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Is Jupiter's Magnetosphere like a Pulsar's or Earth's?

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1. Introduction

Can Jupiter teach us about pulsars? The many prima facie analogies between Jupiter and pulsars--both are oblique magnetic rotators generating and containing healthy fluxes of relativistic particles, both are sources of cosmic rays and radio emissions, they even have comparable magnetic moments--make the above question an interesting one. At a deeper level, the recent Pioneer 10 encounter revealed a magnetic structure in Jupiter's outer magnetosphere reminiscent of hydromagnetic outflow solutions postulated for pulsars (Michel, 1969, 1971) and also suggested for Jupiter (Piddington, 1969; Ioannidis and Brice, 1971; Hill et al., 1974; Michel and Sturrock, 1974).

One way to approach the above question is to turn it around: Can pulsar physics teach us about Jupiter? In this paper, we treat Jupiter's magnetosphere as an astrophysicist would when a new exotic object has just been discovered. We will impose upon the data--and upon our conceptualizations!--a variety of oversimplified theoretical models whose function is to illuminate broad areas of consistency or conflict between theory and experiment. With such a procedure, we must expect that what the models fail to explain may be fully as interesting as any experimental number s they happen to fit.

We compare two possible models of Jupiter's magnetosphere --a pulsar-like radial outflow model and an earth-like convection model. In Chapter 2, we ask what kind of super-Alfvénic radial outflow model does the available Pioneer 10 data seem to require. We concentrate on estimating the total particle and energy fluxes which must be provided by Jupiter--or its magnetosphere within the Alfvén radius--to power the outflow. In Chapter 3, we consider a convection model, concentrating upon weakening the objections previously held by theoreticians against a dominant role for convection in Jupiter's magnetosphere. In Chapter 4, we report our preliminary and incomplete consideration of one fundamental assumption underlying all outflow models and nearly all convection models. We ask to what extent can Jupiter actually enforce corotation on its magnetosphere. Since much of our paper is a compilation of the simple order of magnitude estimates derivable from the various models we have posed, the reader may wish to turn first to Chapter 5 where the point of view which emerges from this compilation is summarized. At present, there appears to be sufficient difficulty with the outflow model that convection ought to be taken seriously.

2. A Radial Outflow Model for Jupiter's Magnetosphere

2.1 Introduction

In this chapter we ask to what extent Jupiter behaves like a spinar (Morrison, 1969); to what extent does the hydromagnetic interaction of Jupiter's spin with the solar wind determine the structure, energy, and evolution of its magnetosphere and possibly its spin. A basic requirement for a spinar-type solution is that Jupiter possesses sources of both particles and energy within the magnetosphere which exceed any external solar wind particle and energy source. To aid the imagination we will assume that Jupiter has a radial outflow solution similar to that constructed by Mestel (1968) for the magnetic deceleration of rotating stars. We then use Pioneer 10 measurements to infer the number and energy source strengths required to drive the postulated radial outflow (Kennel and Coroniti, 1974).

Following Mestel (1968) we assume for simplicity that Jupiter's rotational and magnetic dipole axes are aligned, and that Jupiter possesses a <u>centered</u> dipole moment with equatorial field strength of 4 Gauss. Near Jupiter the magnetic field is assumed to be that of a rotating dipole field. This condition persists out to a certain critical equatorial radius, where the flow and magnetic stresses become equal. Beyond this radius we assume that a two-dimensional radial outflow solution of the type discussed by Weber and Davis (1967) prevails near the spin-magnetic equatorial plane. The magnetic field has only radial and azimuthal components B_r, B_φ; the absence of the field component B_z, normal to the outflow disk, is a shortcoming of this solution. The observations indicate that if a radial outflow solution exists, it exists in a thin outflow disk of half-height h above the spin-magnetic equatorial plane. We do not discuss here what might happen to field lines above the radial outflow disk, although reconnection of Jovian and solar wind field lines might produce a magnetopause similar to earth's there. The critical radius is defined to be the Alfvén point of the Weber-Davis solution, where $4\pi\rho U^2 / B_r^2 = 1$, and ρU^2 is the dynamic pressure of the radial outflow. The Jovicentric distance r_a to the Alfven point is estimated by assuming that $B_r(r_a)$ is roughly equal to the vacuum dipole field $B_D(r_a)$ at distance r_a. Our model is sketched in Figure 1. While Pioneer 10 did not measure a synoptic set of hydromagnetic flow parameters, it did provide us with the mass density ρ_s, flow speed U_s, and dynamic pressure $\rho_s U_s^2$ of the solar wind upstream of Jupiter's bow shock prior to magnetopause encounter, the Jovicentric distance to the magnetopause r_m, and, from the 10-hr "flapping" of the disk, a rough estimate of its height h. In addition, Pioneer 10 measured the magnetic field strength B at the magnetopause, the sign of the azimuthal component B_φ, and rough average values of $|B_\varphi / B_r|$ in the distant magnetosphere. We will restrict our present discussion to published data from Pioneer 10's first magnetopause crossing, but in principle it is an easy matter to perform the same analysis for other magnetopause crossings. The data are sufficient to permit us to estimate certain basic parameters of the assumed outflow solution.

2.2 Required particle and energy outflows

If, as postulated, the radial outflow is super-Alfvénic, it must be terminated by a fast shock near the magnetopause which decelerates the flow as it enters the magnetosheath. The magnetopause fast shock differs from Jupiter's bow shock, which decelerates the solar wind. The flows behind the bow and magnetopause shocks would be separated by a tangential discontinuity if strict magnetohydrodynamics were applicable. Near the edge of the disk, $z \approx h$, the flow is presumably Alfvénic, and so above the disk a fast shock is not a necessary part of the magnetopause structure. In steady state, pressure equality should apply across this system of shocks. Near the subsolar point, where Pioneer 10 first encountered the magnetopause, this implies the rough equality

$$N_m M_{:} U_m^2 \simeq N_s M_H U_s^2 \qquad (2.1)$$

where N_m and U_m are the number density and radial flow velocity of the internal flow at the magnetopause, and M_s and U_s are the corresponding values in the solar wind ahead of the bow shock. M_H is the mass of a hydrogen ion, and M_+ the mass of the ions flowing out from Jupiter.

We estimate U_m as follows: In the Weber-Davis solution, assuming $r_m >> r_a$, we have the relation

$$B_\varphi / B_r = - r\Omega / U \tag{2.2}$$

where r is the Jovicentric distance and Ω is the angular velocity of the field lines at $r = r_a$. Pioneer 10 magnetic observations (Smith et al., 1974; E.J. Smith, private communication) indicate that while B_φ/B_r is highly variable within the disk, the time-averaged B_φ/B_r is negative--consistent with the "garden hose" field expected with radial outflow--and its magnitude $|B_\varphi/B_r| < 1$. While it is not yet entirely clear to us whether this information applies to the center of the disk as well as to its edges, we will explore its consequences. Inserting into the relation $U_m = r_m \Omega_J |B_r/B_\varphi|$ the observed $r_m \simeq 100\ R_J$, $\Omega = \Omega_J = 1.74 \times 10^{-4}$ rad/sec--Jupiter's spin frequency, we find that $U_m \simeq 10^8 |B_r/B_\varphi|$ cm/sec. In other words, the required flow energy is $5(M_+/M_H)(B_r/B_\varphi)^2$ keV. From (2.1) we may now estimate N at the magnetopause

$$N_m = N_s (M_H/M_+)(U_s/r_m\Omega)^2 (B_\varphi/B_r)^2 \tag{2.3}$$

and the particle number flux

$$N_m U_m = (N_s U_s^2 / r_m \Omega_J)(M_H/M_+) |B_\varphi/B_r| \tag{2.4}$$

The total particle outflux $\dot{\eta} = N_m U_m A_m$, where A_m is the <u>dayside</u> frontal area of the outflow disk, follows immediately by estimating $A_m \simeq 2\pi r_m h$, whereupon

$$\dot{\eta} = N_s U_s^2 (M_H/M_+) \; (2\pi/\Omega_J) |hB_\varphi/B_r| \tag{2.5}$$

The energy outflow $\dot{W} = \frac{1}{2} N_m M_+ U_m^3 A_m$ is similarly estimated

$$\dot{W} \simeq \pi \rho_s U_s^2 \Omega_J r_m^2 |hB_r/B_\varphi| \tag{2.6}$$

We may normalize $\dot{\eta}$ and $\dot{W}$ to $\dot{\eta}_s$ and $\dot{W}_s$, the solar wind number flux and flow energy flux crossing the area πr_m^2

$$\dot{\eta}/\dot{\eta}_s = 2(M_H/M_+)(U_s/U_m)(h/r_m)$$

$$\dot{W}/\dot{W}_s \simeq (2\Omega_J h/U_s) |B_\varphi/B_r| (M_+/M_H) = 2(U_m/U_s)(M_+/M_H)(h/r_m) \tag{2.7}$$

According to Wolfe <u>et al.</u> (1974), before the first shock encounter, $N_s \simeq 3 \times 10^{-2}$ cm^{-3} and $U_s \simeq 420$ km/sec. Thus, expressing h in units of $R_J = 7 \times 10^9$ cm

$$N_m \approx 3 \times 10^{-3} |B_\varphi/B_r|^2 \text{ cm}^{-3}$$

$$\dot{\eta} \approx 10^{28} (M_H/M_+) |hB_\varphi/B_r| \text{ par/sec}$$

$$\dot{\eta}/\eta_s \approx 10^{-2} (M_H/M_+) |hB_\varphi/B_r|$$

$$\dot{W} \sim 10^{20} |hB_r/B_\varphi| (M_+/M_H) \text{ ergs/sec}$$

$$\dot{W}/W_s \sim 5 \times 10^{-2} |hB_r/B_\varphi| \qquad (2.8)$$

It seems that typical values for h and $|B_\varphi/B_r|$ are a few R_J and 1/3 respectively, so that $|hB_\varphi/B_r|$ is 0(1) and $|hB_r/B_\varphi|$ is 0(10).

