MAGNETOSPHERES OF THE PLANETS

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Abstract. Scaling laws for possible outer planet magnetospheres are derived. These suggest that convection and its associated auroral effects will play a relatively smaller role than at Earth, and that there is a possibility that the outer planets could have significant radiation belts of energetic trapped particles.

1. Introduction

Of the outer planets, only Jupiter is known, from radio astronomical investigations, to have a magnetosphere, which requires that the pressure of the planetary magnetic field be sufficiently large to stand off the dynamic pressure of the solar wind flow. At present, observation does not rule out magnetospheric interactions of the solar wind with the other planets. Any well-conceived program for the exploration of the outer planets must therefore be prepared for the eventuality that one or more might have magnetospheres. This eventuality implies that the design of a suitable complement of detectors for the exploration of the unknown magnetospheres must be considered. In the absence of hard experimental information, such considerations will rely, however unwisely, upon theoretical extrapolations from what is known about Earth and Jupiter. In this spirit then, this paper presents a highly speculative discussion of hypothetical outer planet magnetospheres. We take what is reasonably well understood about the Earth's magnetosphere, what is guessed at about Jupiter's magnetosphere, and extrapolate to possible magnetospheres of Saturn, Uranus, and Neptune. The theoretician's point of view is adopted throughout. Since the attenuation of the solar wind with increasing heliocentric distance implies that the magnetic moments of the outer planets need not be large for them to have magnetospheres, it does not seem unlikely a priori that they will. However, with the exception of Jupiter, their magnetic moments are completely unknown. Therefore, we will concentrate upon developing a set of relations which scale the outer planets' magnetospheres to their unknown magnetic moments and to the properties of the solar wind extrapolated theoretically to the appropriate heliocentric distance. In order to illustrate the implications of these scaling laws, we will then compute some properties of the outer planets' magnetospheres, based upon the assumption that their magnetic moments scale as their rotational angular momentum. Clearly this procedure looks only under the lamppost where there is some light; yet the extrapolation of terrestrial physics is the only intellectual procedure available. Prudence dictates that we must expect it to err.

In Section 2, we scale the size of a magnetosphere to its planet's magnetic moment

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and heliocentric distance, assuming that the balance of forces at the boundary of the magnetosphere – magnetopause – is Earth-like – namely, a pressure balance between a vacuum dipole planetary field and the solar wind. We also estimate the strength of its internal convection flow assuming it is driven as at Earth, by magnetic reconnection at the nose of the magnetosphere. We discuss procedures by which the density of plasma of ionospheric origin trapped in the magnetosphere may be estimated.

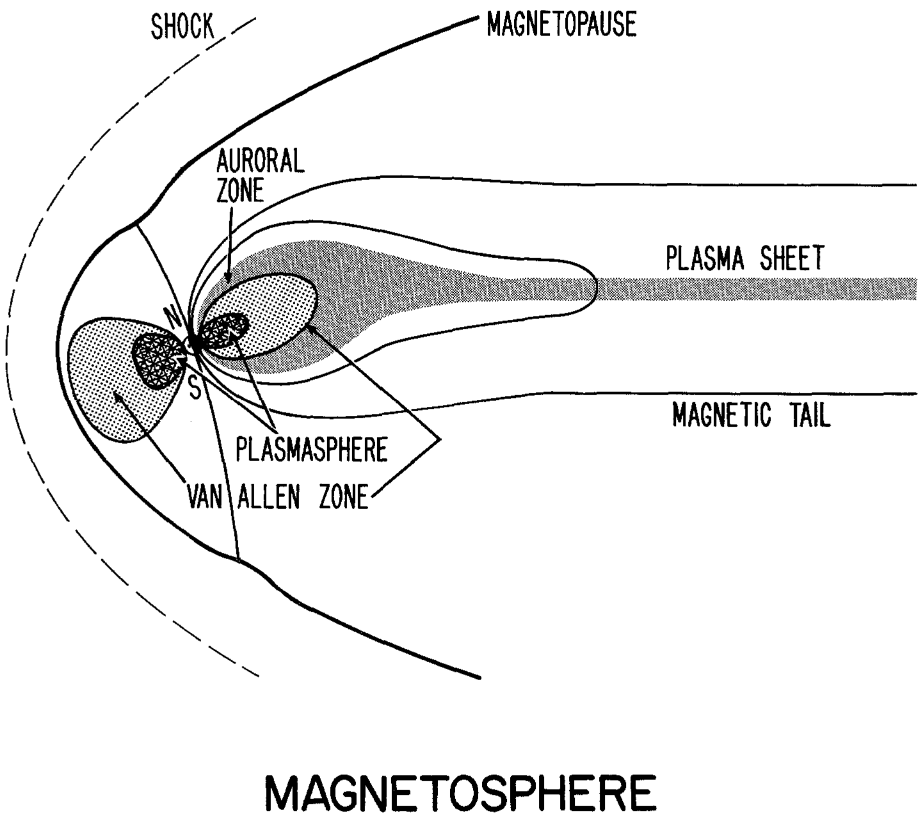

Fig. 1. *Earth's magnetosphere* – Shown here is a slice through the noon-midnight meridian of the Earth's magnetosphere, with the relative geometrical locations of various features to be discussed subsequently in the text.

In Section 3, we discuss possible radiation belts of trapped energetic particles. Here the limitations of our method are most starkly delineated. It is a general truism about turbulent plasmas that they generate energetic particles in a variety of ways. Yet only one of the mechanisms suggested for the generation of the Earth's radiation belts – let alone the energetic particles in laboratory and astrophysical plasmas – radial diffusion, can be scaled a priori to arbitrary magnetospheres. Therefore, we pursue the consequences of the only hypothesis we can make. In Section 4, we present with all humility a table of properties of possible outer planet magnetospheres, based upon the assumption that their dipole moments scale as their rotational momentum. At this point, our method of extrapolation of terrestrial physics leads us to a very illuminating contradiction, namely, that the effects of planetary rotation are likely to be much more pronounced at the outer planets that at Earth. This leads us to doubt, for example, that present calculations of magnetospheric shape, and perhaps even scale size, are adequate for the outer planets, and to the speculation that the outer planets could have powerful radiation belts. These general conclusions may retain some validity even though our specific magnetic moment estimates may err greatly.

Limitations of space unfortunately force us to presume of the reader a reasonable working knowledge of basic magnetospheric physics. For general reference, however, we present in Figure 1 a schematic of the Earth's magnetosphere in which various features to be discussed are put in geometrical perspective – the magnetopause, the boundary between the shocked solar wind and the magnetosphere, the bowshock standing upstream of the magnetopause, the plasmasphere where cold plasma of ionospheric origin corotates with the Earth, the Van Allen belts, and part of the geomagnetic tail. The view is of a slice through the noon-midnight magnetic meridian, and most of the geomagnetic tail, which is some thousand Earth radii long, is not shown.

