute intensities, energy spectra, angular distributions, and spatial distributions of energetic protons and electrons in the external magnetic field of Jupiter. Fourteen comprehensive papers on this subject are contained in the book Jupiter (1976), based on the Tucson conference of May 1975. These papers, not cited individually, are basic references in the discussion that follows.

The magnetosphere of Earth, discovered by the author in 1958, is the prototypical planetary magnetosphere. It has been investigated extensively, both observationally and theoretically, and may be said to be "understood" in first order. The magnetosphere of Jupiter has a certain gross similarity to that of Earth but is quite different in important ways:

(a) Because the magnetic moment of Jupiter is 1.9×10^4 times that of Earth and because the number density of charged particles in the solar wind at 5 AU is 4 percent of that at 1 AU, the physical scale of the Jovian magnetosphere is greater by a factor of the order of 100. By the same token the intensities and characteristic energies of inward diffusing electrically charged particles in the planet's magnetic field are also much greater.

(b) At the same planetocentric distance as measured in the respective planetary radii the centrifugal force on a parcel of corotating plasma in the equatorial plane of Jupiter is 65 times as great as that at Earth. For this reason as well as for the reason that the quasi-thermal plasma in Jupiter's magnetosphere is much hotter than that in Earth's magnetosphere, the great equatorial magnetodisc of Jupiter has no terrestrial counterpart; rather, Jupiter's magnetosphere has a certain resemblance to a pulsar, though the magnitudes of characteristic parameters are very much different.

(c) The periodic emission of energetic particles from Jupiter's magnetosphere is a newly-found planetary phenomenon.

(d) Moon's orbit lies beyond the central magnetosphere of Earth and no lunar effect thereon has been shown to exist. In contrast, the three inner Galilean satellites and Amalthea have orbits within the central magnetosphere of Jupiter and produce massive effects on the population and distribution of energetic particles therein. Both particle sweeping and particle accelerating effects apparently exist. Conversely, the satellites are presumed to be subjected to intense particle bombardment with consequent sputtering, outgassing, X-ray and neutron emissions, and a wide variety of plasma physical effects.

(e) The solar wind flow past Jupiter is thought to be fundamental to the formation of its magnetosphere in at least two senses: the creation of an axially asymmetric situation and the application of a motional electromotive force of the order of 1×10^7 volts. However, the power to drive magnetospheric processes and supply the losses may possibly be derived from the rotational energy of the planet (Gold 1976) and from the orbital energy of the inner satellites rather than from the solar wind.

(f) The energetic particles in the terrestrial radiation belts come from the solar wind and the earth's ionosphere -- in an unknown relative proportion but probably mostly from the solar wind. There is some reason to think that the relative importance of the respective sources may be inverted at Jupiter. In addition, acceleration of ambient particles by motional electric fields associated with the inner satellites (particularly Io) may be important.

(g) Corotation in Earth's magnetosphere occurs only within a radial distance of $\approx 4\ R_E$ but in Jupiter's magnetosphere out to the magnetopause at $\approx 65\ R_J$.

In addition to the basic planetological significance of the magnetospheres of Earth and Jupiter, they provide accessible examples of plasma-physical systems on a huge scale. Hence their study has broad astrophysical significance in understanding the quite pervasive phenomenon of the acceleration of charged particles elsewhere in the universe.

2. Current Studies

A reliable, though incomplete, descriptive knowledge of Jupiter's magnetosphere has been obtained by Pioneers 10 and 11. Absolute intensities and crude energy spectra, angular distributions, and spatial distributions of energetic protons and electrons have been observed along the respective fly-by trajectories of the two spacecraft during two brief epochs separated by one year. The corresponding magnetic field measurements form the basis for models of internal planetary current systems and for models of external current systems.

Improvements in all of the measurements are, of course, desirable. Perhaps the principal shortcoming of the existing body of data is the complete absence of observations to large radial distances on the dusk and midnight sides of the planet. Nonetheless a great deal of fruitful

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interpretative work is in progress as sketched in the following sections.

3. General Nature of the Data

Figures 1 and 2 show the encounter trajectory of Pioneer 11 with Jupiter. The hyperbolic encounter trajectory was retrograde in a plane inclined at 51°.8 to the planet's equatorial plane and had periapsis at 1.60 R_J (1 R_J = 71,372 km, the adopted value of the equatorial radius of the planet).

As an example of observed data, Figure 3 shows corrected values of counting rates of five of the University of Iowa detectors on Pioneer 11 as a function of time during traversal of the central magnetosphere. An abridged summary of the characteristics of the several detectors is given in Table I. The intensities of the higher

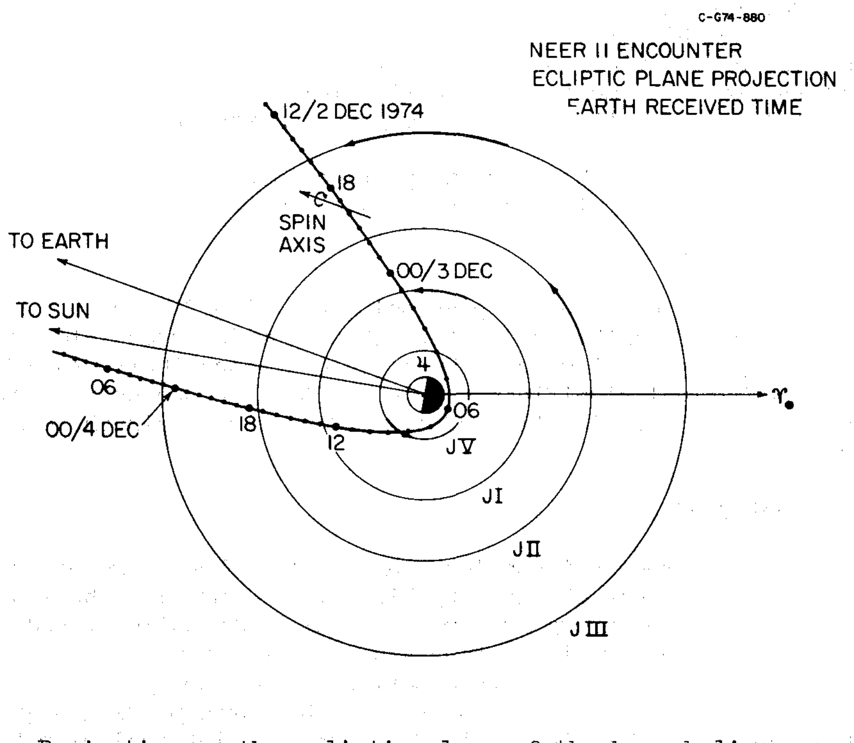

Fig. 1. Projection on the ecliptic plane of the hyperbolic encounter trajectory of Pioneer 11 with Jupiter and the orbits of the four inner satellites. The view is from the north ecliptic pole. Dots on the trajectory at one-hour intervals show the positions of the spacecraft when the data received on Earth at the labeled times were being taken. The heavy arc with an arrow on each satellite orbit represents the motion of that satellite between inbound and outbound crossings of its L-shell by the spacecraft. $\gamma_{\oplus}$ is the vernal equinox of Earth.