Equation (2.8) does not support the notion that particle and energy input from the solar wind could be neglected, even if Jupiter had a radial outflow solution. For example, the earth's magnetosphere captures 10^{-3-2} of the particles crossing πr_m^2 at the earth; there the number of particles circulating through its magnetospheric convection pattern is $\approx 10^{26-27}$ sec and $\eta_s \approx 10^{29}$ sec. Similarly, the energy dissipated by the solar wind into the earth's magnetosphere is $\approx 10^{18}$ ergs/sec and $\dot{W}_s \sim 10^{20}$ ergs/sec. Thus, Jupiter, strictly speaking, probably cannot be a pure spinar. Moreover, it is difficult to see how Jupiter generates particle fluxes $\approx 10^{28}$ sec $(\text{assuming } M_+ = M_H)$ and energy fluxes $\approx 10^{21}$ ergs/sec within its Alfvén radius. For example, if all the ions produced by solar UV ionization in Jupiter's dayside ionosphere were sucked into the radial outflow before recombining, a gross upper limit, only 10^{28} par/sec would flow out (Hill et al., 1974). Similarly, Io's atmosphere produces a torus of neutral gas near the orbit of Io. Some 10^{27} neutrals/sec are required to maintain this torus (R. Carlson, private communication). Even if all the neutrals were lost by ionization and no charge exchange occurred, Io's ring could not provide the required plasma number flux. Frank (1974) has reported generation of a few hundred eV ions near Europa, but no source strength has been given. In any case, even if the number flux could be accounted for it is difficult to see how the plasma generates some tens of keV mean energy at the Alfvén point, since the corotation energy at the Alfvén point (to be computed in Chapter 4) is only a keV or so.

2.3 Summary

Several serious questions bedevil the simple radial outflow model for Jupiter's magnetosphere posed in this chapter. Particle and energy sources of 10^{28} par/sec and 10^{21} ergs/sec respectively must be found within the Alfvén radius. It is unlikely that photoionization in the Jovian ionosphere can produce the requisite particle source. Even if the requisite internal number and energy sources could be found, our estimates do not make a compelling case that particle and energy input from the solar wind can be safely neglected.

3. A Convection Model of Jupiter's Magnetosphere

3.1 Introduction

It is now abundantly clear that magnetic field line reconnection occurs regularly and is, in fact, responsible for convection in the earth's magnetosphere. The Dungey (1961) model of the earth's magnetosphere is essentially correct. Two tests indicate that reconnection at the nose of the earth's magnetosphere occurs. First, the field lines in the earth's polar caps are definitely open, permitting rapid access of solar cosmic ray electrons (Lin and Anderson, 1966). Second, the intensity of the magnetospheric convective circulation pattern is largest when the solar wind field is southward, the theoretically optimum configuration for reconnection at the nose of the earth's magnetosphere (see Arnoldy, 1971 and references therein). The phenomenological studies between various measurables within the magnetosphere and conditions in the solar wind seem now to be providing answers to two questions concerning field line reconnection on which laboratory experimentation and theory shed at best a dim light. These are "how does the reconnection rate depend upon the relative orientations of the magnetic field directions on either side of the neutral sheet" and "how fast can the reconnection rate be". The answers seem to be that except possibly for the special case where the magnetic fields are parallel on both sides of the neutral sheet, some reconnection will occur (Mozer et al., 1974). Moreover, the response of the magnetosphere to changes in the solar wind field direction (Burch, 1974) suggests that the nose reconnection rate follows small changes in the solar wind field "sweetly and docilely". Satellite observations of several hundred kV potentials across the earth's polar caps (Gurnett and Frank, 1973)--a significant fraction of the total solar wind $\underline{U}_s \times \underline{B}$ potential across the width of the earth's magnetosphere--indicate that at times, reconnection can be very rapid. In fact, the auroral and magnetospheric substorm may well be a consequence of changes in the reconnection rate. The simplest picture of a substorm--still controversial outside UCLA--holds that it has two phases, a "growth" and a "breakup" phase (McPherron, 1970; Coroniti and Kennel, 1973). Nose reconnection starts the growth phase in this picture. Following an increase in the nose reconnection rate, the convective flow increases in intensity; magnetic flux is added to the geomagnetic tail, so that the polar caps increase in area; and the entire magnetosphere goes through an identifiable sequence of configurational changes (Coroniti and Kennel, 1972). When this has proceeded long enough, explosive reconnection occurs in the earth's plasma sheet 15 - 30 R_E from the earth (Nishida and Nagayama, 1973), thereby initiating the "breakup" phase of rapid injection of plasma into the dipolar region of the geomagnetic field and great intensification and poleward motions of the auroral arcs bounding the equatorward edge of the polar cap. Recently Siscoe and Crooker (1974) have found a theoretical relation between nose reconnection rate and the rate of energy injection into the inner magnetosphere which places the tail reconnection region at 15 - 30 R_E, in agreement with observation.

All in all, sound advice for those constructing models of other magnetospheres seems to be that one neglects reconnection at his peril. If the magnetic field configuration allows for the possibility of reconnection, it is much better to assume that it does occur then to assume that it does not (Kennel, 1974). There is, therefore, no doubt that reconnection will occur in Jupiter's magnetosphere. The real question is whether it will have significant effects. We might ask, for example whether the solar wind can dissipate as much energy into Jupiter's magnetosphere as it seems Jupiter must provide to power the postulated radial outflow discussed in Chapter 2. We can compute an upper limit to the reconnection energy dissipation rate as follows. The solar wind $\underline{U}_s \times \underline{B}_s$ emf Φ across the width 3 r_m of Jupiter's magnetosphere is given by

$$\Phi = \frac{3U_sB_s}{e} r_m \simeq 10 \text{ MV} \qquad (3.1)$$

where U_s = 400 km/sec, $B_s \simeq 1\gamma$, and r_m 100 R_J. The energy dissipation rate $\dot{W}$ is given by computing the total current in the reconnection region of the dayside magnetopause and multiplying by Φ, assuming all the solar wind flux crossing Jupiter's magnetosphere is reconnected. The current per unit length along the magnetosphere is $c\Delta B/4\pi$ where ΔB is the jump in magnetic field strength at the magnetopause. The total current I is then approximately $(c\Delta B/4\pi)\ell_{eff}$ where ℓ_{eff} is the effective length, normal to the ecliptic plane, of the reconnection region

$$\dot{W} = (C\Delta B/4\pi)\ell_{eff}\Phi \sim 2 \times 10^{21} \text{ ergs/sec} \qquad (3.2)$$

where we choose $\Delta B \approx 4\gamma$, the measured field at the magnetopause (Smith et al., 1974) and $\ell_{eff} \approx r_m \simeq 100\ R_J$ above. For the earth, (3.2) yields 10^{19} ergs/sec.

The reconnection upper limit energy dissipation rate, (3.2), and the energy outflow required by the radial outflow model, (2.8), are comparable in magnitude. This suggests that even if Jupiter did possess a strong radial outflow, it would be unwise to neglect reconnection and convection driven by the solar wind. Moreover, the reconnection dissipation rate is sufficiently large to make reasonable the consideration of a pure convection model where all the particles and energy come from the solar wind rather than from Jupiter's inner magnetosphere. This we shall do in the remainder of this chapter. In view of our discussion in Chapter 2, a reconnection model possesses several attractive features. Since the radially extended magnetic field observed in Jupiter's outer magnetosphere reveals the presence of significant hydromagnetic stresses, it is likely that the hydromagnetic outflow theory discussed in Chapter 2 may indicate at least the order of magnitude of the grossest features of any hydromagnetic flow solution. If so, a convection model may not have any particular difficulties supplying the requisite number and energy fluxes circulating through Jupiter's magnetosphere. Moreover, since convection in the earth's magnetosphere easily creates plasma temperatures in the ring current of some tens of keV when the solar wind emf is of order 100 kV, supplying high temperature plasma if it is needed for Jupiter seems to be no problem either.

3.2 Length of Jupiter's magnetic tail and convection flow time

The length of Jupiter's magnetic tail may be computed, following Dungey (1965) if Φ and the radius of the polar cap r_{pc} are known. The electric field in Jupiter's ionosphere is of order $\Phi/2r_{pc}$ in magnitude; the convection speed is therefore $\sim c\Phi/2r_{pc}B_I$ where B_I is the ionospheric magnetic field. The foot of a field line in the ionosphere crosses the polar cap in a time $\tau = 4r_{pc}^2 B_I / C\Phi$, and the length of the tail $L_T \simeq U_s\tau$.

We define $r_{pc} = R_J/\sqrt{L_{pc}}$ where L_{pc} is the L-shell of the last closed field line, and estimate Φ as before by $3r_m\left(U_s B_s/c\right)\beta$ where $\beta < 1$ parameterizes the efficiency of reconnection, whereupon

$$\tau \simeq \frac{R_J}{r_m}\frac{B_J}{B_s}\frac{R_J}{U_s L_{pc}\beta} \approx \frac{14}{\beta}\ \text{hours} \tag{3.3a}$$

$$\frac{L_T}{R_J} = \frac{R_J}{r_m}\frac{B_I}{B_s}\frac{1}{L_{pc}\beta} \approx \frac{300}{\beta} \tag{3.3b}$$

In (3.3) we chose $R_J/r_m \simeq 10^{-2}$, $B_I = 8$ Gauss, $B_s \simeq 1\gamma$. L_{pc} is not known. We chose $L_{pc} \simeq 30$ corresponding to the radial Jovicentric distance where distortions from a dipolar field begin to become small (Smith et al., 1974). Choosing $\beta \simeq 0.1$, we arrive at $L_T \sim 3000\ R_J$, roughly the estimate Kennel (1973) arrived at by a completely different means. We note that Jupiter rotates once in 14 hr minimum convection time and if $\beta << 1$ may rotate many times in a convection time.

3.3 Locating Jupiter's plasmapause and magnetopause

Given Jupiter's magnetic moment $\vec{M}$ and its spin $\vec{\Omega}$ and one simple fact--that reconnection imposes a more or less uniform electric field E_c of order $\beta U_s B_s/c$ across the magnetosphere--can one locate Jupiter's plasmapause and magnetopause? We begin by reconstructing Brice and Ioannidis' (1970) model for Jupiter's plasmapause. We assume that Jupiter is an aligned rotator, $\vec{M} \parallel \vec{\Omega}$, and that corotation is imposed at the foot of all field lines with the angular velocity Ω_J. Then in the spin-magnetic equatorial plane the convection potential φ_c is given by

$$\varphi_c = E_c r \sin\theta \tag{3.4}$$

where r is the Jovicentric distance, and θ is measured clockwise from the midnight meridian. The corotation electric field E_{CR}, for a dipole magnetic field, is

$$E_{CR} = \frac{\Omega r B}{c} = \frac{\Omega R_J B_0}{c}\left(\frac{R_J}{r}\right)^2 \tag{3.5}$$

and points radially outwards. B_0 is the equatorial surface field strength. At local dusk, $\theta = \pi/2$, there is a stagnation point in the flow where the corotation and convection speeds just cancel. The Jovicentric distance r_p to the dusk plasmapause may be found by equating the magnitudes of E_c and E_{CR}

$$\left(\frac{r_p}{R_J}\right) = \left[\frac{\Omega_J R_J B_0}{cE_c}\right]^{\frac{1}{2}} = \left[\frac{\Omega_J R_J B_0}{\beta U_s B_s}\right]^{\frac{1}{2}} \tag{3.6}$$

The corotation potential is given by

$$\varphi_{CR} - \varphi_{CR}\left(r_p\right) = \frac{\Omega_J R_J^2 B_0}{c}\left[\frac{R_J}{r} - \frac{R_J}{r_p}\right] \tag{3.7}$$

and the total corotation potential $\varphi_T = \varphi_{CR} + \varphi_c$ is

$$\varphi_T = \frac{\Omega_J R_J^2 B_0}{c}\left(\frac{R_J}{r} - \frac{R_J}{r_p}\right) + E_c R_J\left[\frac{r}{R_J}\sin\theta - \frac{r_p}{R_J}\right] \tag{3.8}$$

where we have defined $\varphi_T\left(r_0\right) = 0$.