2. Scaling of Earth-Like Magnetospheres

2.1. Characteristics of the Solar Wind

A planet P located at a distance r AU from the Sun and within the heliosphere boundary, has a magnetic moment M_{P}, radius R_{P}, and rotation period T_{P}. With this information, together with an appropriate scaling of solar wind parameters, we may outline a model of its magnetosphere, assuming only that it is Earth-like. We scale the solar wind number density N, flow speed u, and radial and azimuthal components of the solar wind magnetic field, B_r and B_θ respectively, according to standard theory (Parker, 1963), normalizing to values typically observed at $r=1$, the Earth's orbit·

$$u = \text{constant} \simeq 4 \times 10^7 \text{ cm s}^{-1} \tag{2.1}$$

$$N = 7/r^2 \text{ cm}^{-3} \tag{2.2}$$

$$B_r = \frac{5\gamma}{r^2} = \frac{5 \times 10^{-5}}{r^2} \text{ G} \tag{2.3}$$

$$B_\theta = \frac{5\gamma}{r} = \frac{5 \times 10^{-5}}{r} \text{ G} \tag{2.4}$$

$$B = (B_r^2 + B_\theta^2)^{1/2} = 5\gamma \sqrt{\frac{1+r^2}{r^4}} \simeq \frac{5\gamma}{r} \quad (r \gg 1). \tag{2.5}$$

The thermal conduction of the solar wind beyond Earth is not well understood. The simplest assumption, which may err, lets the electron and ion temperatures,

T_e and T_i separately scale adiabatically.

$$T_e \simeq \frac{1.5 \times 10^5\ \mathrm{K}}{r^{4/3}}, \qquad T_i \simeq \frac{2 \times 10^4\ \mathrm{K}}{r^{4/3}}. \tag{2.6}$$

Scarf (1969) has discussed the expected characteristics of the solar wind near Jupiter in more detail. In particular, he suggests that the temperature anisotropy will reverse, so that near Jupiter the perpendicular temperature $T_\perp$ will exceed the temperature $T_\parallel$ parallel to the magnetic field direction. As a consequence, different electromagnetic wave instabilities (Kennel and Petschek, 1966) than those encountered near Earth (Kennel and Scarf, 1968) would be expected to reduce the thermal anisotropies.

2.2. Nose of the Magnetopause

The nose radius D_P of the planetary magnetopause can be estimated assuming that the dipole field is essentially a vacuum field, whose moment is oriented more or less normal to the ecliptic plane. Then, according to Spreiter and Alksne (1969a), the radial distance D_P to the magnetopause at the subsolar point is determined by the balance of solar wind dynamic pressure and magnetic pressure, the dipole field having been doubled by magnetopause surface currents:

$$D_P = (M_P^2/2\pi M_i N u^2)^{1/6}, \tag{2.7}$$

where M_i is the proton mass, and N is given by Equation (2.2). Normalizing to the Earth, we find

$$D_P/D_E = (M_P/M_E)^{1/3}\, r^{1/3}, \tag{2.8}$$

where $D_E \simeq 10\ R_E = 6.4 \times 10^9$ cm. Magnetohydrodynamic solutions for the shape of the magnetopause, which scale as the single parameter D, indicate that the distance between the local dawn and evening magnetopause, is 3 D. The magnetospheric magnetic field at the nose of the magnetosphere is $\sqrt{8\pi\varrho u^2} \simeq 70\gamma/r$, $\varrho = NM_i$.

The criterion $D_P = R_P$ defines the minimum planetary magnetic moment for which a magnetospheric interaction is expected since, when $D_P = R_P$, the surface magnetic field pressure is just large enough to stand off the solar wind dynamic pressure. In units of the Earth's magnetic moment, M_E, the minimum planetary magnetic moment M_P^* is

$$\frac{M_P^*}{M_E} \simeq \frac{10^{-3}}{r}\left(\frac{R_P}{R_E}\right)^3. \tag{2.9}$$

2.3. Characteristics of Planetary Bow Shocks

Magnetohydrodynamic calculations (Spreiter and Alksne, 1969b) indicate that a bow shock should stand a distance 0.3 D_P upstream from the nose of the magnetosphere. Shocks are expected at all the outer planets since the Alfvén Mach number remains constant and the sonic Mach number increases with r, based upon Equations (2.1–2.7). However, the *structures* of the shocks encountered could differ from those at Earth. For example, a significant component of the Earth's bow shock is a large amplitude magnetic whistler mode wave train (Fredricks *et al.*, 1970). In order to stand ahead of the shock in the solar wind, the whistler phase speed upstream must match the solar wind speed. Since the maximum whistler phase speed is $\frac{1}{2}\sqrt{M_i/M_e}C_A$, where C_A is the Alfvén speed, whistler wave trains are possible when

$$C_A < u < \tfrac{1}{2}\sqrt{M_i/M_e}\, C_A \qquad (2.10)$$

which is satisfied for $r > 1$ if it is satisfied at $r = 1$, since C_A is independent of r from Equations (2.1–2.7). M_i/M_e is the ion to electron mass ratio. On the other hand, electron plasma oscillations, which do not play a role in the Earth's bow shock, could be important beyond $r = 1$ (Scarf, 1969). The *minimum* phase velocity of these waves is the order of the electron thermal speed a_e, where, from Equation (2.6), $a_e \simeq (2 \times 10^8/r^{2/3})$ cm s^{-1}. Whenever $u/a_e > 1$, electron plasma oscillations could stand in the shock. Very little is known theoretically or experimentally about shocks which are supersonic to electrons. Scarf (1969) has also suggested that the gravitational interaction between the solar wind and the massive outer planets may modify the flow configuration about their magnetospheres, since the gravitational potential energy of an ion in the solar wind just beyond the bow shock can exceed its thermal energy, for example, at Jupiter.

2.4. Reconnection on the dayside magnetopause

Dissipative interactions leading to tangential stresses at the magnetopause are responsible for the geomagnetic tail (Dungey, 1961; Axford *et al.*, 1965), the internal convection of plasma and magnetic field within the magnetosphere (Axford and Hines, 1961), and energetic particle bombardment of the auroral zone ionosphere by the convecting plasma (Kennel, 1969; Axford, 1969). Whether the dissipation is due to enhanced viscosity arising from plasma turbulence at the magnetopause (Axford, 1964), or to the resistive reconnection of solar wind field lines with magnetospheric field lines (Dungey, 1961; Levy *et al.*, 1964), or both, has not been clearly established. However, it does appear that magnetospheric substorms (Akasofu, 1969), which are due in part to enhanced convective flow, result from increased field-line reconnection, since they correlate with the solar wind field component anti-parallel to the Earth's dipole field (see Arnoldy, 1971, and the references therein). For this reason, we will evaluate only the consequences of reconnection, and not turbulent viscosity.

The electric field, imposed on the magnetosphere by reconnection, should be proportional to uB_A/c where B_A is the component of solar wind field antiparallel to the magnetopause magnetic field. B_A has considerable temporal variation, leading to temporally unsteady convection and substorms in the Earth's magnetosphere. However, B_A ought roughly to scale as the magnitude of the average solar wind magnetic field. Assuming that the proportionality between the planetary convection electric field E_P and uB_A/c does not vary with heliocentric distance, we find

$$\frac{E_P}{E_E} \simeq 1/r, \qquad (2.11)$$

where $E_E \simeq 1$ kV/R_E is a typical terrestrial convection electric field. Equation (2.11) scales identically as the estimate of Brice and Ioannidis (1970), who used a specific theoretical model of reconnection (Petschek, 1964) to scale E_P.

We may estimate the solar wind energy input, $\dot{W}_P$, into the magnetosphere as follows. If b is the magnetosheath magnetic field downstream from the bow shock, the flux of magnetic energy transported towards the magnetopause to be dissipated by reconnection into internal magnetospheric convection is roughly $(cE/b)(b^2/8\pi)$. The area of the dayside magnetopause is the order of πD^2, so that

$$\dot{W}_P = \pi D_P^2 \frac{cE_P}{b} b^2/8\pi . \tag{2.12}$$

When the bow shock is strong, b will scale as the solar wind field B, so that we may use Equations (2.5), (2.8) and (2.11) to scale (2.12)

$$\frac{\dot{W}_P}{\dot{W}_E} \simeq \left(\frac{M_P}{M_E}\right)^{2/3} \frac{1}{r^{4/3}} \tag{2.13}$$

where $\dot{W}_E \simeq 5 \times 10^{17-18}$ erg s^{-1} (Axford, 1964). Since there exist no generally accepted theories or laboratory experiments which scale the reconnection rate to plasma parameters, the estimates, Equations (2.11) and (2.13) may err. However, it is dangerous to assume that no reconnection occurs at all.