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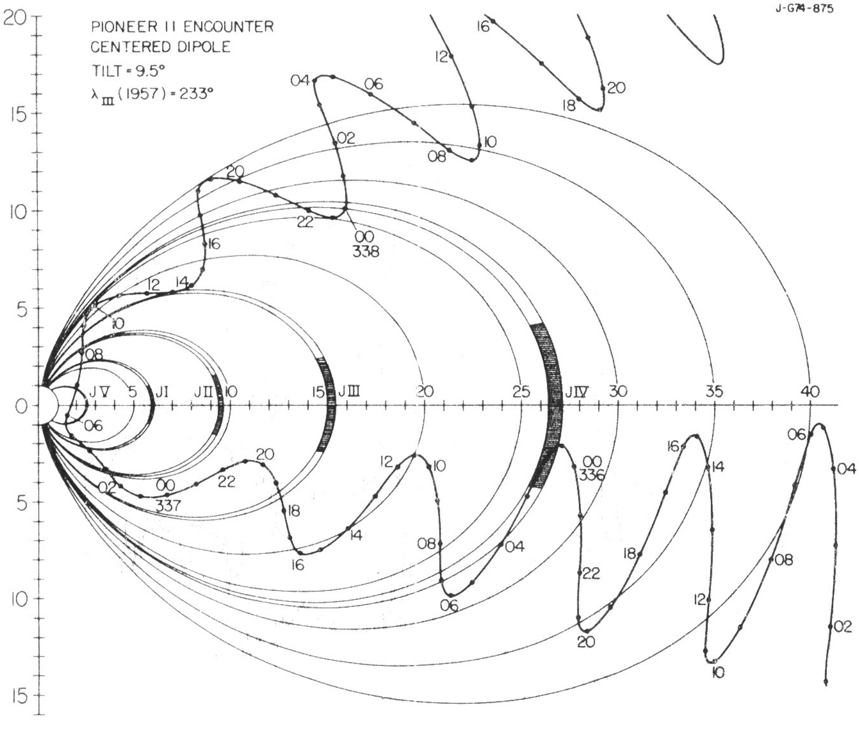

Fig. 2. Time-labeled trace of Pioneer 11's encounter trajectory on a magnetic meridian plane through the spacecraft. The assumed Jovian dipolar model is specified. The cross-hatching shows the regions that bound the orbits of JV (Amalthea), JI (Io), JII (Europa), JIII (Ganymede), and JIV (Callisto) in this coordinate system. The time is "Earth Received Time" as in Figure 1.

energy electrons (C and D) have a relatively smooth dependence on position but the intensity curves for lower energy electrons (A and B) and protons (G) are much more complex. Prominent in the latter three curves are the sweeping effect of the satellite Io and, in A and B, the prominent spike of low energy electrons associated with the inbound transit of Io's magnetic shell. This spike is thought to represent accelerative effects of the satellite, possibly by the Gurnett process (Gurnett 1972; Shawhan et al. 1973; Hubbard et al. 1974; and Shawhan et al. 1975). It is also clear from Figures 2 and 3 that the energy spectrum of electrons in the inner magnetosphere (magnetic shell parameter $L < 6$) is notably deficient in electrons with energy $E_e < 5$ MeV compared to spectra for $L > 10$. This spectral change appears to be attributable to the fact that Io sweeps out (i.e., absorbs

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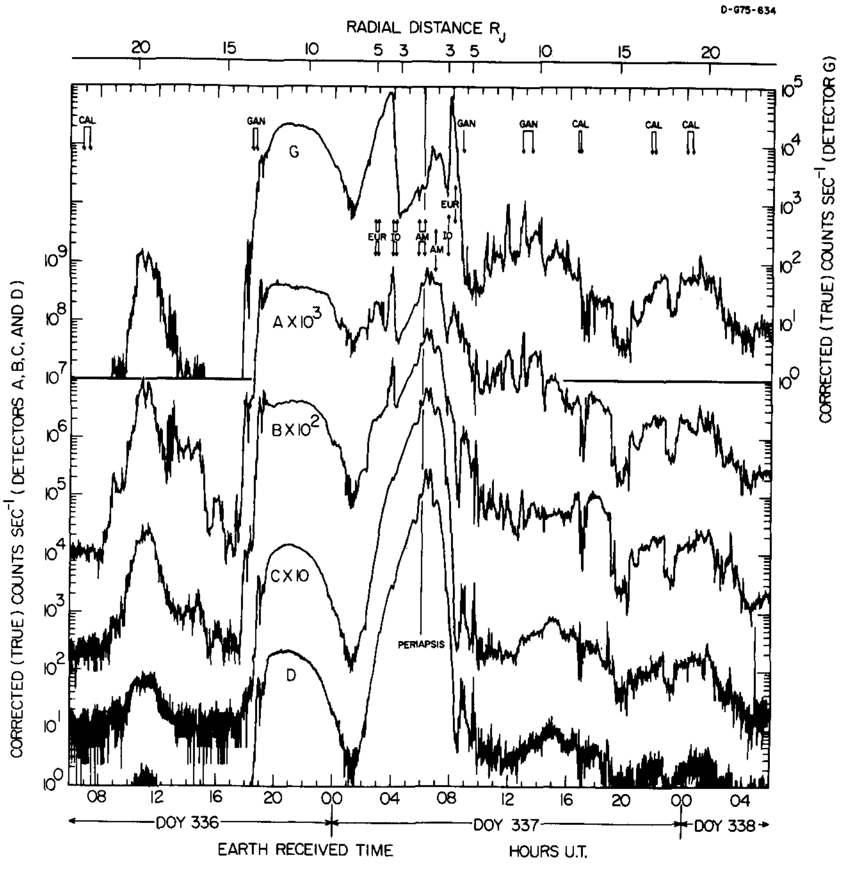

Fig. 3. Time dependence of the corrected, spin averaged counting rates of five particle detectors (cf. Table I) during a portion of the encounter with Jupiter. The times of traversal of nominal dipolar magnetic shells of the five inner satellites are shown by vertical arrows. These times may be appreciably in error for JII, JIII, and especially JIV by virtue of distortion of the magnetic field from dipolar form. DOY means day of year. The year is 1974.

or scatters into the loss cone) the lower energy electrons much more effectively than the higher energy ones. The trend of the curves in Figure 3 suggests that, if this sweeping effect were absent, the intensities of electrons $E_e < 5$ MeV in the inner magnetosphere would be greater by a factor of 10 to 100 than is the case. The result would be a marked increase in decimetric radio emission and a shift of emission toward longer wavelengths. Also it appears that the

Table I

Abridged Summary of Characteristics of
University of Iowa Detectors on Pioneer 11

Detector[1]	Energy Range, MeV		Inverse Omnidirectional Geometric Factor[2], (1/Q) in cm^{-2}	
	Electrons	Protons	Electrons	Protons
G	[3]	$0.61 < E_p < 3.41$	---	310
A-C	$0.040 < E_e < 21$	[4]	740	---
B-C	$0.56 < E_e < 21$	[4]	830	---
C	$E_e > 21$	[4]	23	---
D	$E_e > 31$	[4]	63	---

Notes:

[1] G is a thin solid state detector. A, B, C, and D are miniature Geiger-Mueller tubes. A, B, and G have directional collimators with axes perpendicular to the spin axis of the spacecraft. C and D are omnidirectionally shielded.

[2] The absolute omnidirectional intensity J in $(cm^2\ sec)^{-1}$ is found by multiplying 1/Q by the spin averaged counting rate (or difference in counting rates) of the respective detectors in the left column, e.g., if (A-C) = $10^4\ sec^{-1}$, $J = 7.4 \times 10^6\ (cm^2\ sec)^{-1}$ for electrons $0.040 < E_e < 21$ MeV.

[3] Insensitive to electrons of any energy.

[4] The response of these detectors in the Jovian magnetosphere is found to be attributable almost entirely to electrons.

intensities of protons $E_p \approx 1$ MeV would be greater by a factor of 100 to 1000 if Io were absent.

4. Distribution of High Energy Electrons and Inferences Therefrom

Figure 4 shows composite, iso-counting rate contours of the counting rates of detectors C ($E_e > 21$ MeV) on Pioneers 10 and 11 and Figure 5 shows the equatorial section through the contour plot. Similar plots have been made for detectors D ($E_e > 31$ MeV). The equatorial angular distributions of energetic electrons can be inferred (Van Allen et al. 1975) from Figure 4 and from the corresponding figure for detector D. Sentman et al. (1976) have used a generalized relativistic form of the Kennel-Petschek (1966) theory of the whistler mode instability to infer the number density of quasi-thermal plasma in the inner magnetosphere from such angular distributions. Their preliminary values are compared with the directly measured values of Frank et al. (1976) in Figure 6. The reasonably close agreement of these curves is taken to establish the whistler mode instability as an important and perhaps dominant mechanism for electron pitch angle scattering in the inner magnetosphere.