The plasmapause is the curve in the spin-magnetic equator on which $\varphi = 0$. At local dawn, $\theta = -\pi/2$, the radius r_p^* of the plasmapause is defined by the condition $\varphi_T\left(r_p^*, -\pi/2\right) = 0$. This leads to the equation $y^2 + 2y - 1$, where $y = r_p^*/r_p$, which has the non-trivial solution $r_p^*/r_p = -1 + \sqrt{2} \simeq 0.4$. Thus the plasmasphere has minimum radius $0.4\ r_p$ and maximum radius r_p. Using $\Omega_J = 1.75 \times 10^{-4}$ rad/sec, $B_0 = 4$ Gauss, $U_s = 4 \times 10^7$ cm/sec, and $B_s = 1\gamma$, we find $r_p \simeq 100/\sqrt{\beta}\, R_J$.

In computing their plasmapause position Brice and Ioannidis (1970) had assumed that the energy density of the convecting plasma was very nearly zero. There were two reasons for this: first, they assumed an undistorted dipole magnetic field everywhere; and second, they neglected all gradient drifts in arguing that all convecting particles would follow equipotentials and would therefore avoid the plasmapause defined by $\varphi_T = 0$. Therefore, the only consistent way of locating the magnetopause was to assume that it formed where solar wind dynamic pressure was balanced by twice the magnetic pressure. The nose radius r_m^o of this dipolar magnetopause is located by the standard relation

$$\frac{r_m^o}{R_J} \sim \left[\frac{B_0^2}{2\pi\rho_s U_s^2}\right]^{1/6} \approx 55\ R_J \tag{3.9}$$

using $B_0 = 4$ Gauss, and $\rho_s U_s^2 \sim 8 \times 10^{-11}$ ergs/cm^3, corresponding to upstream solar wind parameters prior to the first Pioneer 10 magnetopause crossing (Wolfe et al., 1974).

Let us compare the mean radius of the plasmapause $0.7 r_p = \tilde{r}_p$ with the dipolar nose radius r_m^o

$$\frac{\tilde{r}_p}{r_m^o} = 0.7\left(\frac{\Omega_J R_J}{\beta B_s}\right)^{1/2}\left(\frac{2\pi B_0 \rho_s}{U_s}\right)^{1/6} \approx \frac{1.25}{\sqrt{\beta}} \tag{3.10}$$

Thus Brice and Ioannidis found that the plasmapause extended beyond the magnetopause. This led them and their followers (Kennel, 1973) to suppose that convection could never be important in Jupiter's magnetosphere, since convection could never penetrate close to the planet. In fact, with these numbers it was difficult to see how the flux carried by convection (if it occurred) could ever penetrate to the frontside of the magnetosphere

There was, however, something Brice overlooked: it is very likely that the flow speed near the plasmapause would be super-Alfvénic. This means that the convective flow energy density would exceed the magnetic energy density near the plasmapause and that the dipolar magnetic field would be strongly distorted. We will establish the plausibility of this point by a <u>reductio ad absurdem</u>: we will assume a dipolar field and then compute the ratio of the E/B convection speed to the Alfvén speed C_A at the mean radius of the plasmapause, 0.7 r_p, where r_p is also computed assuming a dipolar field. Let us call this ratio $\mathcal{R}$. Substituting $E_c \simeq \beta \frac{U_s B_s}{c}$, and $r_p/R_J = \left[\frac{\Omega_J R_J B_0}{\beta U_s B_s}\right]^{\frac{1}{2}}$ and reducing, we find

$$\mathcal{R} = \frac{\sqrt{N}}{\beta^2}(0.7)^6 \frac{B_0}{\left(U_s B_s\right)^2}\left(\Omega_J R_J\right)^3 \sqrt{4\pi M_H} \qquad (3.11)$$

where N is the number density at the plasmapause and M_H is the proton mass. Substituting $U_s = 4 \times 10^7$ cm/sec, $B_s = 1\gamma$, $\Omega_J R_J = 1.2 \times 10^6$ cm/sec, $B_0 = 4$ Gauss, we find for Jupiter

$$\mathcal{R}_J = \frac{20\sqrt{N}}{\beta^2} \qquad (3.12)$$

whereas substituting $B_0 = 1/3$G, $U_s = 4 \times 10^7$, $B_s = 5\gamma$, $\Omega_E R_E = 4 \times 10^4$ cm/sec, we find for a much less restrictive condition for earth

$$\mathcal{R}_E = \frac{3 \times 10^{-6}\sqrt{N}}{\beta^2} \qquad (3.13)$$

Thus, for the flow to be sub-Alfvénic at Jupiter's plasmapause the plasma density must satisfy $N < 4 \times 10^{-3}\beta^4$ cm^{-3}, whereas at earth it must satisfy $N < 10^{11}\beta^4$ cm^{-3}. On this basis we may conclude that it is very likely that the convection flow is sub-Alfvénic at the earth's plasmapause and super-Alfvenic at Jupiter's.

What does this all mean? It means first of all that Brice and Ioannidis' (1970) computation of the plasmapause location was incorrect since for all but the most unrealistically low densities the super-Alfvénic flow stresses will strongly distort the dipolar magnetic field. It also means that the standard computation of the magnetopause nose radius is incorrect, since the flow energy density beyond the plasmapause exceeds the magnetic energy density near the magnetic equator. This suggests that convection will push out the magnetopuase in the magnetic equatorial plane. A full hydromagnetic theory of this kind of flow is very difficult, and we are far from even complete conceptual understanding of it, much less an analytic theory. Nonetheless, the above arguments suggest that convection in Jupiter's outer magnetosphere would mimic what one expects from radial outflow solutions. Both would have relatively thin disks of super-Alfvénic flow and radially extended magnetic fields. Figure 2 summarizes our arguments.

At this point it is useful to note that the earth may have Jupiter-like magnetopauses during strong convection events--magnetic storms and substorms. The magnetometer experiment on OGO-1 (Heppner <u>et al.</u>, 1967) found a large region of constant magnetic field strength near the morning magnetopause, which was pushed out farther than the calculated magnetopause position based upon a dipole field during substorms. Figure 3 shows one of their events in which the magnetic field strength increased as the spacecraft crossed the magnetopause into the magnetosheath. Heppner et al. (1967) argued that this was due to the presence of high pressure plasma near the magnetopause. The above arguments suggest, however, that, following substorm breakup and during strong convection events in general, the flow in the earth's outer magnetosphere may be super-Alfvénic near the dipole equator, just as it is super-Alfvénic in the plasmasheet at these times. In view of the absence of a good theory of super-Alfvénic convection in Jupiter's outer magnetosphere, the possibility that earth may have such solutions is in our opinion a very strong reason for taking a convection model of Jupiter's magnetosphere seriously. If the analogy is a true one, then the observed great variability of Jupiter's magnetopause location might have a simple explanation: it is due to substorms.

The above arguments indicate that further studies of the earth's dayside magnetopause might be extremely illuminating, both in and for themselves, and as a possible analog for the behavior of Jupiter's magnetopause. For example, it is thought that the earth's magnetopause moves inward prior to substorm breakup (Aubry et al., 1970; Coroniti and Kennel, 1973); does it move outward following breakup? Does it begin to move outward in less than the Alfvén travel time between the tail neutral line and the dayside magnetopause? Is the field near the magnetopause radially extended? Does the magnetopause bulge near the equatorial plane following breakup?

3.4 Summary

1. Reconnection at the nose of Jupiter's magnetosphere can dissipate as much energy as the radial outflow solution discussed in Chapter 2. Even if an internally driven outflow exists, it would therefore be unwise to neglect convection.

2. Brice and Ioannidis' original plasmapause solution (1970) overlooked the likelihood that convection would be super-Alfvénic in Jupiter's outer magnetosphere. This implies that the standard computation of Jupiter's magnetopause nose radius is incorrect. Just as in the radial outflow solution, convection would push out Jupiter's magnetopause. Since either solution has a super-Alfvénic flow near the magnetopause, shocks are a necessary part of the magnetopause solution.

3. OGO-1 may have observed Jupiter-like earth magnetopauses in the local morning sector during substorms. If so, these observations are a good reason for taking a convection of Jupiter's magnetosphere seriously.

4. Pioneer 10 encountered magnetopauses from 100 to 240 R_J on its outbound pass through Jupiter's dawn sector. Since with super-Alfvénic convection the magnetopause position depends not only on variations in the solar wind dynamic pressure but also on variations in the convection dynamic pressure, the observed variability of Jupiter's magnetopause location could be due to substorms if, as at earth, convection is time-variable.

4. Coupling of Jupiter's Ionosphere and Atmosphere to either Radial Outflow or Convection Magnetospheres

4.1 Introduction

We now turn to one feature which distinguishes planetary from pulsar magnetospheres--the existence of a neutral non-conducting atmosphere separating the highly conducting planet from the conducting ionosphere--where convection first interacts with neutral material gravitationally bound to the planet. This means that hydromagnetic stresses cannot be communicated directly between the planet and ionosphere the way such stresses are known to be communicated between the earth's ionosphere and magnetosphere--by a circuit involving field-aligned currents between ionosphere and magnetosphere which exert stresses as they close by currents flowing perpendicular to the magnetic field in the ionosphere and magnetosphere. The effect permits significant convection in the earth's ionosphere, since a convection electric field can exist in the ionosphere yet be very small in the earth's crust. In effect, the ionospheric field lines can "slide over" the field lines below the ionosphere which are held in place by the high conductivity of the earth.

For aligned rotators, rotation does not induce an electric field, in the non-rotating frame, between the conducting planet and conducting ionosphere. Since the conductivity law in the ionosphere has the form $\vec{j} = \underset{\approx}{\sigma}\left(\vec{E} + \vec{V}_n \times \vec{B}/c\right)$ where $\underset{\approx}{\sigma}$ is the conductivity tensor and $\vec{V}_n$ the neutral velocity, there can be an equivalent corotation electric field $(\vec{\Omega} \times \vec{r}) \times \vec{B}/c$ induced by the rotation of the neutral atmosphere with angular velocity $\vec{\Omega}$. This makes it clear, however, that corotation can only be enforced on the magnetosphere through upward diffusion of atmospheric angular momentum, which then couples to the ionosphere through ion-neutral collisions. In steady state, the angular momentum acquired by the magnetosphere must balance that provided by the atmosphere (Hines, 1974).