2.5. Tail of the Magnetosphere

Assuming E_P is approximately uniform, then the electric potential ϕ_P across the magnetosphere is approximately 3 $E_P D_P$, so that

$$\frac{\phi_P}{\phi_E} = \left(\frac{M_P}{M_E}\right)^{1/3} r^{-2/3}, \tag{2.14}$$

where $\phi_E \simeq 30$–100 kV is a reasonable value. Magnetic flux is transported into the magnetospheric tail at the rate $\dot{F} = c\phi_P$, where

$$\dot{F} = (c\phi_E)\left(\frac{M_P}{M_E}\right)^{1/3} r^{-2/3} = 3 \times 10^{12} \left(\frac{M_P}{M_E}\right)^{1/3} r^{-2/3} \text{ Mx s}^{-1}, \tag{2.15}$$

where $\phi_E \simeq 30$ kV was chosen. Since magnetic flux cannot accumulate indefinitely, a second magnetic neutral line is expected in the magnetospheric tail, at which reconnection again occurs (Dungey, 1961; Axford *et al.*, 1965). The reconnected flux in the tail should then be convected towards the nose of the magnetosphere to replenish that which has been stripped off, by reconnection at the nose, to feed the tail. In steady state, the two flux transport rates must be equal. By analogy with the geomagnetic tail, a plasma sheet, containing energetic plasma heated by Joule dissipation during reconnection and other processes, would be expected planetward of the tail neutral line. Since there is presently no adequate understanding of the temperature and density observed in the Earth's plasma sheet, nothing concrete can be said about the density and temperature of any other plasma sheets, other than that the total plasma plus magnetic pressure must be constant across the plasma sheet and equal to the magnetic pressure in the lobes of the tail. Energetic particles precipitating from the convecting plasma in the plasma sheet should produce aurorae in the high latitude planetary ionosphere (Kennel, 1969, Axford; 1969).

It is not understood theoretically why the geomagnetic tail contains the flux it does; consequently, reliable estimates for the flux stored in other possible magnetospheric tails are not possible. However, let us suppose that the length of the tail L_P scales geometrically as the Earth's which is some 100 nose radii D_E long (Dungey, 1965), so that $L_P = 100 D_P$. An estimate for the steady state convection time T_c is then

$$T_c = \frac{L_P}{u} = \frac{100\, D_P}{u} \quad \text{and} \quad \frac{T_c(P)}{T_c(E)} = \left(\frac{M_P}{M_E}\right)^{1/3} r^{1/3}, \tag{2.16}$$

where $T_c(E) \simeq 1.6 \times 10^4 \text{s} \simeq 4$ h. During the time T_c reconnection would transfer a flux $\dot{F} T_c$ to the magnetospheric tail. In steady state, this is the flux stored in each lobe of the tail, F_P, so that

$$F_P \simeq 100\, c\phi_P D_P / u \tag{2.17}$$

and using Equations (2.8) and (2.15),

$$\frac{F_P}{F_E} \approx \left(\frac{M_P}{M_E}\right)^{2/3} r^{-1/3}. \tag{2.18}$$

We may estimate the tail magnetic field as follows. Beyond a distance D_P downstream from the planet, the magnetic field should be stretched out in a tail-like configuration, in two lobes, with field in the solar direction in one lobe and the antisolar direction in the other. The lobes should be separated by a plasma sheet. Assuming the field is essentially a vacuum field, and therefore uniform across the tail cross-section, the magnetic field in the tail is then

$$B_T \simeq 2F_T / \pi R_T^2, \tag{2.19}$$

where R_T is the tail radius. Equation (2.19) corresponds to one of the basic assumptions in the flaring tail models of Tverskoy (1968) and Spreiter and Alksne (1969b), who model the tail by a cylinder bifurcated by a thin plasma sheet. Near the planet, the tail must join smoothly with the nose of the magnetosphere. Consequently, we take $R_T \simeq 1.5\, D_P$, the radius of the magnetopause on the dawn-dusk meridian. Thus, combining Equations (2.17) and (2.19) we find

$$B_T \simeq \frac{30\, c\phi_P}{u D_P} = 2 \times 10^4 \frac{\phi_P}{D_P} \tag{2.20}$$

$$\frac{B_T(P)}{B_T(E)} \simeq 1/r, \tag{2.21}$$

where $B_T(E) \simeq 40\gamma$. The tail field should decrease monotonically with distance downstream approaching the value $\sqrt{8\pi P_0}$ at asymptotically large distances (Spreiter and

Alksne, 1969b), where P_0 is the static pressure in the solar wind. We may now estimate the area A_P of the polar cap, the region of field lines directly connected to the solar wind, since the flux leaving (or entering) each polar cap must equal the flux in each lobe of the tail. Thus,

$$A_P = \frac{F_P}{2B_P^s} = \frac{100\, c\phi_P D_P}{2uB_P^s}, \tag{2.22}$$

where B_P^s is the surface equatorial magnetic field strength. Assuming $A \simeq \pi r_0^2$, where r_0 is a characteristic dimension, then

$$r_0 \approx \sqrt{\frac{50c\phi_P D_P}{\pi u B_P^s}}$$

and the colatitude λ of the boundary of the polar cap is roughly r_0/R_P.

In the terrestrial ionosphere, an auroral 'oval' of enhanced particle precipitation and magnetic activity surrounds the polar cap (Akasofu, 1969). A significant fraction of the convective flow energy is dissipated as auroral precipitation and ionospheric heating. The area of the terrestrial auroral oval is comparable with that of the polar cap. Assuming this scaling prevails at the outer planets, an upper limit for the energy input per unit area in the auroral oval, $\dot{\omega}_P \approx \dot{W}_P/A_P$, may be found by combining Equations (2.13) and (2.22) whereupon

$$\frac{\dot{\omega}_P}{\dot{\omega}_E} \simeq \left(\frac{B_P^s}{B_E^s}\right)\frac{1}{r} \tag{2.23}$$

where the actual energy dissipation rate per unit area in the terrestrial auroral oval is of order 1–10 erg cm^{-2} s^{-1}.

2.6. Corotation and Convection

Figure (2A), from Brice and Ioannidis (1970), schematically illustrates the streamlines, in the magnetic equatorial plane, of the convective flow from the plasma sheet towards the nose of the Earth's magnetosphere. There are two distinct regions, of open and closed streamlines. The open streamlines correspond to convective return of magnetic flux and plasma to the nose of the magnetosphere; near the Earth, where corotation dominates convection, the flow streamlines are closed. The plasma remains in the corotation region long enough to approach thermal equilibrium with the ionosphere so that the plasma density is relatively high. Outside the corotation region, plasma escaping from the ionosphere is convected rapidly to the magnetopause where it is lost. Consequently the density is lower in the convection region (Brice, 1967; Nishida, 1967). The 'plasmapause', separating the high density plasmasphere and the low density convection region, is ordinarily quite sharp. Figure (2B) describes the calculated plasmasphere at Jupiter, where corotation is much more powerful than at Earth.