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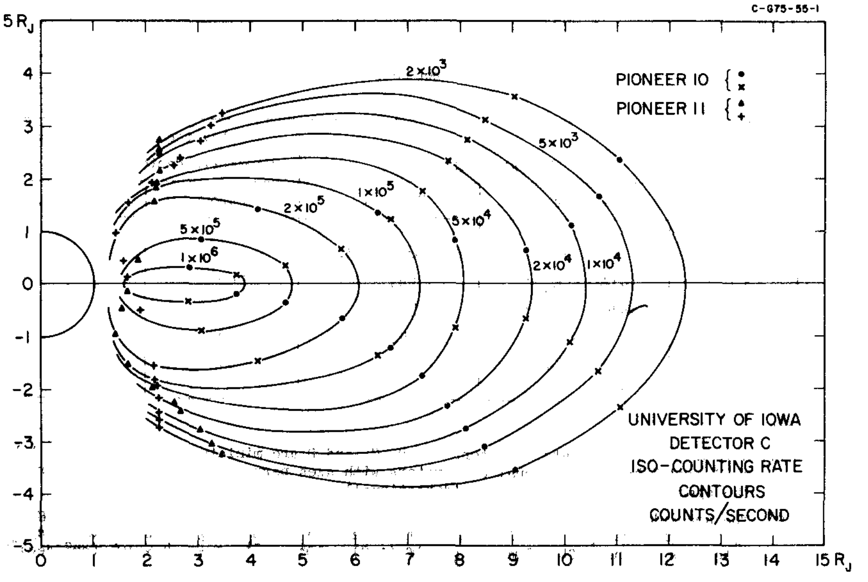

Fig. 4. Iso-counting-rate contours for energetic electron detector C. Absolute omnidirectional intensities of electrons $E_e > 21$ MeV in $(cm^2\ sec)^{-1}$ are found by multiplying the counting rates by 23. The figure shows combined observations from the Pioneer 10 and Pioneer 11 encounters based on use of a centered dipole model with a tilt of 9°.5 toward System III (1957.0) longitudes of 230° and 233°, respectively. Circles and triangles are observed points for Pioneer 10 and Pioneer 11, respectively; multiplication signs and addition signs are corresponding reflections in the magnetic equatorial plane.

5. Diffusion Coefficients

The sweeping (physical absorption) effects of the satellites (particularly Io and Europa) provide, potentially, a powerful basis for determining diffusion coefficients of electrons and protons separately and as a function of energy and magnetic shell parameter L.

For example, the marked but incomplete sweeping effect of Io shows that protons of energy $E_p \approx 1$ MeV diffuse inward by the diameter of the satellite in a time comparable to but several fold greater than the 13-hour synodic corotational period. Thus a very crude estimate of the apparent diffusion coefficient D for such protons at L = 6 is

$$D \approx \frac{(3.6 \times 10^8\ \text{cm})^2}{(1.5 \times 10^5\ \text{sec})} \approx 8.6 \times 10^{11}\ \text{cm}^2\ \text{sec}^{-1}$$

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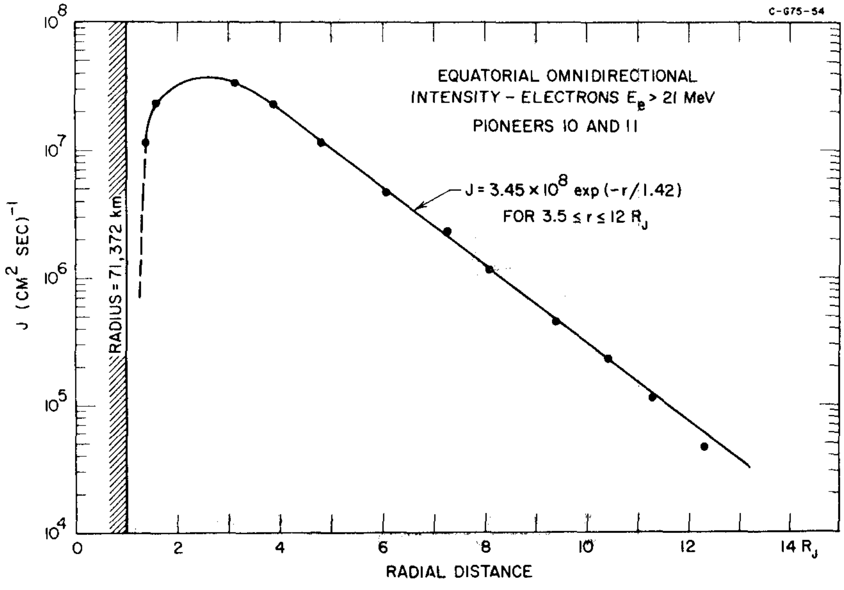

Fig. 5. An equatorial profile through the contours of Figure 4.

or $D \approx 1.7 \times 10^{-8}\ R_J^2\ \mathrm{sec}^{-1}$.

For electrons of energy $E_e \approx 0.5$ MeV, the apparent value of D is an order of magnitude greater whereas for electrons of energy $E_e \approx 20$ MeV it is two orders of magnitude greater at this L value.

A considerably more refined study of this matter and a critical review of the present state of the subject are given by Thomsen and Goertz (1976). Definitive results on the important matter of the L-dependence of D do not yet exist.

6. The Magnetodisc

One of the most striking observations on the outbound pass of Pioneer 10 through the dawn-side magnetosphere was the 10-hour modulation of particle intensities as shown in Figure 7.

This effect was interpreted on geometric and simple physical grounds by Van Allen et al. (1974b) to imply that the outer magnetosphere is a spun-out, rigid, planar "magnetodisc" in the magnetic equatorial plane of the planet (at least on the dawn side) (Figure 8). A rather similar but bent disc model was favored by the magnetometer experimenters (Smith et al. 1974). However, the bent disc model is inconsistent with geometric requirements and with the magnetic data

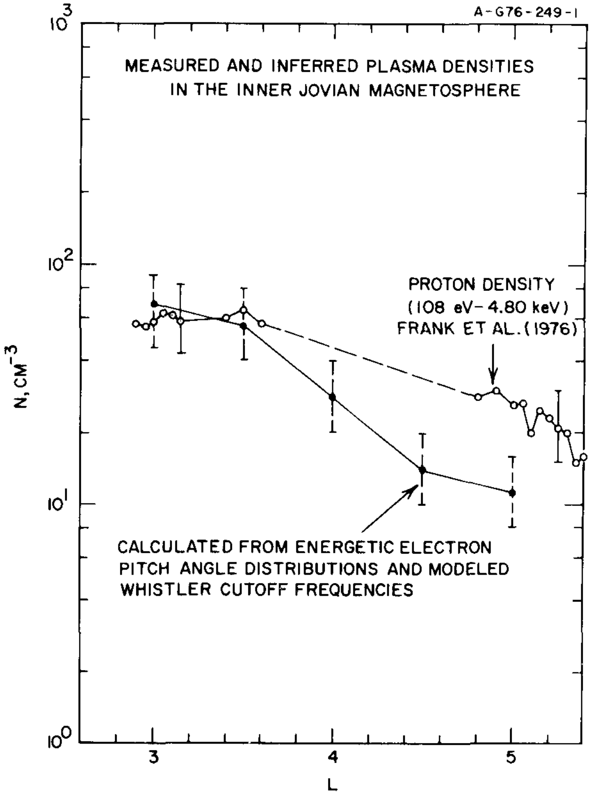

Fig. 6. Comparison of the L-dependence of measured and inferred values of quasi-thermal plasma density in the inner Jovian magnetosphere, near the equatorial plane (see text).

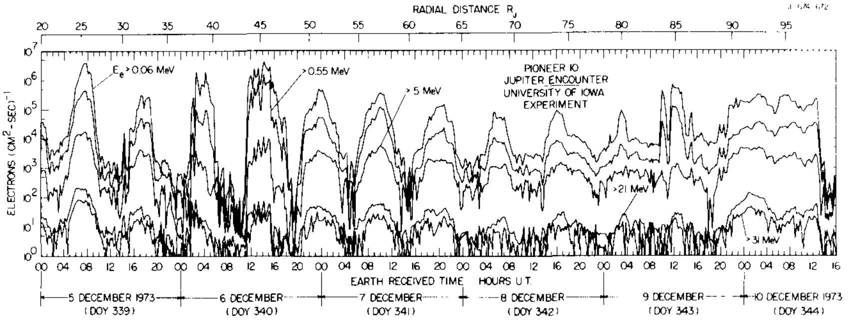

Fig. 7. Time dependences of the omnidirectional intensities of electrons in five different energy ranges during the Pioneer 10 outbound traversal of the outer magnetosphere on the dawn side of the planet.