In this chapter we investigate the validity for an aligned rotator of one of the key assumptions underlying the discussions of both Chapters 2 and 3. In Chapter 2 we assumed that the solid body angular frequency Ω_J was imposed on all the flux tubes involved in the radial outflow. The model of the plasmapause discussed in Chapter 3 tacitly assumed that planetary corotation could be imposed upon convecting field lines. While significant differences exist between aligned and oblique rotators, nonetheless, our discussion of the aligned rotator case raises the question of how and to what extent corotation can be imposed on Jupiter's ionosphere, magnetosphere, and upper atmosphere.

4.2 Coupling of atmospheric torque to radial outflow

In this section we first compute the spindown torque T_z implied by the radial outflow solution of Chapter 2. This torque is exerted on Jupiter's ionosphere and atmosphere by a system of field aligned currents threading Jupiter's polar cap, which we sketch in Figure 4. We then estimate the torque exerted upon the magnetic field lines of ionospheric levels by the upward viscous diffusion of angular momentum.

Knowing the mass outflux $\dot{M} = \eta\dot{M}_+$, we could compute the spindown torque T_z if we knew the Alfvén radius, since according to Weber and Davis (1967), $T_z = \Omega r_a^2 \dot{M}$. We estimate r_a as follows: Assuming that U depends weakly on r, then $N_a/N_m = (r_m/r_a)^2$. We then compute the location where $4\pi N_a M_+/B_D(r_a) = 1$, where B_D is the vacuum dipole field. The result is given by

$$r_a/R_J = \left[B_D^2/4\pi\rho_s U_s^2\right]^{\frac{1}{4}} \left(R_J/r_m\right)^{\frac{1}{2}} \qquad (4.1)$$

For the parameters leading to (2.8), $r_a \simeq 35\ R_J$. This result does not contradict observation, since the measurable B_φ was encountered beyond 35 R_J (E.J. Smith, private communication), but it is not clear that these observations support this theory.

The torque T_z then becomes

$$T_z = \Omega_J r_a^2 \dot{M} \simeq 2 \times 10^{23}\ |hB_\varphi/B_r|\ \text{dyne-cm} \qquad (4.2)$$

And the rotational energy invested in the flow, $T_z\Omega_J$ is

$$T_z\Omega \simeq 3.5 \times 10^{19}\ |hB_\varphi/B_r|\ \text{ergs/sec} \qquad (4.3)$$

We note that $T_z\Omega_J/\dot{W} < 1$, again posing the question of where the energy in a radial outflow would come from. Assuming Jupiter's moment of inertia $I \sim 10^{49}$ gm/cm^2, we may estimate Jupiter's spindown time τ from the above torque to be 3×10^{14} yrs, so the torque is cosmogonically insignificant.

In his model of pulsars Sturrock (1971) pointed out that a hydromagnetic torque is communicated to the neutron star by a system of currents which for an aligned dipole, flow in along field lines over the poles; across the field in the neutron star crust, where a $J \times B$ force opposing rotation is exerted; and out along the magnetic field line connecting to the Alfvén point. For Jupiter, the cross-field current flows in the ionosphere, not in the planet.

It is worth noting that the field-aligned current flowing out of the equatorward edge of Jupiter's polar cap should connect to field lines in the outflow disk. Using $B \approx 4 \times 10^{-5}$ Gauss and $h \approx$ a few R_J to estimate the magnetic flux in the disk, we find that field-aligned current should leave the ionosphere in an annular ring of a few hundred km thickness poleward of the field lines connecting to the Alfvén point. The field-aligned current density then turns out to be $\approx 10^9$ el/cm^2/sec, probably large enough to be unstable in Jupiter's topside ionosphere. If such upward field-aligned currents behave as they do at earth, we would expect them to be carried by beams of energetic electrons and to produce an aurora. This current configuration is sketched in Figure 4.

The angular momentum radiating outward is taken first from the atmospheric neutrals at ionospheric levels, which in an aligned rotator can only be replaced by viscous angular momentum diffusion upward from below the ionosphere. Furthermore, the current configuration of Figure 4 makes it clear that only the polar cap atmosphere exerts a torque on the radial outflow. Hines (1974) has estimated the viscous diffusion of angular momentum as follows: The atmospheric angular momentum density is $\rho r^2\Omega$, where ρ is the atmospheric mass density, r the distance from the spin axis, and Ω the spin frequency. The angular momentum flux is $D(d/dz)\left(\rho r^2\Omega\right)$, where D is a kinematic diffusivity and z denotes altitude. Then, treating it as a thin disk, the torque exerted by the entire polar cap is

$$T_z = 2\pi\int_0^{r_{pc}} r dr D(d/dz)\left(\rho r^2\Omega\right) \simeq (\pi/2) r_{pc}^4 D(d/dz)(\rho\Omega) \quad (4.4)$$

where r_{pc} is the radius of the polar cap. We estimate an upper limit to the torque by assuming that at one atmospheric scale height H below the ionosphere $\Omega = \Omega_J$. Then

$$T_z \simeq (\pi/2)\left(\rho r_{pc}^4 D\Omega_J/H\right) \quad (4.5)$$

We estimate r_{pc} by $\left(R_J^3/r_a\right)^{\frac{1}{2}}$.

According to Atreya <u>et al.</u> (1974) sunlight forms an ionosphere with a peak ion density at the level where $\rho \approx 10^{10}$ H atoms/cm^3. H is the order of 10 km. While D is highly uncertain, they chose $D \approx 10^6/\text{cm}^2$ sec as an illustrative value. With these values equation (4.5) becomes

$$T_z \approx 10^{19} \rho_{10} D_6/H \text{ dyne/cm} \quad (4.6)$$

where ρ_{10} is in units of 10^{10} H atoms/cm^3 = 1.6×10^{-14} g/cm^3, D_6 is measured in units of 10^6 cm^2/sec, and H is normalized to 10 km.

The atmospheric torque, eq. (4.6), is some 4 orders of magnitude smaller than the hydromagnetic torque inferred by assuming a radial outflow solution. The atmospheric torque could exceed the estimate (4.6) if for example, D_6 is large. According to Atreya et al. (1974), D is highly uncertain. Alternately, the peak conductivity region of Jupiter's polar cap ionosphere could be formed at a denser layer of Jupiter's atmosphere, where ρ_{10} is large. If the photochemistry of Atreya et al. (1974) prevails, this seems unlikely, since we have already applied their midlatitude model to the polar cap. On the other hand, there could conceivably be energetic electron precipitation to the polar cap. All in all, the four orders of magnitude difference between the hydromagnetic and atmospheric torques makes it an interesting question whether at least the aligned rotator can support corotation.

Another way to perceive the above question, if not the answer to it, is to estimate the moments of inertia of the polar cap ionospheres of Jupiter and the earth. The moment of inertia of a thin uniform disk is $I = MR^2/4$, a sufficient approximation for our purposes. We estimate M by $\pi R^2 H\rho$ where H and ρ are the neutral scale heights and density of the atmosphere where the strongest hydromagnetic coupling occurs. We estimate R by $R_p/\sqrt{L_{pc}}$ where R_p is either R_E or R_J. Thus, over all

$$I = \pi/2 \left(R_p^4/L_{pc}^2\right)H\rho \qquad (4.7)$$

and the ratio I_J/I_E is

$$I_J/I_E \simeq \left(R_J/R_E\right)^4\left(H_J/H_E\right)\left(\rho_J/\rho_E\right)\left(L_{pc},\hat{E}/L_{pc},\hat{J}\right)^2 \qquad (4.8)$$

Magnetosphere-ionosphere coupling at earth occurs in the E-region, where there are 10^{13} NO^+ atoms/cm^e, whereas according to Atreya <u>et al.</u> (1974) the coupling region for Jupiter is 10^{10} H atoms/cm^3. $H_J \simeq 2\ H_E \simeq 10$ km, $\left(R_J/R_E\right)^4 \approx 10^4$, and $L_{pc,E} \simeq 10$, $L_{pc,J} \simeq 35$, so that overall $I_J \simeq I_E$. Since the greater scale of Jupiter's magnetosphere suggests that much larger hydromagnetic stresses will be exerted upon its ionosphere and atmosphere than on the earth's, the equality of the moments of inertia of their polar cap atmospheres leads one to wonder whether Jupiter's atmosphere, acting as a flywheel, can spin-up its magnetosphere for long.

4.3 <u>Coupling of convection to Jupiter's ionosphere and Atmosphere</u>

4.3.1 Convection in the polar cap ionosphere

Coroniti <u>et al.</u> (1973) and Coroniti (1974a) first pointed out the significant effects of the low inertia of Jupiter's atmosphere at ionospheric levels on Jupiter's magnetosphere. Fleshing out an idea originally proposed by Brice and McDonough

(1973), they argued that intermittent convection events--in effect, substorms--would couple to planetary scale atmospheric neutral wind modes. These in turn would couple at low Jovian latitudes to fluctuating dynamo electric fields to drive radial diffusion of radiation belt particles with the $D = D_o L^3$ diffusion coefficient required by the observed profiles of synchrotron radiation. They based their arguments on Jupiter's small ionosphere-atmosphere coupling time $\tau = \left(M_N N_N / M_I N_I\right) \nu_{in}^{-1}$ (Fedder and Banks, 1972), where M_N and M_I are the neutral and ion masses and N_N and N_I their number densities. They estimated $\tau_J \approx 40$ minutes, much shorter than any conceivable convection time. In effect, like the earth's F-region atmosphere, Jupiter's atmosphere at ionospheric levels would tend to follow the ionospheric convection pattern.

The above argument has led us to ask whether an aligned rotator with Jupiter's ionospheric parameters could have a corotating polar cap atmosphere at ionospheric altitudes when reconnection drives convection through the polar cap. We shall make our point with another <u>reductio ad absurdem</u>. Suppose, as sketched in Figure 5, that corotation is rigidly enforced throughout the polar cap. We note that a magnetosheath field line which reconnects at the nose of Jupiter's magnetosphere will take 5 hours to travel 100 R_J at a speed of 400 km/sec. At this point, the magnetosheath end of the field line would be over the polar cap while its ionospheric end would have corotated to local midnight. Five hours later, the magnetosheath end would still not have reached the tail reconnection point, while the ionospheric end would have corotated back to local noon. If such a picture of convection were correct, the foot of the field line would trace out a cycloidal pattern as it progresses across the polar cap. But then, the ionospheric electric field would have to be double-valued. This dilemma is resolved by the twist in the field lines above the polar cap--an Alfvén wave carrying field-aligned current whose function is to communicate angular momentum between the ionosphere and magnetosheath. This torque spins down the ionosphere and atmosphere and spins up the magnetosheath flow. In view of Jupiter's low atmospheric inertia, we suspect that its polar cap atmosphere should spin about once in a characteristic convection time.