There are several means by which the relative importance of corotation and con-

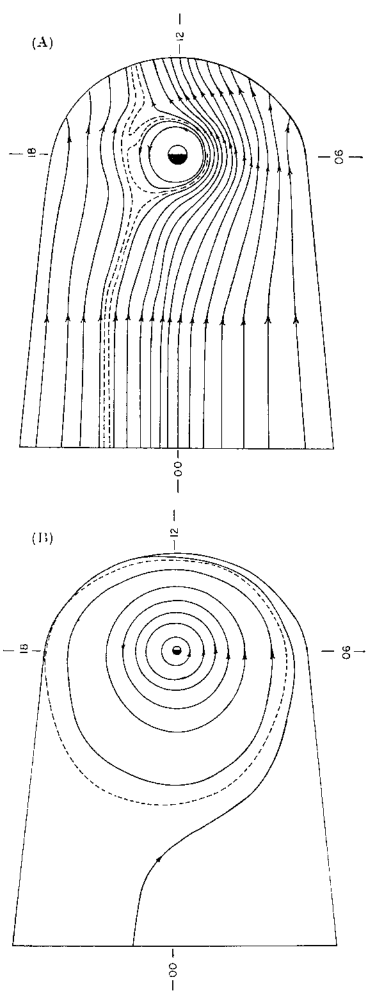

Fig. 2. *Convection and corotation at Earth and Jupiter* – (A) is a schematic of the streamlines of the Earth's convective flow in the magnetic equatorial plane, taken from Brice and Ioannidis (1970). Local magnetic times are indicated, with the solar direction, local noon, at the top of the figure. The region of closed streamlines, the corotation or plasmasphere, contains relatively dense cold plasma of ionospheric origin. (B) is a similar schematic for Jupiter.

vection may be parametrized. For example, we may compute the ratio of the convection time Equation (2.16) to the rotation period T_{P}.

$$\frac{T_{\mathrm{c}}(P)\,T_{\mathrm{E}}}{T_{\mathrm{c}}(E)\,T_{\mathrm{P}}} \simeq \left(\frac{M_{\mathrm{P}}}{M_{\mathrm{E}}}\right)^{1/3} r^{1/3}\,\frac{T_{\mathrm{E}}}{T_{\mathrm{P}}} \tag{2.24}$$

$T_{\mathrm{c}}/T_{\mathrm{P}} < 1$ implies a dominant convection region, as for Earth, whereas $T_{\mathrm{c}}/T_{\mathrm{P}} > 1$ implies a dominant corotation region, as for Jupiter. Similarly, we may compare the magnitudes of the corotation and convection electric fields. At the magnetic equator on a given tube of force the corotation field E_{CR} is

$$E_{CR} = \frac{2\pi}{T_P} \frac{LR_P B(L)}{c} = \frac{2\pi}{T_P} \frac{R_P B_P^s}{cL^2}, \qquad (2.25)$$

where L measures the distance in units of planetary radii. The minimum E_{CR} occurs at the magnetopause, where $L = D_P/R_P$ so that $E_{CR} \geqslant (2/T_P)(M_P/cD^2)$. The ratio Δ_{CR} of the minimum corotation field to the convection field is, using Equations (2.11) and (2.8),

$$\frac{\Delta_{CR}(P)}{\Delta_{CR}(E)} = \left(\frac{T_E}{T_P}\right)\left(\frac{M_P}{M_E}\right)^{1/3} r^{1/3}, \qquad (2.26)$$

where $\Delta_{CR}(E) \simeq 0.3$–$1$. Again, when $\Delta_{CR}(P) > 1$, corotation dominates. The criteria (2.24) and (2.26) are identical. Finally, the rotational plasma energy density could distort the dipole field (Melrose, 1967; Brice and Ioannidis, 1970), an effect measured by β_{CR}, the corotation energy density divided by the magnetic energy density. For a given plasma mass density ϱ_M at the magnetopause, β_{CR} maximizes in the dipole equatorial plane at the magnetopause:

$$\beta_{CR} = \frac{8\pi}{B^2} \frac{1}{2} \varrho_M \left(\frac{2\pi D_P}{T_P}\right)^2 \approx \frac{1}{2}\left(\frac{\varrho_M}{\varrho_s}\right)\left(\frac{2\pi D_P}{uT_P}\right)^2, \qquad (2.29)$$

where $B^2/8\pi \approx \varrho_s u^2$ at the magnetopause; ϱ_s is the solar wind mass density. The ratio $Q = (2\pi D_P/uT_P)^2$ scales as

$$\frac{Q_P}{Q_E} \simeq \left(\frac{M_P}{M_E}\right)^{2/3} r^{2/3} \left(\frac{T_E}{T_P}\right)^2, \qquad (2.30)$$

where $Q_E \simeq 10^{-4}$. When β_{CR} approaches 1, the magnetopause calculations of Section 2.1 should fail because centrifugal forces were not included in the stress balance.

2.7. Plasma density profile

Ioannidis and Brice (1971) have estimated the plasma density in the Jovian magnetosphere by a method which can be scaled to other planets. First, they noted that only photo-electrons have sufficient energy to escape over Jupiter's gravitational potential energy barrier. They then scaled the terrestrial flux of photo-electrons deduced by Perkins and Yngvesson (1968) by a factor $1/r^2 \cos\theta$, where θ is the solar zenith angle at the foot of a given line of force in the ionosphere. Thereupon, they computed the flux and energy of escaping electrons, and assumed that hydrogen ions would be pulled out of the ionosphere to ensure charge neutrality. From this, they deduced a diffusive equilibrium density model, assuming no plasma loss, which predicted extremely large densities beyond $L = 6$. Therefore, it was amended by the inclusion of loss processes, of which the most significant is outward radial diffusion driven by interchange instabilities which set in when $\beta_{CR} = 1$. Thus $\beta_{CR} = 1$ fixes an upper limit for the plasma density, and in the absence of other loss mechanisms, determines the density. Figure 3 shows the Jovian plasma density profile computed by

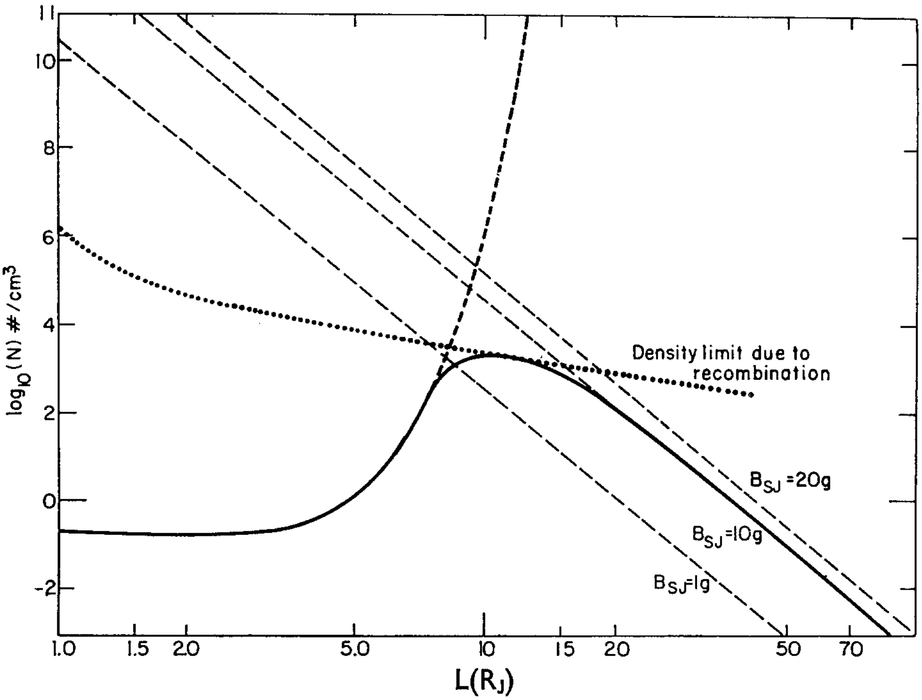

Fig. 3. *Plasma density in the magnetosphere of Jupiter* – This figure is taken from Ioannidis and Brice (1971). The dashed line approaching infinity near $L=10$ is the result of loss-less diffusive equilibrium calculations; the dotted line indicates the density limit set by recombination, and the dashed lines labelled $B_{SJ}=1$, 10, 20 g indicates the density limit set by interchange instability for various values of Jupiter's surface magnetic field B_{SJ}. Centrifugal effects confine these densities largely. to the Jovian magnetic equatorial plane.