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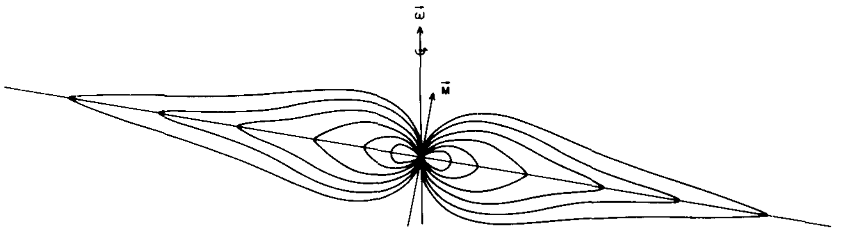

DISC MODEL OF JUPITER'S MAGNETOSPHERE

Fig. 8. Schematic drawing of the magnetodisc model of the outer magnetosphere of Jupiter, showing topology of the magnetic field and the region of trapped energetic particles. The outer tip of the sketch is at $\approx 100\ R_J$. The planet's rotational axis is denoted by $\vec{\omega}$ and its magnetic axis by $\vec{M}$.

themselves as well as with physical properties of a plasma sheet (Goertz 1976; Goertz et al. 1976). Both Pioneer 10 and Pioneer 11 data show that the disc is much blunted (i.e., more extended in latitude and less extended in radial distance) on the sunward side, presumably by solar wind pressure. There is no information on its form in the dawn to midnight to dusk sector.

7. Recirculation of Energetic Particles

A recent finding of importance is that both electrons and protons stream away from the planet at high latitudes (invariant latitudes $\Lambda \gtrsim 75°$) from both hemispheres. This result coupled

(a) with the hypothesis of Nishida (1976) on trans-L diffusion of particles at low altitudes with little change in energy,

(b) with observed angular distributions in the equatorial plane (Sentman and Van Allen 1976), and

(c) with the expectation that particles have a high probability of pitch angle scattering and thus of a stochastic increase in their first adiabatic invariant upon crossing the very weak magnetic field in the equatorial neutral sheet

has led Sentman et al. (1975) to suggest recirculation of energetic particles as a significant feature of the Jovian magnetosphere. This suggestion is illustrated schematically in Figure 9. The recirculation process, if in fact true, provides a plausible explanation for the observed presence of high energy electrons ($E_e \gtrsim 1$ MeV) in the outer fringes of the magnetosphere and for the puzzlingly high

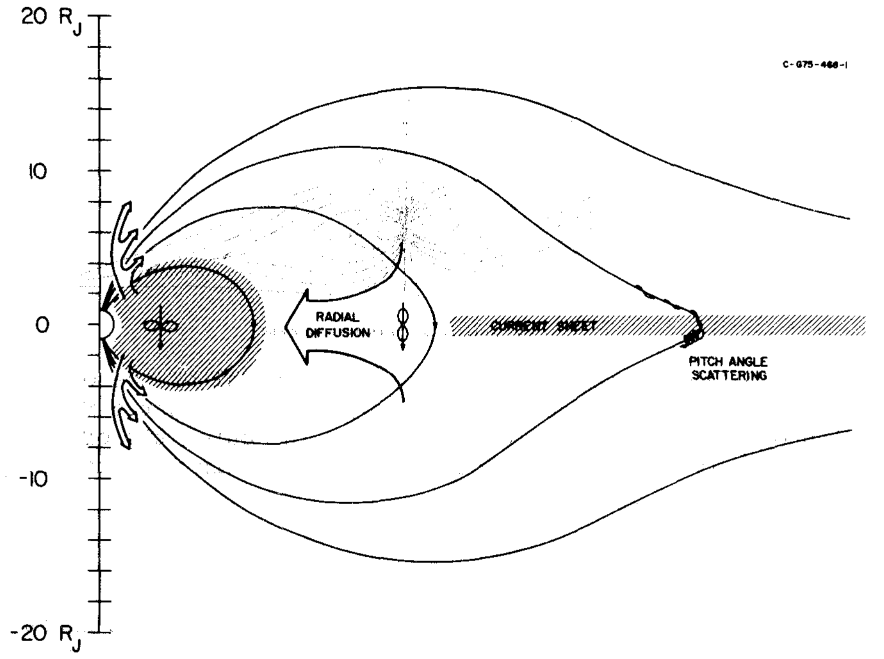

Fig. 9. A schematic magnetic meridian cross section of the Jovian magnetosphere illustrating the recirculation of energetic particles therein. The special features of this model are trans-L shell diffusion at high latitudes near the planet with little change in energy and pitch angle scattering in the equatorial neutral sheet.

values of magnetic moment ($\mu \geqslant 10^4$ MeV/gauss) of electrons in the inner magnetosphere. These facts appear to be incompatible with the capture of thermalized solar wind particles at the magnetopause and their subsequent inward diffusion with μ = constant, as does the persistent "dumbbell" form of angular distributions of electrons in the intermediate region of the magnetosphere $12 < r < 25\ R_J$.

8. Magnetotail

It was noted by Van Allen et al. (1974a) soon after the Pioneer 10 encounter that the spacecraft would cross a region of space possibly containing an extended magnetotail of Jupiter in March-April 1976 at a downstream distance of ≈ 4.5 AU (Figure 10). This crossing occurred recently. Wolfe et al. (1976) have reported that the number density of the solar wind dropped by a factor > 10 (i.e., below the background of their plasma analyzer) for about a 24-hour period on DOY (Day of Year) 79 and again on DOY 103 of 1976, reminiscent of the

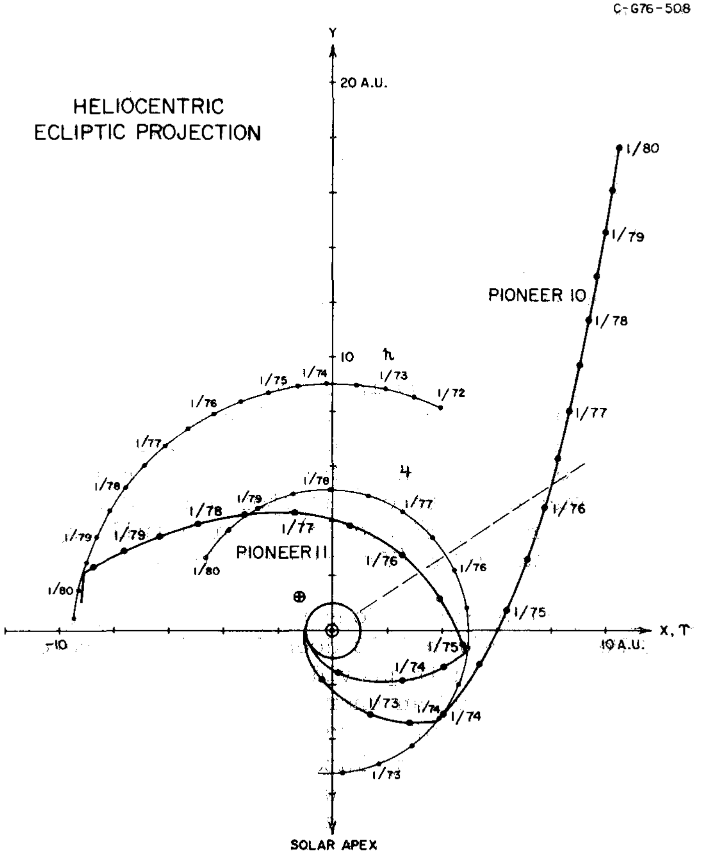

Fig. 10. Ecliptic plane projections of the trajectories of Pioneers 10 and 11 and of the orbits of Earth, Jupiter, and Saturn in a heliocentric inertial coordinate system. The kinks in the respective trajectories occurred at the times of encounter with Jupiter. Dots are at six months intervals, e.g., 1 January 1975, 1 July 1975, 1 January 1976, etc. The dashed radial line in the first quadrant shows the condition in March 1976 during which Pioneer 10 and Jupiter had the same heliocentric ecliptic longitude. Note that Pioneer 11 will encounter Saturn on 1 September 1979.