4.3.2 Enforcement of corotation

A basic assumption underlying Brice's models of the plasmapauses of Jupiter and the earth is that corotation is enforced at the feet of the field lines. Assuming that the convective flow in the tail is symmetric around the local midnight meridian in the distant geomagnetic tail, convection at asymptotically long distances carries no net angular momentum towards the earth. However, in the Brice solutions more mass and angular momentum flows past the dawn meridian plane beyond the plasmapause than flows past the evening meridian. The planet's ionosphere must have exerted a torque on the flow at this point. If the dayside magnetopause were very far away the difference in angular momentum flowing past dawn and evening would eventually be restored to the ionosphere as the flow again approaches symmetry about the local noon meridian plane. In this case, convection would exert no net torque on the ionosphere. However, the flux tubes cross the magnetopause into the magnetosheath before complete symmetry is re-attained, and since a significant fraction of the difference between the angular momentum fluxes at dawn and evening is transferred to the magnetosheath, angular momentum is probably lost from this system, although some of the angular momentum acquired by the magnetosheath could be restored to the earth again as the magnetosheath plasma flows over the polar cap.

We will estimate the earth's angular momentum loss to be the difference between that flowing past dawn and evening in the Brice plasmapause model. We again assume the magnetic field to be an aligned undistorted dipole and the convection electric field to be spatially uniform. A dipole field line has the equation $r = LR_p\cos^2\theta$, where L is McIlwain's (1961) L-shell parameter, R_p is either planet's radius, and θ is the magnetic latitude. The distance from the spin axis $r_\perp$ at any point on a dipolar field line is $r_\perp = r\cos\theta = LR_p\cos\theta^3$. The azimuthal velocity v_φ of any point on the field line is related to its equatorial value V_φ by $v_\varphi = V_\varphi(L)\cos^3\theta$. The angular momentum flux of any element of mass on a given flux tube is given by $\rho LR_p V_\varphi^2\cos^9\theta$ where ρ is the mass density. The element of meridional plane area of a flux tube dA is given by $dA = LdR_p^2\cos^4\theta d\theta$, so that the angular momentum flux $d\dot{J}$ carried by a flux tube between L and L + dL is

$$d\dot{J}/dL = \rho L^2 R_p^3 v_\varphi^2 \int_0^{\theta^*} \cos^{13}\theta d\theta \qquad (4.9)$$

where $\theta^* \simeq \cos^{-1}(1/\sqrt{L})$ denotes the latitude where the flux tube hits the atmosphere.

By entirely similar reasoning the mass flux $\dot{M}$ flowing between L and L + dL is given by

$$d\dot{M}/dL = \rho(L) v_\varphi(L) R_p^2 L \int_0^{\theta^*} \cos^7\theta d\theta \qquad (4.10)$$

In both (4.9) and (4.10) we assume that the particles are isotropic in pitch angle so that the mass density $\rho(L)$ is independent of magnetic latitude. The total angular momentum and mass fluxes flowing between any two L_1 and L_2 are

$$\dot{J} = R_p^3 \int_{L_{13}}^{L_2} \rho(L) v_\varphi^2 L^2 dL_\varphi \int_0^{\theta^*} \cos^{13}\theta d\theta \qquad (4.11)$$

$$\dot{M} = R_p^2 \int_{L_1}^{L_2} \rho(L) v_\varphi L dL \int_0^{\theta^*} \cos^7\theta d\theta \qquad (4.12)$$

For the Brice model of convection, the azimuthal equatorial speed in the dawn (+) and evening (-) meridians is

$$v_\varphi = c/B\left[E_c \pm \frac{\Omega_p B_o R_p^3}{cr^2}\right] = \left(c/B_o\right) E_c L^3 \pm \Omega R_p L \qquad (4.13)$$

The net torque is

$$\dot{T}_z = R_p^3\int_0^{\theta*}\cos^{13}\theta*\left\{\left[\int_{0.4L_o}^{L_m}\rho(L)\left[\frac{cE_c}{B_o}L^3 + \Omega R_p L\right]^2 L^2 dL\right.\right.$$

$$\left.- \int_{L_o}^{L_m}\rho(L)\left[\frac{cE_c}{B_o}L^3 - \Omega R_p L\right]^2 L^2 dL \qquad (4.14)\right.$$

where we have neglected a weak dependence of $\theta*$ on L. L_o is the L-shell of the evening plasmapause and L_m is that of the magnetopause in the dawn-evening meridian plane.

For the earth, $L_m >> L_o$, and the convection speed greatly exceeds the corotation speed at the magnetopause. Making these approximations we find

$$T_z \simeq R_E^3\int_0^{\theta_o^*}\cos^{13}\theta\left\{\int_0^{L_m} 4\frac{cE_c}{B_o}\Omega R_E L^6 \rho(L) dL\right\} \qquad (4.15)$$

where we have noted that the integrals in (4.14) depend weakly on their lower limit.

We model $\rho(L)$ by assuming that in the distant tail all the convecting flux tubes have the same volume and density and therefore total mass. If, further, no mass is lost as they convect towards the earth, the density in the dawn or evening meridians will vary inversely as the volume of the flux tube, i.e., $\rho = \rho_o L^{-4}$ where ρ_o is a constant. With this assumption

$$T_z \simeq \frac{4\rho_o}{3}\frac{cE_c}{B_o}R_E^4 L_m^3 \Omega\int_0^{\theta*}\cos^{13}\theta d\theta \qquad (4.16)$$

With the same approximations that led to (4.16), the total mass flux carried by convection is approximately

$$\dot{M} \simeq 2\rho_o R_E^2 \frac{cE_c}{B_o} L_m \tag{4.17}$$

So that, finally

$$T_z \simeq (2\alpha/3)\Omega r_m^2 \dot{M} \tag{4.18}$$

where

$$\alpha = \int_0^{\theta^*} \cos^{13}\theta d\theta \Bigg/ \int_0^{\theta^*} \cos^7\theta d\theta \tag{4.19}$$

and $r_m \equiv L_m R_E$. Because of the many approximations made it is proper to take only the basic scaling $T_z \sim \Omega r_m^2 \dot{M}$, and not the numerical factor $2\alpha/3$ seriously

For the earth, $\dot{M} = 200$ g/sec, corresponding to $\dot{N} = 10^{26}$ protons/sec. Then, using $\Omega_E = 7 \times 10^{-5}$ rad/sec and $r_m \simeq 10^{10}$ cm, $T_z = 1.5 \times 10^{18}$ dyne cm, corresponding to an energy dissipation rate $T_z \Omega_E \simeq 10^{14}$ ergs/sec. Our estimate (4.13) does not conflict with either Coleman's (1971) or Hirshberg's (1972), both of whom estimated upper limits to the torque of the order 10^{20-21} dyne-cm. Hines (1974) has estimated the torque produced by viscous diffusion in the earth's atmosphere to be of order 10^{20} $\Delta\Omega/\Omega$ dyne-cm, where $\Delta\Omega$ is the difference in angular velocity between the earth and the neutrals at E-region levels. Combining Hines' estimate with (4.19), we conclude that $\Delta\Omega/\Omega \leq 1\%$, so that the earth's atmosphere can enforce corotation on the convective return flow in Brice's earth plasmapause calculation.

Can a plasmapause be formed at Jupiter? A precise evaluation of this question cannot yet be formulated. Equation (4.13) cannot be correct, since two of its basic assumptions--undistorted dipole field and sub-Alfvénic flow everywhere--are violated. Nonetheless, if a plasmapause is formed, the torque should be expressed in the form $T_z = \Omega_J r^{*2}\dot{M}$ where $R_J < r^* < r_m$. Let us estimate the convection mass flux $\dot{M}$ by $\delta\dot{M}_s$, where $\dot{M}_s = M_H N_s U_s \pi r_m^2 \simeq 2 \times 10^{30}$ protons/sec, the solar wind mass flux across the cross-section of Jupiter's magnetosphere. We compute the lower estimate to the torque

$$T_z > \Omega_J R_J^2 \delta \dot{M}_s = 3 \times 10^{22} \delta \text{ dyne/cm} \qquad (4.20)$$

At earth, the trapping factor $\delta \simeq 10^{-3} - 10^{-2}$. Thus, unless $\delta < 10^{-3}$, even the lower estimate torque exceeds the atmospheric torque (4.6)

We do not feel that the question of whether or not Jupiter's atmosphere can enforce corotation can be resolved at present. In his accompanying review article, Coroniti (1974b) suggests that energetic electron precipitation could significantly modify the structure of the ionosphere, and, therefore, the basis on which the atmospheric torque (4.6) was estimated. Until model ionospheres including electron precipitation are computed we have no solid foundation on which to base an estimate of atmospheric torque. A particularly urgent need is to evaluate the effects of soft electron precipitation from the solar wind on Jupiter's polar cap ionosphere. Such computations have yet to be carried out even for earth, except for the polar cusp (Kennel and Rees, 1972).

We can ask, however, what would happen if no corotation were imposed. Then the convection streamlines from the tail would be straight lines towards the sun until that point where, according to Bernouilli's Law, the magnetic pressure of the dipole deflects the flow. While the flow streamlines reach the dayside magnetopause, the energetic electrons from Jupiter's plasmasheet might have a sharp inner boundary, as they do at earth. We may estimate the Jovicentric distance of the midnight meridian inner boundary following Kennel (1969). Should microscopic plasma turbulence keep the electron pitch angle isotropic, the electron precipitation lifetime will approach the electron minimum lifetime, T_M. According to Kennel and Petschek (1966), $T_M = 2T_B L^3$ where T_B is the electron quarter-bounce time, $2L^3$ is the "mirror ratio" for dipolar field lines, and L is the McIlwain (1961) L-parameter. The inner boundary of the plasma sheet is formed at that point where T_M first equals the flow characteristic time T_F. Beyond this point, electrons are lost from the flow before the tubes of force can cross a scale length.