Brice and Ioannidis (1971) in this fashion. Scarf (private communication, 1972) has pointed out that their calculation can easily be extended to Saturn, provided M_P is known. Since Saturn's gravitational field and rotation period are comparable to Jupiter's, the flux of escaping photo-electrons will be $1/r^2 \simeq \frac{1}{4}$ as large at Saturn as at Jupiter. Thus, near Saturn, the plasma density would be $\frac{1}{4}$ that near Jupiter, and far from the planet would be determined by the condition $\beta_{CR}=1$.

3. Radiation Belts

3.1. Radial diffusion

The origin of the energetic particles trapped in the Earth's magnetosphere is not completely understood quantitatively. Particles up to a few tens of keV are injected during magnetospheric substorms, when rapid convection from the geomagnetic tail to the inner magnetosphere greatly compresses and heats the plasma (Axford, 1969). The maximum particle energy attainable by flow compression is given by the convection potential across the magnetosphere. Thus, from (2.15), convection should provide particles with energies ε not exceeding $\varepsilon_E(M_P/M_E)^{1/3}r^{-2/3}$, where $\varepsilon_E \simeq 30$–100 keV. Plasma turbulence can also statistically accelerate particles to high energies within the magnetosphere (Kennel, 1969). Such mechanisms are poorly understood at present and cannot be scaled to other magnetospheres. It has been suggested (see Tverskoy, 1969, and the references therein) that the energetic component of the Earth's radiation belts is generated by injection of low energy particles at the magnetopause followed by inward radial diffusion driven by variable electric and/or magnetic fields. If the field variations have sufficiently low frequency, the particles' first adiabatic invariant $\mu = \varepsilon_\perp/B$ (where $\varepsilon_\perp$ is the component of particle energy in motion perpendicular to the magnetic field) is conserved. Therefore, as particles diffuse from weak to strong magnetic field regions, their energy increases. If a typical magnetic moment can be estimated for particles injected at the magnetopause, then typical particle energies at any point in the dipole field can also be estimated from μ-conservation. Since the ultimate source of the radiation belt particles is the solar wind, it is useful to compute the magnetic moment in the solar wind, based upon the flow energy density:

$$\mu = \tfrac{1}{2}M_i u^2/B = 16r \text{ MeV G}^{-1}. \tag{3.1}$$

If μ is conserved for that small fraction of the impinging solar wind flux which not only traverses the shock and magnetosheath but penetrates the magnetopause boundary, we may use (3.1) to estimate the energy of radiation belt particles. On the other hand, should the particle's magnetic moments be randomized by turbulence in the bow shock and magnetosheath, the magnetic moments of particles at the magnetopause could be somewhat smaller than (3.1). The maximum particle energy produced by radial diffusion will be of order μB_P^s, where B_P^s is the planetary surface field. If $B_P^s \simeq 0.5$ MeV, electrons with sufficient energy to generate synchrotron radiation could in principle be produced.

The intensity of the radiation belts produced by radial diffusion is proportional to the fraction of the solar wind particle flux which diffuses across the magnetopause. How this occurs at Earth is not well understood. However, one thing seems clear. The magnetopause of a rapidly rotating planet may differ considerably from the Earth's. For example, if $\beta_{CR} = 1$, the magnetopause could be subject to interchange motions. Should there be counterstreaming of corotating magnetospheric and flowing magnetosheath plasma, two-stream instabilities could increase the particle transfer rate. Clearly, the structure of the Earth's magnetopause cannot be extrapolated to the outer planets with confidence.

The radial diffusion coefficient is determined by the power in time-varying electric and magnetic fields with periods comparable to the particle's azimuthal drift periods around the planet. The particle drifts stem from three sources: electric field drifts from the combination of corotation and convection, drifts due to gradients in the magnetic field strength, and drifts due to field line curvature (Hess, 1969). The time for a nonrelativistic particle to drift once around the planet via the magnetic gradient drift alone is

$$T_D(\mu) = \frac{2\pi e}{3c} \frac{L^2 R_P^2}{\mu}, \tag{3.2}$$

where $e = 5 \times 10^{-10}$ esu, $c = 3 \times 10^{10}$ cm s^{-1} and LR_P is the radial distance from the center of the planet to the particle. Equation (3.2) may be generalized to include the magnetic curvature drift, and relativistic effects (Lew, 1961). For particles with the same L, T_D scales as R_P^2/μ, and so using (3.1), we find

$$\frac{T_D(L;P)}{T_D(L;E)} = \frac{1}{r}\left(\frac{R_P}{R_E}\right)^2, \tag{3.3}$$

where $T_D(L;E) \simeq 0.15\, L^2$ h. Since T_D is proportional to L^2 for a given μ, the radial diffusion coefficient when magnetic drifts predominate depends upon different frequency components of the fluctuating electric and magnetic fields at different L; similarly particles with different μ resonate with difference frequency components at a given L.

Low frequency variation in the convection electric field, due to a variable solar wind, may drive radial diffusion at Earth (Fälthammar, 1965; Birmingham, 1969; Cornwall, 1971; Mozer, 1971) and have been considered for Jupiter by White (1971). For a given μ and L, the diffusion coefficient D is of order $cE^2(\omega_D)/B^2(L)$, where $E\,(\omega_D)$ is the electric field amplitude at the drift frequency ω_D, and $B(L)$ is the equatorial magnetic field strength. At low frequencies, the electric field amplitude should be reasonably uniform spatially: if furthermore the frequency spectrum is reasonably smooth, then $D \propto L^6$ in a dipole field, since $B(L) \sim L^{-3}$. Perturbations of the magnetospheric magnetic field stemming from irregular magnetopause motions, again driven by solar wind variations, have been considered for Earth by Nakada and Mead (1965) and for Jupiter by Chang and Davis (1962) and Hess and Mead (1971). This mechanism has a basic L^{10} dependence. Consequently, both electric and magnetic diffusion are weakest on inner L-shells, where the highest energy particles are involved.

When corotation dominates the magnetic drifts, $T_P/T_D \ll 1$, so that even energetic particles circle the planet in approximately one rotation period, electric and magnetic field amplitudes at the corotation frequency determine the radial diffusion coefficient over a wide range of both μ and L. It then seems possible that the time-varying fields driving radial diffusion may not stem from irregular solar wind variations, but could be relatively more coherently driven by corotation itself. One such radial diffusion mechanism has been proposed for Jupiter by Brice (1971) and Brice and McDonough (1972). Solar illumination periodically heats the planetary atmosphere, creating tidal wind systems. The winds then couple to ions in the dynamo region of the ionosphere to drive Hall currents; polarization of the Hall currents then leads to electric fields which map along magnetic field lines out into space. The net electric potential associated with the atmospheric dynamo is of order $WB_P^s R_P/c$, where W, a typical wind velocity is of order one-tenth the sound speed. For Jupiter, this potential is roughly 10 MV, so fluctuating fields greatly in excess of that expected from solar-wind irregular convection may be possible. Furthermore, the radial diffusion coefficient may have a much weaker L-dependence than those associated with solar wind variability. For both these reasons radial diffusion could turn out to be surprisingly efficient in corotation dominated magnetospheres.