effect observed in crossing the magnetotail of the earth at a downstream distance of ≈ 1000 R_E (Ness et al. 1967; Wolfe et al. 1967). They have not previously observed such an effect in the interplanetary medium and have interpreted it tentatively to mean that the magnetotail of Jupiter extends at least 9400 R_J downstream and was bent transiently upward so as to engulf the spacecraft. There is no confirmation of the detailed nature of the corresponding magnetic field signature because of previous failure of the Pioneer 10 magnetometer. On DOY 67, the heliocentric ecliptic longitudes of Pioneer 10 and Jupiter were the same (Figure 10) and the heliocentric ecliptic latitude of Pioneer 10 was 3°.96 greater than that of Jupiter. The perpendicular distance from Pioneer 10 to the Sun-Jupiter line had a minimum value of 1364 R_J on DOY 62; at this time the Jupiter-Pioneer 10 distance was 9400 R_J. When aberration of the solar wind is taken into proper account, the date of the foregoing minimum perpendicular distance is shifted to about DOY 81, with other parameters only slightly affected.

On neither DOY 79 nor DOY 103 is there any discernible increase in the counting rates of any particle detector in the University of Iowa instrument on Pioneer 10. In absolute terms, the average unidirectional intensity of electrons $E_e > 60$ keV required to produce a 3 σ increase in the counting rate of detector G is 70 (cm^2 sec sr)$^{-1}$ for a half-hour period or 25 (cm^2 sec sr)$^{-1}$ for a full day's observation, using observed values of σ (Van Allen 1976a).

The foregoing negative result does not, of course, contradict the interpretation of Wolfe et al. but it does introduce a note of skepticism. Additional skepticism is provided by the University of Iowa observations with Pioneer 11 of an energetic proton event of extraordinarily high intensity (and of probable interplanetary origin) on DOY's 51-56, with maximum intensity late on DOY 52. This is the most intense interplanetary event observed with Pioneer 11 since DOY 254 of 1973 and the third most intense since launch. Another intense event occurred on DOY's 77-79, about 26 days later, with a maximum on DOY 78. These two events suggest unusually great disturbances in the solar wind at 3.7 AU and precede by the expected corotation and radial propagation times the respective plasma density drop-outs observed by Pioneer 10 at 9.7 AU. There is no University of Iowa proton detector on Pioneer 10 by which a direct, homogeneous comparison could have been made.

If no further drop-outs of solar wind density occur during, say, the next six months it will be reasonable to attribute the two already observed to the magnetotail of Jupiter. But if such episodes recur when Pioneer 10 is quite remote from the sun-planet line, it will appear most likely that they are interplanetary in nature with no relationship to Jupiter.

Part B. SATURN

1. Introduction

By virtue of Saturn's large size (equatorial radius = 60,000 km = 1 R_S) and its rapid and latitude-dependent rotational rate (rotational period increases from $10^h\ 2^m$ at the equator to $11^h\ 8^m$ at 57° latitude) (Newburn and Gulkis 1973) and perhaps by analogy to Jupiter, it has long been thought likely that Saturn is a strongly magnetized body. Also, Pioneer 10 measurements have established that orderly flow of the solar wind continues to and beyond 10 AU. Hence, it is likely that Saturn has a fully developed magnetosphere of dimensions comparable to those of the magnetosphere of Jupiter.

An important difference is that the particulate rings of Saturn must preclude a population of magnetically trapped energetic particles on magnetic shells interior to the one passing through the outer edge of the A ring ($L = 2.3$), thus greatly diminishing the potential for synchrotron radiation. This is seen as follows.

If the magnetic equatorial plane of the planet is coincident with the ring plane, a trapped particle will pass through the ring plane twice for each latitudinal oscillation. The latitudinal oscillation period τ is (to within $\pm$ 38%) given by

$$\tau = \frac{4\ r_o}{v}$$

(Hamlin et al. 1961), where r_o is the equatorial crossing radius of the pertinent dipolar line of force and v is the particle's rectilinear velocity. For $r_o = 2\ R_S = 1.2 \times 10^{10}$ cm and for a 1.0 MeV electron ($v = 2.8 \times 10^{10}$ cm/sec), $\tau = 1.7$ sec. The optical opacity of the A and B rings is of the order of 0.5. Hence, a 1 MeV electron has a lifetime of the order of one second on lines of force passing through the A and B rings.

If the magnetic equatorial plane is tilted substantially to the ring plane, particles having equatorial pitch angles of about 90° pass through the ring plane only near the two nodes and hence have a lifetime of the order of half of the corotation period, or about 6 hours, a value less than the lifetime against all other loss processes by at least two orders of magnitude. Radially-thin radiation belts of low intensity may possibly exist within Cassini's division, and interior to the inner edge of the C (crape) ring by virtue of trans-L diffusion of particles at high latitudes. There is, however, evidence for a D ring (Guérin 1973; Coupinot 1973) of low opacity inside the C ring as well as for a D-prime ring of very low opacity external to the A ring (Feibelman 1967). If the opacity of the D-prime ring is as small as 10^{-6}, then the particle lifetime is only a few days. Thus even a very sparsely populated ring will have a dramatic effect on the nature of the inner magnetosphere of Saturn. Figure 11 gives a schematic idea of the expected intensity of energetic particles as a function of radius in the Saturnian magnetosphere.

There is no radio observational evidence against the existence of a high intensity radiation belt at Saturn. The matter has been studied parametrically by Luthey (1973). Figure 12 from his paper

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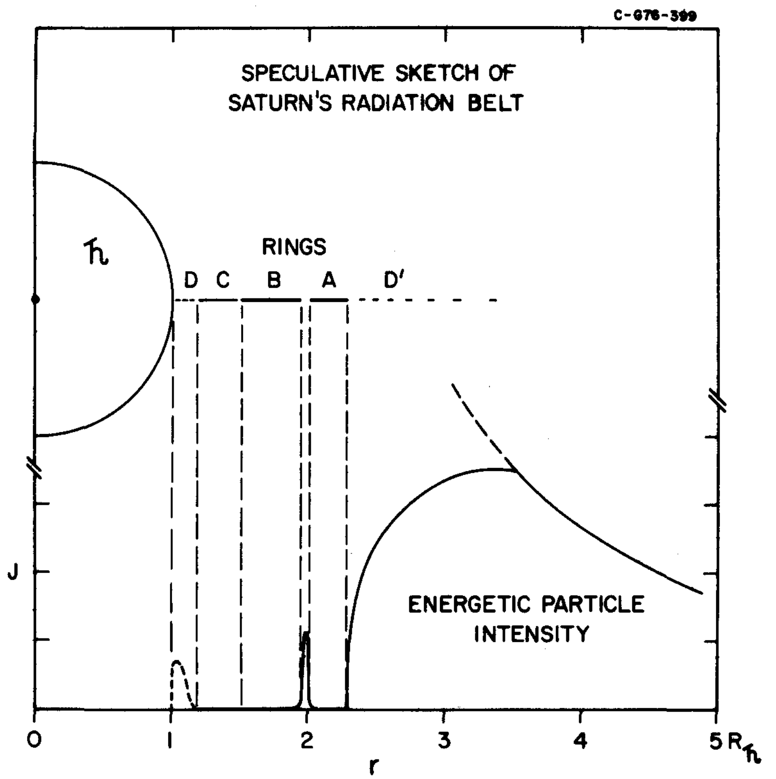

Fig. 11. The upper part of the diagram is a scale drawing of a meridian cross section of Saturn and its D, C, B, A, and D-prime rings of particulate matter. The lower part is a speculative sketch of the radial dependence of the intensity of energetic particles in its magnetosphere. The nature of the curve for $r > 2.3\ R_S$ is a sensitive measure of the opacity of the D-prime ring.

illustrates a sample possibility. Confirmation or denial of its existence by ground-based techniques requires measurements of flux, polarization, and spatial distribution of the source at wavelengths greater than 100 cm, a very difficult undertaking. The first opportunity for in situ measurements at Saturn will be the fly-by of Pioneer 11 (Figure 10) with closest approach to the planet on 1 September 1979.