We shall estimate T_B by $LR_J/v_{\parallel}$ where $v_{\parallel}$ is the electron velocity component perpendicular to the magnetic field. We estimate T_F to be the dipolar magnetic field gradient length $LR_J/3$ divided by the convection speed cE_c/B. Assuming that at the inner boundary the plasma pressure does not distort the dipolar field significantly, we may estimate the L-shell of of the inner boundary L_B:

$$L_B = \left[\frac{v_{\parallel} B_o}{6\beta U_s B_s}\right]^{1/6} = 19\left(\frac{v_{\parallel}}{\beta c}\right)^{1/6} R_J \qquad (4.21)$$

Coroniti's radiation belt model (1974a) assumed that radial diffusion carried electrons from a distant plasmapause to the synchrotron radiation region near the planet. An inner boundary was formed at $L \approx 20$ where the minimum lifetime matched the radial diffusion scale time. However, (4.21) indicates that if corotation were not a factor, convection could transport energetic electrons to $L = 20$ directly. Or course, the estimate (4.21) was based on the assumption that electrons precipitate at their maximum rate. As argued previously, such precipitation could affect the coupling of atmospheric rotation to the magnetosphere.

4.4 Summary

An aligned rotator with an ionosphere similar to that of Atreya et al. (1974) would have difficulty enforcing corotation, due to the very low inertia of the atmosphere at ionospheric altitudes. Thus, one basic assumption underlying both radial outflow models and most convection models may be questionable.

5. Discussion

We have treated Jupiter's magnetosphere as an astrophysicist would when faced with incomplete observations and correspondingly undeveloped theoretical conceptualizations. We have imposed various simplified models on the data in order to identify broad areas of consistency or conflict between theory and experiment. Our major goal has been to try to decide between a radial outflow pulsar-like model of Jupiter's magnetosphere and an earth-like convection model.

In Chapter 2, we imposed on the data a simple super-Alfvénic radial outflow model for an aligned rotating dipole similar to those constructed by Mestel (1968) for non-relativistic flows around rotating magnetic stars and those by Michel (1969) for relativistic flows away from rapidly rotating magnetized neutron stars. Our aim was to estimate the internal particle and energy sources required to drive a super-Alfvénic outflow consistent with the Pioneer 10 measurements reported in Science. These came out to be stringent: 10^{28} particles/sec and at least 10^{21} ergs/sec. It is not obvious that photoelectrons from Jupiter's ionosphere can be an adequate source of particles. On the other hand, secondary electrons from the precipitation of energetic electrons to Jupiter's atmosphere could conceivably be a more potent source--a source we did not estimate. However, this does beg the question of what magnetospheric processes energize the precipitating electrons, which would be important for a final self-consistent treatment. Jupiter's satellites could also be a significant particle source, though Io's neutral particle ring may be inadequate. None of the above arguments address the question of where the outflowing particles get their energy, which we estimated to be of order 50 KeV. It must be remembered that our estimates depend completely upon interpreting the measured B_φ/B_r as the garden-hose angle of a super-Alfvénic outflow. At present, the information on B_φ/B_r near the magnetopause is sparse. However, if $|B_\varphi/B_r| < 1$ and if the model applies at all, the outflowing particles would have high energy and low density.

Even if Jupiter had particle and energy sources strong enough to drive a radial flow, our estimates indicated that they would at best be comparable with the solar wind particle and energy fluxes across the frontal area of Jupiter's magnetopause. This suggested that the solar wind could be a significant source of particles and energy. This conclusion was bolstered by our estimate of the energy input due to reconnection at Jupiter's magnetopause--again roughly 10^{21} ergs/sec. This raised a class of questions which we did not address specifically. A whole spectrum of hydromagnetic models exists between the two extremes of a pure radial outflow, with all energy and mass fluxes provided by Jupiter itself or its inner magnetosphere, and a pure convection model, where all the energy and particles come from the solar wind. Such mixed model magnetospheres offer many challenging theoretical problems which never have been addressed. For example, if reconnection as well as radial outflow is important, radial outflow solutions with magnetic field components normal to the flow direction are needed. Furthermore, the flows could well be super-Alfvénic, so that one might expect shocks and other discontinuities within the magnetosphere where the convection and radial flows clash. If we could understand such flows, we might learn something about x-ray sources in binary orbit, like Hercules X-1. It is commonly thought that these may be spinning magnetized neutron stars which gain energy by accretion from the atmosphere or stellar wind of its stellar companion (e.g., Davidson and Ostriker, 1973). Since pulsars not in binary orbit are known to be energy and particle emitters, the possibility exists that a mixed model might apply to the x-ray sources.

We did consider qualitatively the other extreme case of a pure convection magnetosphere, concentrating primarily on weakening the objections previously held by the theoretical community against an important role for convection in Jupiter's magnetosphere. These objections were:

1. The plasmapause, according to Brice and Ioannidis (1970), was so distant that convection could not transport plasma anywhere near the planet. It could not, therefore, significantly energize particles. Furthermore, the computed plasmapause was near or beyond the position of the magnetopause expected prior to Pioneer 10 encounter. There was little or no room within the magnetosphere to return magnetic flux to the dayside magnetopause as is required by a reconnection model.

2. After Pioneer 10 encounter, it appeared that the observed radially extended magnetic field observed in Jupiter's outer magnetosphere simply didn't look like the earth's magnetic field. Besides the magnetopause was too far out, 100 R_J and more, whereas Brice and Ioannidis (1970) and Kennel (1973) had estimated no more than 50 R_J. Jupiter's outer magnetosphere, at first glance, does resemble what one expects from a radial outflow model.

However, in section 3, we compared the plasma densities required to make the convection flows sub-Alfvénic at the plasmapauses of earth and Jupiter, as is implicitly required by conventional plasmapause models. We concluded that it is likely that Jupiter's convection flow will be super-Alfvenic in its outer magnetosphere. In this case, the dynamic pressure of the convection flow would exceed that of the magnetic field at least near the dipole equator, and one might well expect a radially extended magnetic field in the outer magnetosphere. In addition, the magnetopause would be pushed out by convection. We then noted that OGO-1 may have observed Jupiter-like earth magnetopauses near local dawn during substorms. If the analogy is a proper one, then the observed variability in Jupiter's magnetopause location might be due in part to substorms or other variable convection events.

In Chapter 4, we discussed one basic presumption underlying nearly all theories of Jupiter's magnetosphere: that corotation be enforced. Again, we investigated first the simplest possible model--an aligned rotator. In addition, we used published models of Jupiter's ionosphere and magnetosphere to estimate the coupling of angular momentum between atmosphere, ionosphere, and magnetosphere. The conclusion of this straightforward, if oversimplified, procedure seems clear: The angular momentum flux which can diffuse upward through Jupiter's polar cap atmosphere seems insufficient to impose corotation upon a radial outflow with parameters similar to those in Chapter 2, or upon the convective return flow of Chapter 3 to form a plasmapause. Goertz et al. (1974) argue that the observed system III longitudes of the appearances of the peak electron flux regions in the magnetodisk can be explained by a slippage of the ionospheric feet of magnetospheric field lines with respect to Jupiter, consistent with a weak coupling between planet and magnetosphere.

If there were no corotation imposed at all--another extreme limit--we estimated that convection could carry plasmasheet electrons to about $L \simeq 20$ where they might form a precipitation inner boundary similar to that of earth (Vasyliunas, 1968; Kennel, 1969). In Coroniti's (1974a) radiation belt model, a similar inner boundary was formed at $L = 20$ where radial diffusion and electron precipitation have similar scale times. The similarity in results is no accident, because in Coroniti's (1974a) model radial diffusion is driven by sporadic convection events, and he specifically presumed that convection would carry the upper atmosphere around with it, so that the electric field would penetrate to low Jovian L-shells.

Chapter 4 should not be allowed to blind us to the salient fact that the Pioneer 10 energetic particle experiments observed a "flapping: of the high intensity flux region of the magnetodisk with roughly a ten hour, and not 20, 30, or 100 hour period. Thus, some aspect of Jupiter's rotation is enforced on the magnetosphere. At our present primitive level of theoretical understanding, we do not know why. Perhaps the current ionospheric models, which do not take energetic electron precipitation into account, underestimate the viscous coupling of angular momentum to the atmosphere. On the other hand, it is also possible that the assumption of an aligned rotator is at fault. In pulsar theory, there is a fundamental physical difference between aligned and oblique rotators. An aligned rotator can only lose angular momentum hydromagnetically by emitting particles (Goldreich and Julian, 1969; Mestel, 1969). On the other hand, an oblique rotator can lose angular momentum even in vacuum (Pacini, 1967). Since rotation now induces a time varying magnetic field, it generates magnetic dipole radiation. Similarly, Jupiter's oblique dipole may produce an electric field in its ionosphere which drives field-aligned currents causing the magnetodisk to flap. Angular momentum would then be carried off by Alfvén waves propagating through the outer magnetosphere. Thus, Chapter 4 raised interesting questions without settling them. Nonetheless, we believe that Chapter 4 indicates that there is a commonality of interest between Jupiter's atmospheric and ionospheric communities, on the one hand, and its fields and particles community on the other. The dynamics of Jupiter's high latitude upper atmosphere may be controlled hydromagnetically and the structure of its ionosphere may be significantly affected by electron precipitation. Conversely, we may not be able to understand the hydromagnetics of Jupiter's magnetosphere until the nature of the boundary conditions at the ionosphere are elucidated. Should Saturn or the other outer planets also have magnetospheres, energetic electron precipitation might also be important for their ionospheres, since the solar photon flux is even smaller than at Jupiter.

How are we to decide between the convection and the radial outflow models? Pioneers 10 and 11 will be unable to make a simple yet decisive test. For example, a directional plasma detector, sensitive in the energy range between 1 KeV--the corotation energy at the inner edge of the magnetodisk--and 50 KeV--the corotation energy at the magnetopause--could determine whether the flow is antisolar or from the planet at the dawn meridian. As it is, our best information may come from much more elaborate versions of what was done in order of magnitude fashion in this paper: comparison of magnetic field measurements with hydromagnetic models. Several simple signatures of convection ought to appear in the magnetic field data. For example, B_φ/B_r could have a sign opposite to that of the conventional gardenhose field. Here, there are two cases. The convection speed could exceed the local corotation speed but be less the Alfvén speed. An onset of rapid convection would then bend the field line towards the sun. The bend would then propagate as an Alfvén wave down the field-line to the ionosphere where it would exert a stress on the atmosphere. We would expect that the anomalous B_φ/B_r would persist for times comparable with the effective ionosphere-atmosphere coupling time--a few hours at most. On the other hand, where the convection speed exceeds both the Alfvén and corotation speed, a sunward B_φ component might persist for the duration of the convection event. In a reconnection magnetosphere, we expect that tangential magnetopause stresses will sweep the field lines back so that in the local midnight-noon sector, B_φ/B_r will have the same sign as the garden-hose field sufficiently near the magnetopause. Goertz et al. (1974) have reported that B_φ/B_r is often though not predominantly anti-gardenhose, however, they are still somewhat uncertain about their data reduction procedure for these cases. In any case, study of sporadic B_φ/B_r anomalies might illuminate the problem of convection. In addition, one might try to establish that magnetopause motions occur with no change in solar wind dynamic pressure and/or are correlated following a suitable delay with northward switches of the solar wind magnetic field. Similarly, convection might cause anomalies in the time of magnetodisk crossings.