3.2. Energetic particle loss mechanisms

High frequency fluctuations near the particles' cyclotron frequencies, which violate the magnetic moment invariant, can slowly diffuse particles in pitch angle until their magnetic moment is sufficiently reduced that they are no longer reflected by the dipole field gradients and so are lost to the atmosphere. An upper limit to the stably trapped particle fluxes is then set by the threshold particle fluxes which trigger high frequency instabilities. One such limit, involving electromagnetic ion cyclotron and whistler instabilities has been calculated for the Earth's radiation belts by Kennel and Petschek (1966) and Cornwall (1966), and for Jupiter by Kennel (1971):

$$J_{\mathrm{P}}^{*} = \frac{5 \times 10^{10}}{L^4} \left(\frac{M_{\mathrm{P}} R_{\mathrm{E}}^4}{M_{\mathrm{E}} R_{\mathrm{P}}^4} \right) \mathrm{cm}^{-2}\, \mathrm{s}^{-1} \tag{3.4}$$

where the limiting omnidirectional flux, J^*, is independent of the particle mass (and is consequently identical for electrons and ions) and of the background plasma density N. However, only electrons and ions which can resonantly interact with the waves can be diffused; this condition implies that only particles with energies greater than the magnetic energy per ion pair, $B^2/8\pi N$, at the magnetic equator, will be scattered by whistler or ion cyclotron waves. Pitch angle diffusion can reduce particle fluxes to the stably trapped limit only when the precipitation lifetime is less than the characteristic radial diffusion time. Since the *minimum* precipitation lifetime (Kennel, 1969), a lower limit to the precipitation lifetime, scales as L^4, precipitation losses are slow on distant L-shells.

Thorne and Coroniti (1971) have arrived at an upper limit model for the intensity of the Jovian radiation belts using these ideas. They assumed electric field diffusion, of sufficient strength to permit particles to diffuse past Io, and that injection at the magnetopause was sufficient to create particle fluxes above the stability threshold for whistler and ion cyclotron waves. Beyond $L = 6$–8 radial diffusion is faster than precipitation, and the particle fluxes can be reduced to the stably trapped limit only when they reach $L = 6$–8. Thus, instabilities are a valve limiting the injection of particles to the inner L-shells in this model. Near Jupiter, $B^2/8\pi N$ exceeds the expected particle energy μB, using the Ioannidis and Brice (1971) plasma density model, so that whistler and ion cyclotron waves may be stable. However, electrostatic instabilities of the loss cone type (Rosenbluth, 1965) could also act as a turbulent loss mechanism. Such instabilities, with frequencies appropriate to scatter electrons, have recently been discovered in the Earth's radiation belts (Kennel *et al.*, 1970), but as yet our knowledge of them is insufficient to permit extrapolation.

3.3. Satellites in magnetospheric physics

Planetary satellites with orbits within the magnetosphere present a completely new type of hydromagnetic interaction for study. For example, Io, at $L=6$ well within the Jovian magnetosphere, should interact with the corotation flow, with the Jovian magnetic field, and with the Jovian radiation belts. Detailed study of the magnetic interaction should yield valuable information concerning Io's internal electrical conductivity. Energetic particles which radially diffuse across the orbit of Io will be partially absorbed by Io; the radial flux profiles in the vicinity of Io's orbit could lead to a determination of the radial diffusion coefficient. Indeed, Hess and Mead (1971) have argued that Io will absorb nearly all radiation belt particles diffusing to its orbit, provided that radial diffusion is as slow as that given by magnetic diffusion in the drift-dominated regime. However, this argument leaves the problem of accounting for the observed synchrotron radiation generated by relativistic electrons within Io's orbit by another mechanism. Io's interaction must not be thought of only as passive, since Io strongly modulates Jupiters' decametric radio emissions. Goldreich and Lynden-Bell (1969) argue that the $\mathbf{v}\times\mathbf{B}$ electric potential, from corotation of the plasma across Io's diameter, which is the order of 0.5 MV, then drives magnetic field-aligned currents in the tubes of force intersecting Io, which close in the Jovian ionosphere. These field-aligned currents then produce instabilities in the Jovian ionosphere, creating waves with frequencies up to the electron cyclotron frequency at the foot of the field line. Similar waves, also apparently associated with field-aligned currents, have been observed in the Earth's ionosphere as auroral hiss. Since the dissipation of field-aligned currents may heat the ionospheric plasma and also produce energetic beams of 'runaway' electrons, there is the interesting possibility that Io could be a source of radiation belt electrons.

4. Hypothetical Magnetospheres

In this section, we estimate the magnetic moments of the outer planets, and derive therefrom the implied properties of their magnetospheres. The Jovian magnetic moment M_J has been estimated from radio astronomical evidence (Warwick, 1970). It is not known whether Saturn, Uranus, and Neptune have magnetic moments. However, current understanding of the dynamo theory of planetary magnetism indicates it would be dangerous to presume they have no magnetic moment, since they are rapidly spinning objects, with a reasonable possibility of having conducting liquid cores. Furthermore, the minimum magnetic moment M^* (Equation (2.9.)) for which a magnetospheric interaction will occur is quite small, $M_S^* \simeq 10^{-1}\, M_E$, $M_U^* \simeq 3\times 10^{-3}\, M_E$, and $M_N^* \simeq 2\times 10^{-3}\, M_E$. For the purposes of illustration, we have scaled the planetary magnetic moments according to the 'Magnetic Bode's Law' (Moroz, 1968) whereby the magnetic moment is proportional to the total planetary angular momentum, a rule which works fairly well for Earth and Jupiter. These estimates of M_P greatly exceed the minimum moment required for a magnetospheric interaction. We have not performed any scalings for Pluto, since it is sufficiently small that it may not have a magnetic moment.

Table I lists the orbital radius r (in astronomical units), the planetary radius R_P, the ratio R_P/R_E, the planetary rotation period T_P, the ratio T_P/T_E, the estimated

TABLE I

Planetary parameters

Planet	r(AU)	R_P(km)	R_P/R_E	M_P/M_E	B_P^s(G)	T_P(h)	T_P/T_E
Earth	1	6.4×10^3	1	1	1/3	24	1
Jupiter	5.2	7.1×10^4	11.1	5×10^4	12	10	0.41
Saturn	9.5	6×10^4	9.4	10^4	14	10	0.41
Uranus	19.2	2.5×10^4	4	2.4×10^2	1.25	10.8	0.45
Neptune	30.0	2.5×10^4	4	1.7×10^2	0.9	15.8	0.66
	Heliocentric distance	Planetary Radius		Magnetic moment	Surface magnetic field	Rotation period	

planetary magnetic moment M_P in units of the Earth's magnetic moment M_E, and the surface field B_P^s derived therefrom for the planets Earth, Jupiter, Saturn, Uranus, and Neptune. All the parameters but M_P (and B_P^s) are well known, and have been taken from Newburn and Gulkis (1971). Table II lists derived parameters defining the magnetospheric configuration: the nose radius D_P normalized to the Earth's nose radius D_E and also to the planetary radius R_P, the length of the geomagnetic tail L_P in astronomical units, and B_N, the magnetic field strength at the nose of the magnetosphere. These hypothetical outer planet magnetospheres are much larger than the Earth's both in absolute units and in units of planetary radii. The estimated length of Jupiter's magnetic tail is significant on the solar system scale. Should the nose radius estimates be correct, then the satellites JV, Io, Europa, Ganymede and Callisto lie within Jupiter's magnetosphere; Janus, Mimas, Enceladus, Tethys, Dione, Rhea, Titan, and Hyperion within Saturn's; and Triton within Neptune's; all of Uranus' satellites lie within its