2. Hectometric Radio Emission

The most important information on the magnetosphere of Saturn comes from Brown's (1975a) 1971-72 observations of sporadic bursts of

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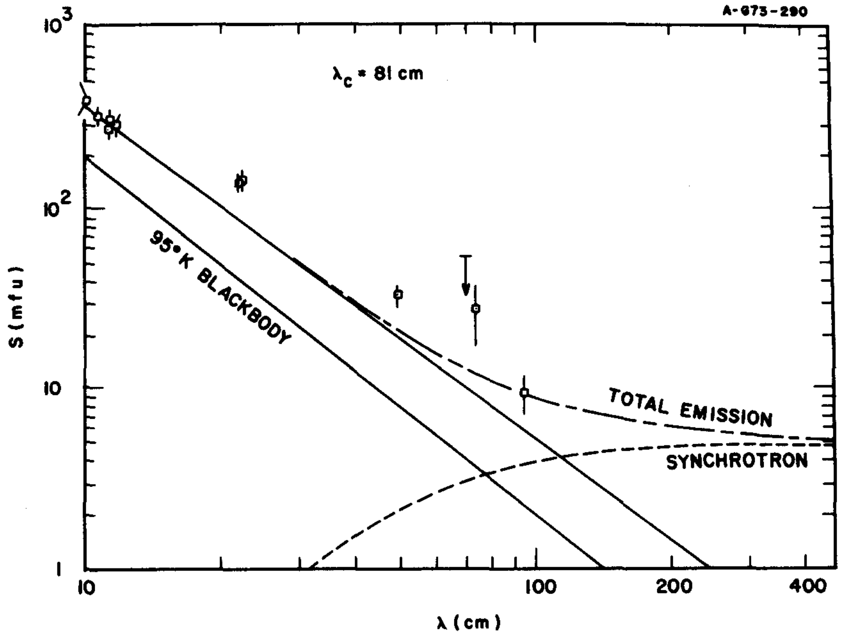

Fig. 12. Observed values of radio spectral power flux from Saturn and an illustrative example of the synchrotron contribution from a hypothetical radiation belt of relativistic electrons (Luthey 1973). 1 milliflux unit (mfu) = 10^{-29} watts m^{-2} Hz^{-1}. The adopted distance is 8.0 AU.

hectometric radio noise from the planet. These bursts are reminiscent of decametric bursts from Jupiter (Warwick 1967; Carr and Gulkis 1969) and kilometric bursts from Earth (Gurnett 1974, 1976; Kaiser and Stone 1975). The spectra in the three cases are of broadly similar shape, with frequency of maximum intensity and upper cutoff frequency, respectively, as follows: Earth 0.2, 1.7; Saturn 1.1, 4.0; Jupiter 8, 40 MHz.

For many years the upper cutoff frequency of the Jovian decametric spectrum has been interpreted to be equal to the electron gyrofrequency on an auroral zone field line, probably at the surface of the planet. The suggested value of magnetic field strength there was about 15 gauss, a value which has been confirmed as remarkably accurate by direct magnetometer measurements on Pioneer 10 and Pioneer 11 (Smith et al. 1975; Acuna and Ness 1976). The more recently discovered terrestrial (or auroral) kilometric radiation is conclusively identified (Gurnett 1974) with active aurorae ($L \approx 7$) and the upper cutoff frequency is approximately equal to the electron gyrofrequency at 1 R_E at auroral latitude. A presumptive application of the same interpretation to the Saturnian data yields an estimate of the magnetic moment of Saturn, namely 1.6×10^{29} gauss cm^3, about 0.1 of that of Jupiter.

It should be noted that a dipolar line of force corresponding to $L \approx 7$ crosses the ring plane far outside of any known or suspected ring of orbiting, particulate material.

3. Concluding Remarks

The six inner satellites of Saturn are in near-circular orbits of inclination less than 1°5 to the equatorial plane of the primary. The radii of their orbits are 2.66, 3.10, 3.97, 4.92, 6.28, and 8.78 R_S, and the estimated radii of their bodies are 110, 200, 250, 500, 575, and 800 km (Morrison and Cruikshank 1974). Although rather small, they may have effects of significance on the magnetosphere of the planet. Titan, the next in order, has a radius of 2500 km and an appreciably eccentric orbit of inclination 0°3 and of semi-major axis 20.37 R_S. It is the only one of the ten known satellites whose size is similar to that of the four Galilean satellites but its orbit probably lies outside of the inner, well ordered magnetosphere as does Callisto at Jupiter. Hence, its effect may be weak or undetectable. Finally, the three outermost satellites are both small and remote.

By direct plasma analyzer measurements with Pioneer 10 (Wolfe et al. 1976) it is now known that the solar wind flow continues in a relatively smooth and orderly manner to beyond a heliocentric distance of 10 AU, i.e., beyond the orbit of Saturn. This fact coupled with the planetary magnetic moment estimated above makes it virtually certain that Saturn has a large, well developed magnetosphere, except inside of $L \approx 3$ (Figure 11). It is reasonable to expect a magnetodisc configuration, as at Jupiter. The number density of ions in the ionosphere is probably much less than at Jupiter because of the four-fold reduction in solar ultraviolet intensity and a much reduced bombardment by energetic particles. Hence, the number density of ions in the plasma sheet will probably be correspondingly less and the magnetodisc less prominent.

Part C. URANUS

1. Radio Evidence

Measured disc temperatures of Uranus in the wavelength range 0.33 to 11.3 cm lie between (105 ± 13) °K and (212 ± 17) °K, whereas the measured infrared temperature at 20 microns is (55 ± 3) °K. There is a reasonably convincing increase in radio brightness temperature from 0.33 to about 2 cm but no clear trend from 2 to 11 cm. The foregoing observations are generally considered attributable "to thermal emission by an atmosphere whose opacity is wavelength-dependent" (Newburn and Gulkis 1973).

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If Uranus were endowed with the Jovian magnetic moment and the Jovian radiation belt of relativistic electrons and if the synchrotron radiation therefrom were attributed to the disc of Uranus, its brightness temperature at 11 cm would be 6000 °K. The observed value at 11 cm is (160 ± 40) °K, insignificantly different from that at 2 cm. Hence, a Uranian radiation belt of relativistic electrons must be less effective than that of Jupiter as a radiator of synchrotron noise by a factor of the order of 200 or greater. However, no existing observational data exclude a Uranian radiation belt comparable to that of Earth (Kavanagh 1975).

On the positive side, Brown (1975b) has found tentative evidence for sporadic bursts of radio noise from Uranus near 0.5 MHz with an upper frequency cutoff at about 0.7 MHz. If such emission is firmly established, it will imply, as discussed in Part B, a magnetic moment $M_U \approx 2 \times 10^{27}$ gauss cm^3.

2. Magnetic Moment

Table II summarizes the current state of knowledge of the magnetic moments of seven planetary bodies. All entries except those for Saturn and Uranus are derived from in situ observation.

Broadly speaking 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 electrical currents in an electrically conductive interior, such currents being driven by self-excited dynamo electromotive forces generated by 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 electrical currents induced in the conducting ionosphere of the planet by fluctuating magnetic fields in the solar wind and/or driven by the unipolar induction electric field caused by the relative motion of magnetic fields in the solar wind as these fields are convected past the planet. In the latter case the electrical circuit is closed through the conductive interplanetary medium.

(e) Electromagnetism similar to type (d), but with return currents in conducting portions of the planetary body itself.