The absence of plasma wave detectors on Pioneers 10 and 11 means that we really do not know whether precipitation of electrons to the atmosphere occurs. Observation of one whistler emission would have settled that. With suitable spectral information, and the cold plasma density inferred by detection of the plasma frequency we could estimate the fluxes and precipitation rates of electrons in the 1 - 100 KeV range currently not measured. A radial profile of whistler amplitude would enable us to infer electron precipitation fluxes with sufficient accuracy to permit believable new ionospheric models to be computed.

Despite some shortcomings, Pioneer 10, and the excitement induced by the preparations for, and the fact of, our first encounter with Jupiter have provided us a good start on a research program which will certainly be vigorous until the end of the century. For the stakes are high. Not only is Jupiter's magnetosphere intrinsically interesting, but it may have already shed a little light on the earth's magnetosphere. Because of Jupiter's rotation and large magnetic moment, we are convinced its magnetosphere will be a useful astrophysical analog. It's just that, right now--at the beginning--we don't yet know what kind of analog it will turn out to be.

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Figure Captions

Figure 1. Radial Outflow Model. Jupiter is assumed to have a centered dipole magnetic field, with dipole and spin axis aligned. The approximately dipolar field is assumed to corotate within the Alfvén radius. Beyond the Alfvén radius, a two-dimensional radial outflow solution is assumed. The Alfvén radius is fixed by assuming that the dipole and radial field components are comparable at the Alfvén point of the radial outflow. The radial outflow terminates in a fast shock at the magnetopause. Approximate dynamic pressure balance prevails across the magnetopause and bow shock. Pioneer 10 measured the upstream solar wind flow parameters, the location of the magnetopause, and the magnetic field near the magnetopause.

Figure 2. High β Super-Alfvenic Convection. The Brice plasmapause, computed assuming an undistorted dipole field, and therefore zero-β sub-Alfvénic convection, would lie at 40 R_J at dawn, 100 R_J at local evening. The conventional magnetopause, computed by balancing the upstream solar wind dynamic pressure prior to Pioneer 10's first magnetopause encounter with the magnetic pressure of the undistorted dipole, would lie at 55 R_J. Since the conventional plasmapuase intersected the conventional magnetopause, it was thought that convection would be unimportant compared to corotation, particularly in view of the fact that there would be little room for the convective return of flux to the dayside magnetopause. However, convection beyond the

plasmapause is likely to be super-Alfvénic. This might create a radially extended magnetic field and push the magnetopause beyond its conventional location near the magnetic equator.

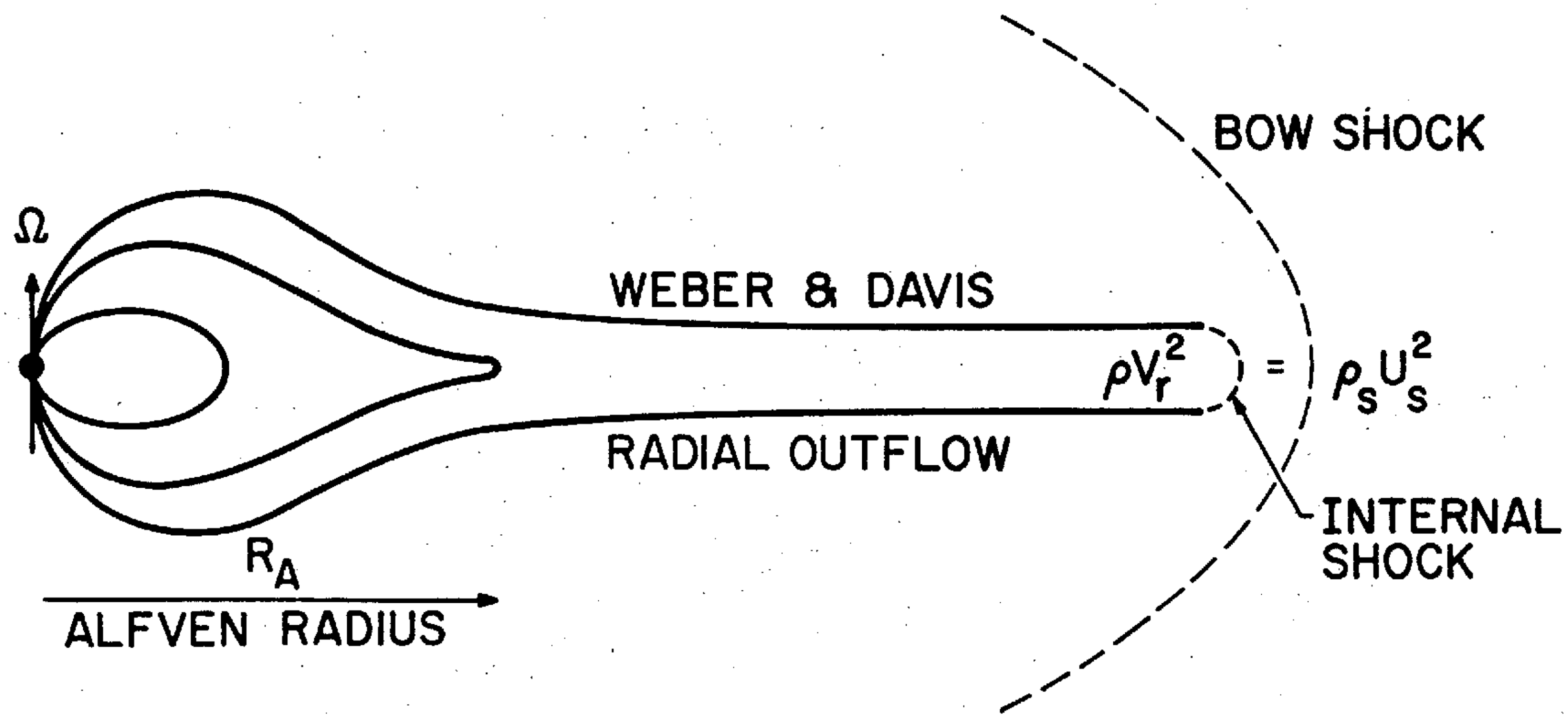
<u>Figure 3. A Jupiter-Like Magnetopause at Earth.</u> Reproduced here is a figure from Heppner <u>et al.</u> (1967). The top inset shows magnetic measurements from a considerable portion of the pass of June 8 - 9, 1965; the middle inset indicates that a sub-storm was in progress; and the bottom inset shows that the magnetic field was larger in themagnetosheath than in the magnetosphere. Could super-Alfvénic convection have caused this magnetopause?

<u>Figure 4. Aligned Rotator Coupling of Torque.</u> The hydromagnetic spin-down torque is communicated to the ionosphere and atmosphere by a system of currents in at the dipole and spin axis, across the ionosphere, and out at the boundary of the polar cap. Where the current flows out, an aurora boreolis may be found, if earth-like physics prevails. The $J_{\perp} \times B$ torque is exerted first on the atmosphere at ionospheric levels. This should be balanced by the diffusion of angular momentum upward from the ionospheric layers below the ionosphere.

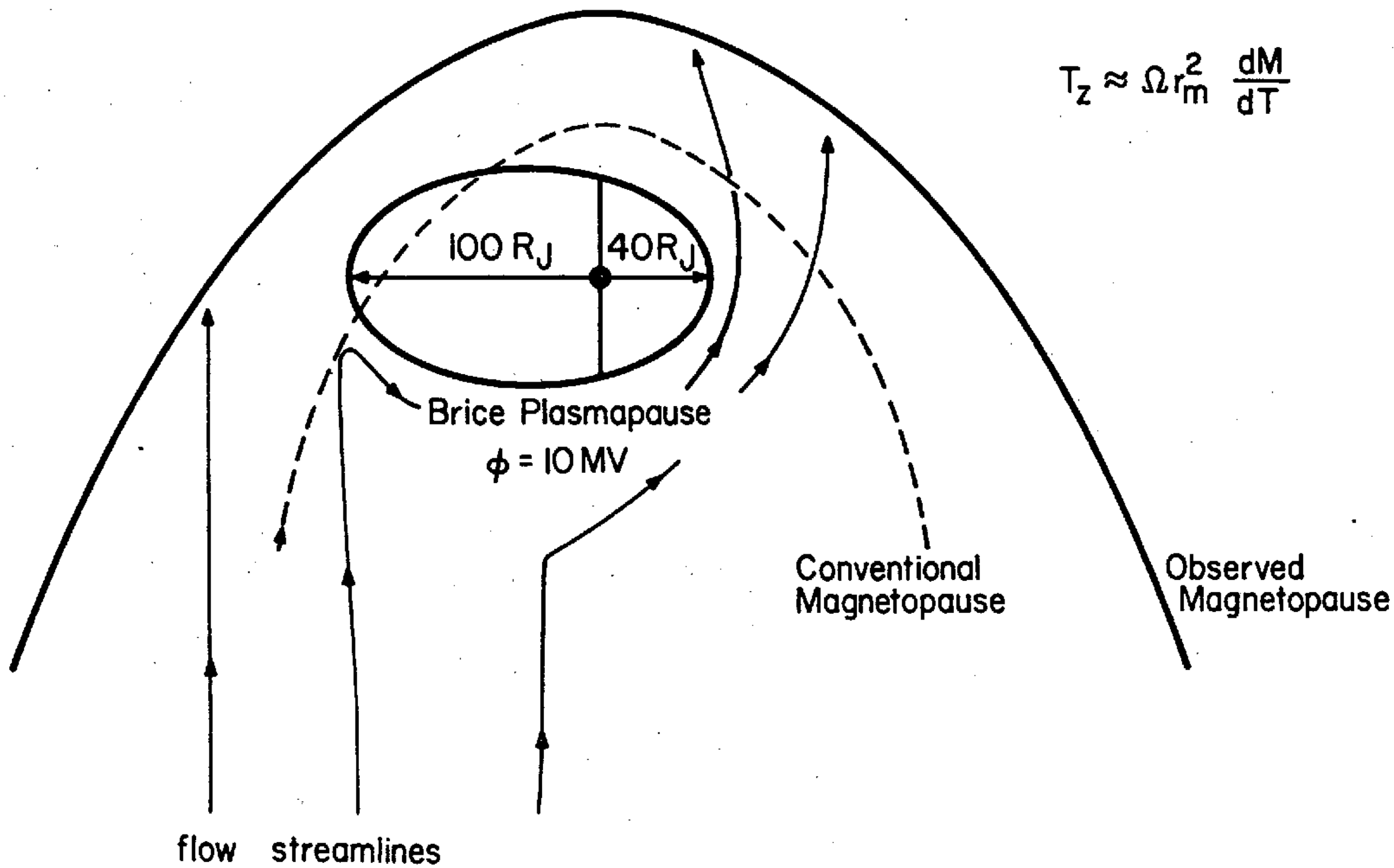
Figure 5. <u>Coupling of Solar Wind Torque to Jupiter's Polar Cap Ionosphere and Atmosphere.</u> Suppose the ionospheric feet of all field lines corotated. Then 5 hours after a field-line reconnected at the nose, it would be over the polar cap. It's foot would have rotated to local midnight. Five hours later,