TABLE II

	Magnetosphere configuration				Convection parameters		
Planet	D_P/D_E	D_P/R_P	$B_N = \sqrt{8\pi\varrho u^2}$	L_P(AU)	ϕ_P/ϕ_E	$\dot{W}_P/\dot{W}_E$	$\dot{\omega}_P/\dot{\omega}_E$
Jupiter	64	57	13γ	2.5	12	160	7
Saturn	45	48	7γ	1.8	4.8	22	1
Uranus	16.5	41	3.5γ	0.66	4.87	0.75	0.2
Neptune	17	42.5	2.2γ	0.68	0.57	0.3	0.1
Earth	$D_E =$ 64000 km	$D_E/R_E = 10$	$B_N = 67\gamma$	0.04	$\phi_E = 30$–100 kV	$\dot{W}_E \approx 5 \times 10^{17-18}$ erg s^{-1}	$\dot{\omega}_E \simeq 1$–10 erg cm^{-2} s^{-1}
	Magnetopause nose radius		Nose magnetic field	Length of magnetic tail	Electric potential	Solar wind energy input	Auroral energy dissipation per unit area

magnetosphere. A rich variety of satellite interactions with planetary magnetospheres may therefore exist.

However large or small the magnetic moments, and consequently the magnetospheres of the outer planets may be, the magnetic field in their outer regions will be considerably weaker than at Earth, due to the attenuation of the solar wind dynamic pressure with increasing heliocentric distance. The estimate of B_N allows us to infer that Neptune's surface field need exceed only 1 or 2 γ for it to have a magnetospheric interaction with the solar wind.

Table II also lists parameters defining internal convection: the electric potential ϕ_P across the magnetosphere; the net energy input $\dot{W}_P$ from the solar wind into the magnetosphere; and the energy flux $\dot{\omega}_P$ into the high latitude ionosphere from auroral dissipation of the convective flow. Jupiter and Saturn should have considerably larger convection potentials, and absorb considerably more energy from the solar wind, than Earth, whereas Uranus and Neptune are comparable to Earth as far as convective energy dissipation is concerned. The auroral particle energy fluxes into the high latitude Jovian ionosphere could considerably exceed those at Earth, and might control its auroral ionospheric structure.

Table III lists parameters necessary for the comparison of corotation and convection: the convection time T_c, the ratio of convection to corotation time T_c/T_P, which is equivalent to Δ_{CR}, the relative ratio of corotation to convection electric fields at the

TABLE III

Corotation parameters

Planet	T_c(h)	T_c/T_P	Q_P/Q_E
Jupiter	256	25.6	6.7×10^2
Saturn	180	18	3.2×10^2
Uranus	66	6	3.6×10^1
Neptune	68	4.2	1.8×10^1
Earth	4	0.15	$Q_E = 10^{-4}$
	Convection time	$\frac{\text{Convection}}{\text{Corotation}}$	Corotation energy density parameter

magnetopause, and Q_P which characterizes β_{CR} at the magnetopause. Both T_c/T_P and Q_P favor corotation at the outer planets relative to Earth. On this basis, then, we expect relatively large regions of corotation flow, and relatively small regions of convection within these magnetospheres. Furthermore, Q_P is more than an order of magnitude larger for all the outer planets than for Earth, which, provided the plasma mass density is large enough, suggests the strong possibility of corotation-induced distortions in the magnetic field and/or interchange instabilities at these planets. This indicates that the simple calculation of the nose radius based upon an undistorted dipole field is incorrect and can at best be regarded as an order of magnitude estimate. Finally, the magnetopauses of the outer planets could be irregular and noisy due to counterstreaming effects, thereby permitting injection of relatively more particles into the radiation belts than at Earth.

Table IV lists several parameters of interest in radiation belt physics: the characteristic magnetic moment μ in the solar wind, the maximum particle energy attainable by radial diffusion μB_P^s, in MeV; the maximum particle energy attainable by convection, $e\phi_P$; the drift time $T_D(L)$ in hours, the ratio T_D/T_P of drift to corotation time, and J^*L^4 where J^* is the stably trapped flux limit defined by (3.4). If radial diffusion could bring particles to the surface of the planet without loss, it would produce several hundred MeV particles at the outer planets. Only protons would achieve such high energies, since electrons would lose energy to synchrotron radiation. The rings of Saturn should sweep out any radiation belt particles, so the maximum particle energy expected at Saturn is probably an order of magnitude smaller than the 600 MeV listed. The ratios T_D/T_P listed in Table IV indicate that beyond $L=2$, Jupiter's radial diffusion should be corotation dominated; Saturn's, beyond $L\approx 3$; Uranus', beyond $L=10$, and Neptune's, beyond $L=14$. The Earth's radial diffusion, by comparison, is never corotation dominated. When the corotation domination region extends close to the planet, as for Jupiter and Saturn, our previous arguments lead us to suspect that there may be efficient cross-field diffusion of high energy particles. Finally, the stably trapped flux limits are fortuitously similar for all the planets. However, whether or not the stably trapped flux limit applies depends upon whether the particle energies exceed $B^2/8\pi N$ – which implies a knowledge of the plasma density N – and whether the minimum precipitation lifetime is less than the radial diffusion time.

5. Discussion

We have scaled the magnetospheres of the outer planets according to the theoretical variation of solar wind parameters and to Moroz's magnetic Bode's law for the magnetic moments. In the absence of better information, we have assumed where necessary that Earth-like physics prevails at the outer planets. The inconsistencies arising from this procedure suggest that the magnetospheres of the outer planets could be very different from the Earth's. Several broad conclusions emerge. First, convection and its associated auroral precipitation should play a relatively smaller role at the outer planets than Earth. Corotation dominates. This in turn suggests that solar wind particles may penetrate a disturbed magnetopause and radially diffuse into the dipole more efficiently than at Earth. The general increase in solar wind magnetic moment with increasing heliocentric distance indicates that the radiation belt particles could be considerably more energetic than at Earth. Thus, the outer planets' magnetospheres could be radiation-belt dominated.