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Table II

Angular Momenta and Magnetic Moments of Ten Planetary Bodies

	$I\omega$ Rotational Angular Momentum (1) (2)	M Magnetic Moment	$\frac{I\omega}{M} \times 10^{-15}$
	gm cm^2 sec^{-1}	gauss cm^3	gm (sec cm gauss)$^{-1}$
Mercury	9.60×10^{36}	5.1×10^{22} (3)	0.19
Venus	1.82×10^{38}	$< 8 \times 10^{21}$ (4)(5)(6)	> 23.0
Earth	5.86×10^{40}	7.98×10^{25} (1)	0.734
Mars	1.98×10^{39}	2.4×10^{22} (7)(8)(9)	83.0
Jupiter	4.28×10^{45}	1.54×10^{30} (10)(11)	2.8
Saturn	7.71×10^{44}	(1.6×10^{29})	(4.8)
Uranus	1.94×10^{43}	(2×10^{27})	(9.7)
Neptune	2.08×10^{43}	--	--
Pluto	$\approx 4.7 \times 10^{38}$	--	--
Moon	2.34×10^{36}	$< 4 \times 10^{20}$ (12)(13)	> 5.9

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Most of the interior volumes of all of the bodies in Table II (with the possible exception of the Moon) are thought to be at temperatures above the Curie temperature of ferromagnetic materials (≈ 1000 °K); hence, remanent ferromagnetism, if any, must be confined to the outer mantles of the bodies. For large, rotating planets having fluid interiors, there is no theory of type (b) magnetism which proceeds from first principles to a confident prediction of the gross magnetic moment of the planet. Nonetheless, it is noted from Table II that the ratios of the rotational angular momenta $I\omega$ to the magnetic moments M for Earth, Jupiter, and Saturn satisfy the following inequality:

$$0.7 < \left(\frac{I\omega}{M} \times 10^{-15} \right) < 4.8 .$$

Evidence for an approximate constancy of the $I\omega/M$ ratio for astronomical bodies was noted by Blackett (1947, 1949) many years ago. He suggested that this ratio might be a fundamental property of matter but later showed by laboratory experiments that this is not the case (Blackett 1952). Also Runcorn et al. (1951) found the suggestion to not apply to Earth, by experiments in deep mines. The lack of validity of the Blackett hypothesis as applied to planetary bodies was noted by Van Allen et al. (1965) on the basis of the measured upper limits on the moments of Mars and Venus (Table II).

The "safe" point-of-view is that the magnetic moment of Uranus is totally unknown.

Nonetheless, empirical evidence gives some support to the rule-of-thumb that $I\omega/M \approx 3 \times 10^{15}$ gm (sec cm gauss)$^{-1}$ for "sufficiently large bodies that are rotating sufficiently rapidly". In this crude framework, Venus may be characterized as being large enough but not rotating rapidly enough (244.3 day sidereal period); Mars, as rotating rapidly enough ($24^h\ 37^m$) but not being large enough; and the Moon and Mercury, as meeting neither criterion. Saturn, Uranus, and Neptune have rotational periods intermediate between those of Jupiter and Earth and also have sizes, gross compositions, and internal pressures intermediate between those of Jupiter and Earth.

In the spirit of the foregoing discussion and giving tentative credibility to Brown's new observations, one may suggest, under peril of being quite wrong, that the magnetic moment of Uranus is $\approx 2 \times 10^{27}$ gauss cm^3 and the surface equatorial field is 0.12 gauss. Even if this conjectured value is too high by a factor of 100, there will very likely be magnetospheric phenomena at Uranus of high interest.

3. Solar Wind at the Orbit of Uranus

The properties of the solar wind have been measured over the heliocentric distance range 0.31 AU (Helios) to over 10 AU (Pioneer 10). Near the sun the solar wind velocity is strongly variable (150-1000 km sec^{-1}) with an identifiable relationship of high velocity and low velocity regimes to specific regions on the sun. With increasing radial distance, the range of variation diminishes but the mean value remains about the same, out to at least 5 AU (Collard and Wolfe 1974). This mean value is about 400 km sec^{-1}. A similar value of the mean velocity has been measured by Van Allen (1976b) out to 9 AU by time-lag analysis of the solar rotational modulation of cosmic ray intensity at Pioneer 10 and Pioneer 11. The mean number density of particles is approximately proportional to the inverse square of the distance, as it must be for constant velocity and spherically symmetric expansion. Also in the range 0.3 - 5.0 AU, the interplanetary magnetic field behaves in an essentially simple manner, with the magnitude of the radial component decreasing as the inverse square of the distance and that of the azimuthal component decreasing as the inverse first power (Smith 1974). The radial dependence of these gross parameters as well as that of the more detailed parameters of the solar wind give no empirical foundation for estimating the position of the outer boundary of the directed flow of the solar wind, sometimes called the heliopause. Van Allen (1976b) finds that the 11-year solar cycle modulation of the intensity of galactic cosmic radiation is by a factor of two at 1 AU and that, during the epoch 1972-76, the intensity increased with heliocentric radial distance by about 2 percent per AU, thus implying that the heliopause lies at or beyond about 50 AU. The most credible of current theoretical estimates (Axford 1973) suggests a similar value as the radial distance of the heliopause in the direction of the solar apex.

At the orbit of Uranus (19 AU) it is therefore "reasonable", though of course speculative, to adopt values of the gross parameters of the solar wind as in Table III.

It may be noted that Pioneer 10 has or will reach heliocentric radial distances R on the dates listed in Table IV.

The present state-of-health of Pioneer 10 and existing telecommunication capabilities suggest that there will be no technical problems in obtaining solar wind and cosmic ray observations to or beyond 20 AU, thus providing a progressively updated assessment of the validity or lack of validity of Table III.

4. Interaction of the Solar Wind with the Magnetic Field of Uranus

(a) If, despite the simple-minded basis for Table III, the radial flow of the solar wind ceases inside 19 AU, and if the planet is unmagnetized, there will be only very weak magnetospheric phenomena at Uranus.

(b) If the radial flow of the solar wind ceases inside 19 AU, but if the planet is magnetized, the physical situation will be that of a magnet rotating in a tenuous, nearly static plasma. Even in

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Table III

Adopted Solar Wind Parameters at the Orbit of Uranus

Velocity:	400 km sec^{-1}
Number Density of Protons and Electrons:	0.014 cm^{-3}
Radial Component of Magnetic Field:	0.012 γ
Azimuthal Component of Magnetic Field:	0.22 γ
Angle of Mean Magnetic Vector to Radius Vector:	93° (+ sector) 273° (- sector)

Table IV

Pioneer 10

R	Date
8 AU	25 August 1975
10	15 May 1976
12	23 January 1977
14	30 September 1977
16	7 June 1978
18	13 February 1979
20	24 October 1979

Asymptotic Value of dR/dt = 2.4 AU per Year

this case, however, there will be <u>some</u> relative velocity between the planet and the medium because of the 6.8 km sec^{-1} orbital velocity of the planet and the presumed 20 km sec^{-1} velocity of the solar system through the interstellar medium. By analogy with the best prevailing interpretation of the dynamics of the Jovian magnetosphere (Van Allen 1975; Gold 1976), this low relative velocity will probably be sufficient to establish a significant axial asymmetry in the topology of the outer magnetic field and thus make it possible for internal processes to develop a body of magnetospheric phenomena, with the necessary energy being drawn from the rotational energy of the planet.

(c) The standoff distance r of the magnetopause on the "windward" side of a planet having magnetic moment M is given by the magnetohydrodynamic stagnation condition

$$n m v^2 = M^2/2\pi r^6$$

where n, m, and v are the number density, mass, and directed velocity of protons in the plasma,

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or $$r = \left(\frac{M^2}{2\pi n m v^2} \right)^{1/6} .$$

Using the data of Table IV

$$r = 40.3\ M^{1/3}\ \text{cm}$$

or $$r/r_U = 1.64 \times 10^{-8}\ M^{1/3}$$

with r_U = 25,400 km, the equatorial radius of Uranus, and M its magnetic moment in gauss cm^3. Examples are given in Table V. If M is as small as 2.2×10^{23} (only 10 times as great as for Mars) or less, the magnetopause will be tangent to the top of atmosphere in a manner resembling that at Venus. No magnetosphere containing durably trapped particles can exist. At the "nominal" value of 2×10^{27} gauss cm^3 a fully developed magnetosphere of large dimensions may be expected. Even if M is comparable to that of Earth, a fully developed magnetosphere may be expected. If the velocity of the planet relative to the local plasma is as small as 20 km sec^{-1}, the standoff distance $r/r_U = 7.6$ for $M = 2 \times 10^{27}$ or 1.64 for $M = 2 \times 10^{25}$.

5. Special Features of a Uranian Magnetosphere

The preceding discussion makes it appear quite likely that there are magnetospheric phenomena associated with Uranus.