Uranus will undoubtedly be very surprising. Its rotation axis is inclined roughly 98° to the normal to its orbital plane, so that twice per orbit, its rotation axis points nearly towards the Sun. This configuration will occur in 1988. This suggests the possibility of a new and unusual magnetospheric configuration, if it turns out that its magnetic moment is aligned more or less along its rotation axis, as is the case for Earth and

TABLE IV

Radiation Belt Parameters

Planet	μ(MeV G^{-1})	$\mu B_P{}^S$(MeV)	$e\phi_P$(keV)	$T_D(L)$ (h)	T_D/T_P	L^*	J^*L^4 cm^{-2} s^{-1}
Jupiter	84	1000	400	2.5 L^2 h	0.25 L^2	2	10^{11}
Saturn	150	6000	150	1.4 L^2 h	0.14 L^2	3	6.5×10^{10}
Uranus	300	375	30	0.125 L^2 h	0.012 L^2	10	5×10^{10}
Neptune	500	450	15	0.075 L^2 h	5×10^{-3} L^2	15	3×10^{10}
Earth	16	5	30	0.15 L^2 h	6×10^{-3} L^2		5×10^{10}
	Magnetic moment of solar wind particles	Maximum energy attainable by radial diffusion	Maximum energy attainable by convection	Drift time	Ratio of drift to corotation time	Distance at which $T_D = T_P$	Stably trapped flux limit

Jupiter. W. P. Olson has calculated the shape of the nose of the Uranian magnetosphere based upon this assumption; his results are presented in Figure 4. In this case, the 'polar cap' points directly towards the Sun, and there exists the possibility of direct penetration of solar wind to the planetary surface. Whether or not this implies an especially intense radiation belt is unclear. Furthermore, it is unclear to this author

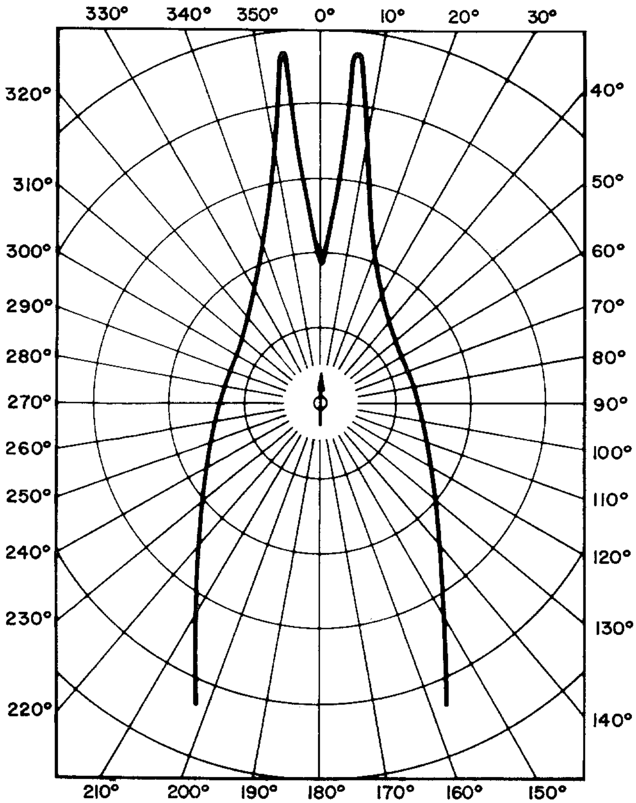

Fig. 4. *Nose of the magnetosphere of Uranus* – Shown here are results of calculations by W. P Olson of the nose of Uranus' magnetosphere. The solar wind impinges upon the planet at 0°. Magnetosheath plasma could directly penetrate the magnetosphere along the 0° line.

whether or not the computed magnetopause configuration is stable. Siscoe (1971) has discussed convection of Uranus and the topology of a possible Uranian magnetic tail: his results are presented in Figure 5. Magnetopause and tail reconnection both take place on lines of force connecting to magnetic poles. It seems likely that the atmospheric tidal dynamo, postulated by Brice and McDonough to drive radial diffusion at Jupiter, will be most unusual at Uranus. Many of the parameters derived above for Uranus must be therefore regarded with especial suspicion.

Let us now discuss some priorities for outer planets exploration. The first priority is clearly just detection of the planetary magnetic fields, by whatever combination of

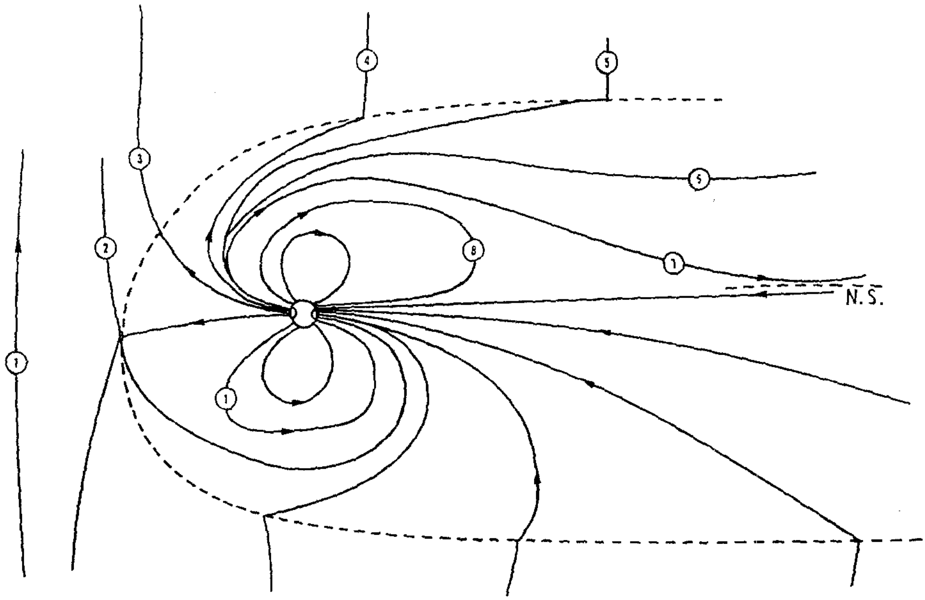

Fig. 5. *Convection and the magnetic tail in the magnetosphere of Uranus* – Reproduced here is a schematic of the convective motions postulated by Siscoe (1971). The numbers label a magnetic tube of force at successive instants in its interaction with Uranus. Point 2 corresponds to field annihilation at the nose of the magnetosphere; N.S. denotes neutral sheet. Corotation around the dipole axis has been neglected; it would be expected to give the field lines a helical twist.

magnetic field, energetic particle, and radio frequency detectors turns out to be appropriate. Since the magnetic fields at the noses of Saturn's and Uranus' magnetospheres are not inordinately small, magnetic detection presents no instrumental difficulties. Detection of magnetic moments of Saturn and Uranus would double the number of data points relating to the dynamo theory of planetary magnetism, and provide valuable information about their deep interiors. The problem of Jupiter is different, since its magnetic moment has already been detected, and a long list of questions concerning its magnetosphere has already been compiled. The most significant such question seems to be that of the intensity of Jupiter's *proton* radiation belts, which are inobservable by radio techniques. Aside from their intrinsic interest, the proton belts could provide a significant radiation hazard to the spacecraft, and so are of considerable engineering interest as well. Presumably, Pioneers 10 and G will detect the radiation belt protons, and define safe regions of the Jovian magnetosphere for future fly-bys. (The radiation hazard at Saturn may also be non-negligible.) At this point, the phase of detailed investigation of the Jovian magnetosphere may begin. The use of Jupiter gravitational assist for missions to the outer planets ensures many passes through Jupiter's magnetosphere. Our state of knowledge concerning Jupiter's magnetosphere indicates that it should be the first planet meriting the detailed observations afforded by an orbiter. Our scaling laws suggest that the other outer planets are more like Jupiter than they are like Earth, perhaps a further justification for seeking detailed understanding of the Jovian magnetosphere. It is often casually stated that of the outer planets, Jupiter and Saturn form a similar pair and Uranus and Neptune another. If this be so, the unusual magnetosphere suggested by the orientation of Uranus' rotation axis suggests a preference for Uranus over Neptune, which is fortunate since Uranus is closer. Elucidation of the possibly many and different interactions of the outer planets' satellites with their magnetospheres is of considerable interest, since it may provide information relating to their deep interiors and to the dynamics of their radiation belts. The modulation of the Jovian decametric radio emissions by Io is one of the enchanting mysteries of magnetospheric physics.

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