A valuable review of the scaling principles of planetary magnetospheres has been given by Kennel (1973). He adopts as plausible a magnetic moment for Uranus of 1.9×10^{28} gauss cm^3 and demonstrates that, in such a case, corotation effects will dominate diffusion effects and that a Uranian magnetosphere will have a closer physical resemblance to that of Jupiter than that of Earth.

Uranus has a close regular system of five known satellites, all of whose orbits are accurately coplanar and nearly circular (Table VI). The rotational period of the planet is not known accurately but the value $10^h\ 49^m$ is commonly adopted as being consistent with both photometric (cyclic variation of brightness) and spectroscopic (Doppler tilt of spectral lines across the visible disc) observations (Alexander 1965). Measurements of the oblateness of the planet are exceedingly difficult but appear to be consistent with an axis of rotation perpendicular to the orbital plane of the satellites. A more persuasive argument to the same effect is based on the persistent coplanarity of the orbits of satellites I-IV over many years of observation. If the plane of the orbits were not coincident with the equatorial plane of the primary, the separate planes of the four satellite orbits would precess at different rates and coplanarity would not exist (Greenberg 1975).

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Table V

Estimated Standoff Distances of Uranian Magnetopause

M	r/r_U
2.25×10^{23} gauss cm^3	1.00
2×10^{25}	4.45
2×10^{27}	20.7 ("nominal")
2×10^{28}	44.5

Table VI

Satellites of Uranus
(Morrison and Cruikshank 1974)
($1\ r_U = 25{,}400$ km)

	Satellite	Orbital Radius		Period of Revolution	Eccentricity of Orbit	Inclination to Planet's Equator	Estimated Radius
V	Miranda	130×10^3 km	$5.1\ r_U$	1.4135 days	0.017	3°.4	110-650 km
I	Ariel	192	7.6	2.520	0.0028	0	300-1700
II	Umbriel	267	10.5	4.144	0.0035	0	200-1100
III	Titania	438	17.2	8.706	0.0024	0	360-2000
IV	Oberon	586	23.1	13.46	0.0007	0	330-1900

(Radii of satellites are inferred from optical brightness and are therefore uncertain by virtue of the unknown albedos of the satellites.)

According to the Explanatory Supplement (1961), the inclination (J) of the orbital plane of satellites I - IV to the equator of Earth and the right ascension (N) of the ascending node are

$$N = 166^\circ.051 + 0^\circ.0142\ (t - 1900.0)$$

$$J = 75^\circ.145 - 0^\circ.0013\ (t - 1900.0)$$

in which t is the Julian year. N and J are referred to the Earth's mean equator and equinox of date (t), the time-variable terms in the above expressions being attributable entirely to the precession of Earth's rotation axis (Duncombe 1975).

The rotational axis of the planet is assumed to be perpendicular to the above plane, with its angular momentum (i.e., "north") pole south of the ecliptic plane by 8°.

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A plot of the angle β between the axis of the planet and the planet-sun is shown in Figure 13. The minimum value of β occurs in October 1985; β is less than 10° for an interval of 1000 days centered on this date.

No other planet has a rotational axis tilted more than 29° to its orbit plane. Thus, the extraordinary orientation of the rotation axis of Uranus makes it a planet of special interest for many types of investigations. The axis is nearly aligned with the planet-sun line in the years 1985 and 2027, whereas it is perpendicular to the planet-sun line in the years 2006 and 2048.

There is, as discussed earlier, no direct knowledge of the magnitude of the magnetic moment of Uranus, much less its orientation. If the magnetic and mechanical axes are approximately colinear (as they are for Earth and Jupiter) then the solar wind flow in 1985 will be also along the same line, whereas centrifugal forces will be perpendicular to this line. The physical nature of the magnetosphere of Uranus

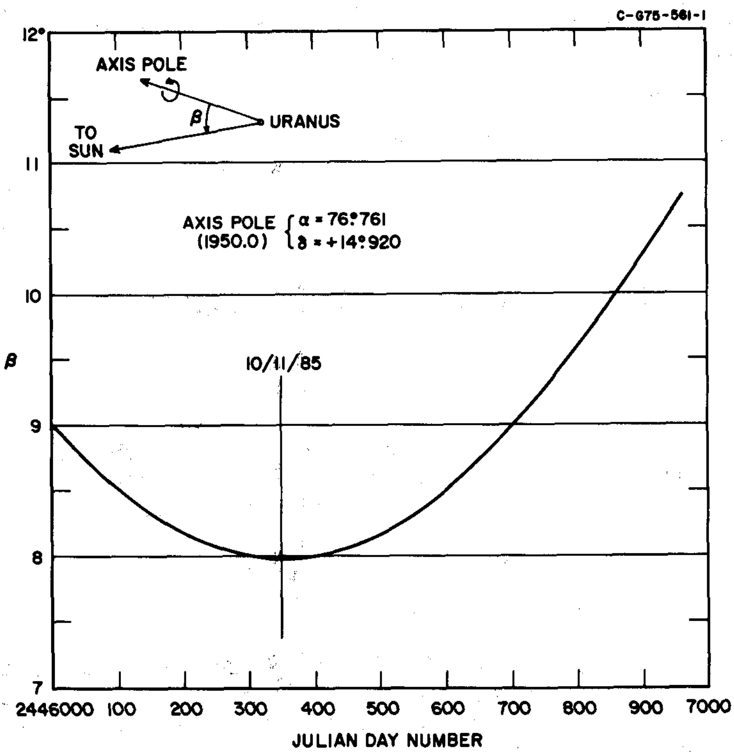

Fig. 13. The time dependence of the angle β between the rotational axis of Uranus and the planet-sun line, showing the especially interesting relationship that will exist during late 1985.

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in this case has been discussed by Olson and more fully by Siscoe (1975). Figure 14 from Siscoe gives a schematic impression of the configuration expected.

If the magnetic axis is strongly inclined to the mechanical axis, then an even more exotic magnetosphere may be expected because of the large diurnal variation that will occur.

Also, it is likely that at least the two inner satellites will contribute particle sweeping and/or particle acceleration effects to the physical melee.

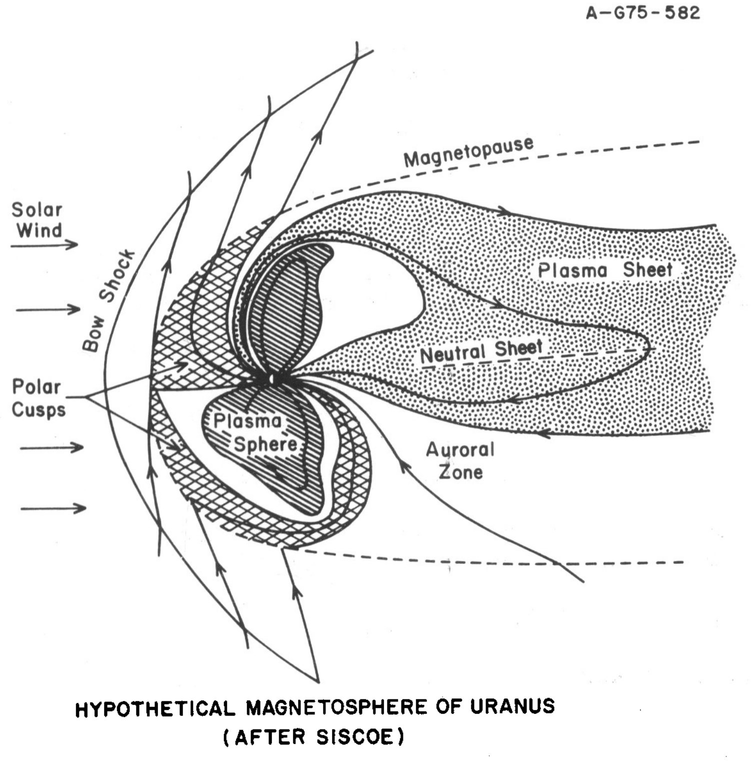

Fig. 14. Hypothetical physical structure of a Uranian magnetosphere during the epoch of pole-on presentation to the solar wind (Siscoe 1975).

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