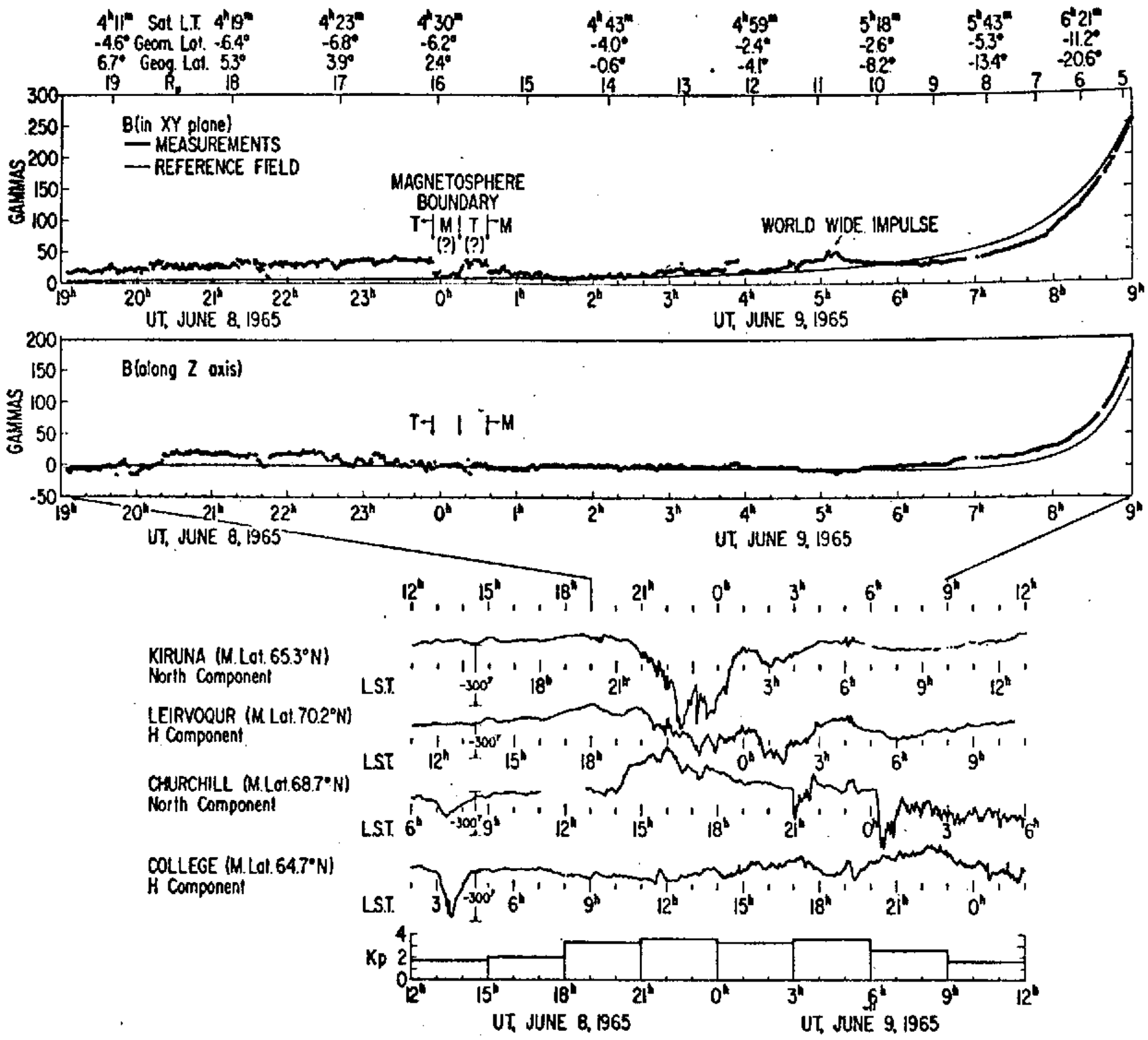
the field line would still not have reached the tail reconnection point, yet its foot would be back at local noon. The twist in the field lines corresponds to an Alfvén wave which carries a field-aligned current into the ionosphere with the same sense as in Figure 4. It therefore communicates angular momentum between the ionosphere and solar wind. If Jupiter's polar cap atmosphere has a small moment of inertia and viscous coupling to the lower atmosphere is weak, Jupiter's polar cap atmosphere will not corotate.

ALIGNED ROTATOR

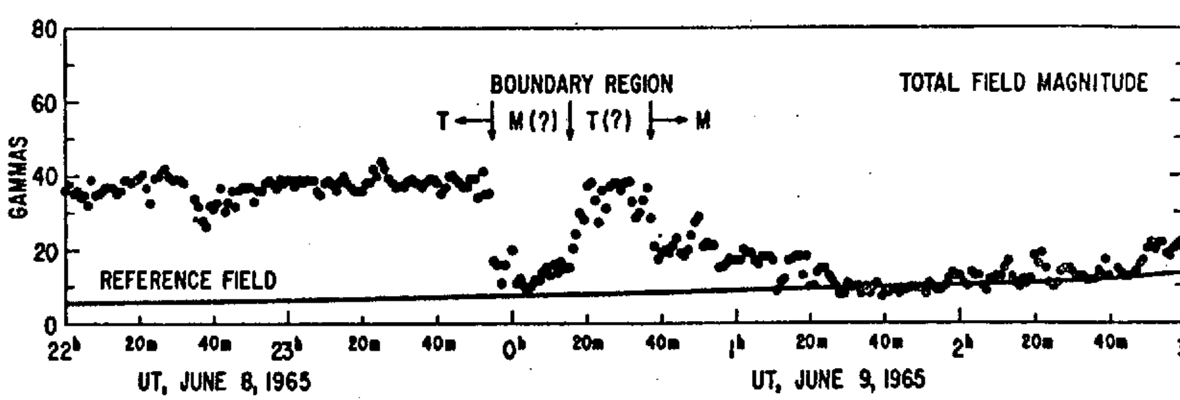


HIGH β SUPER-ALFVENIC CONVECTION

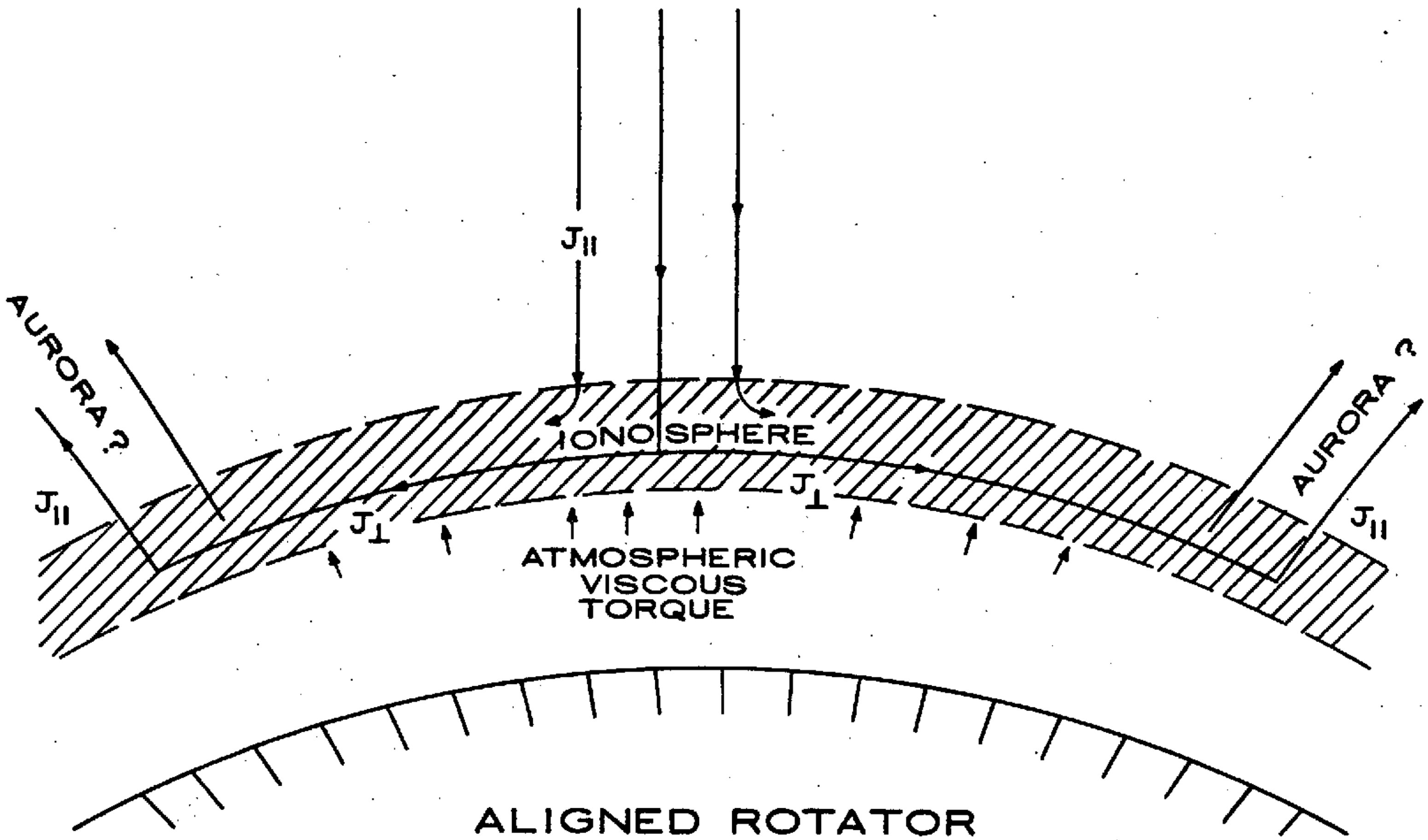




Inbound pass of June 8-9, 1965.

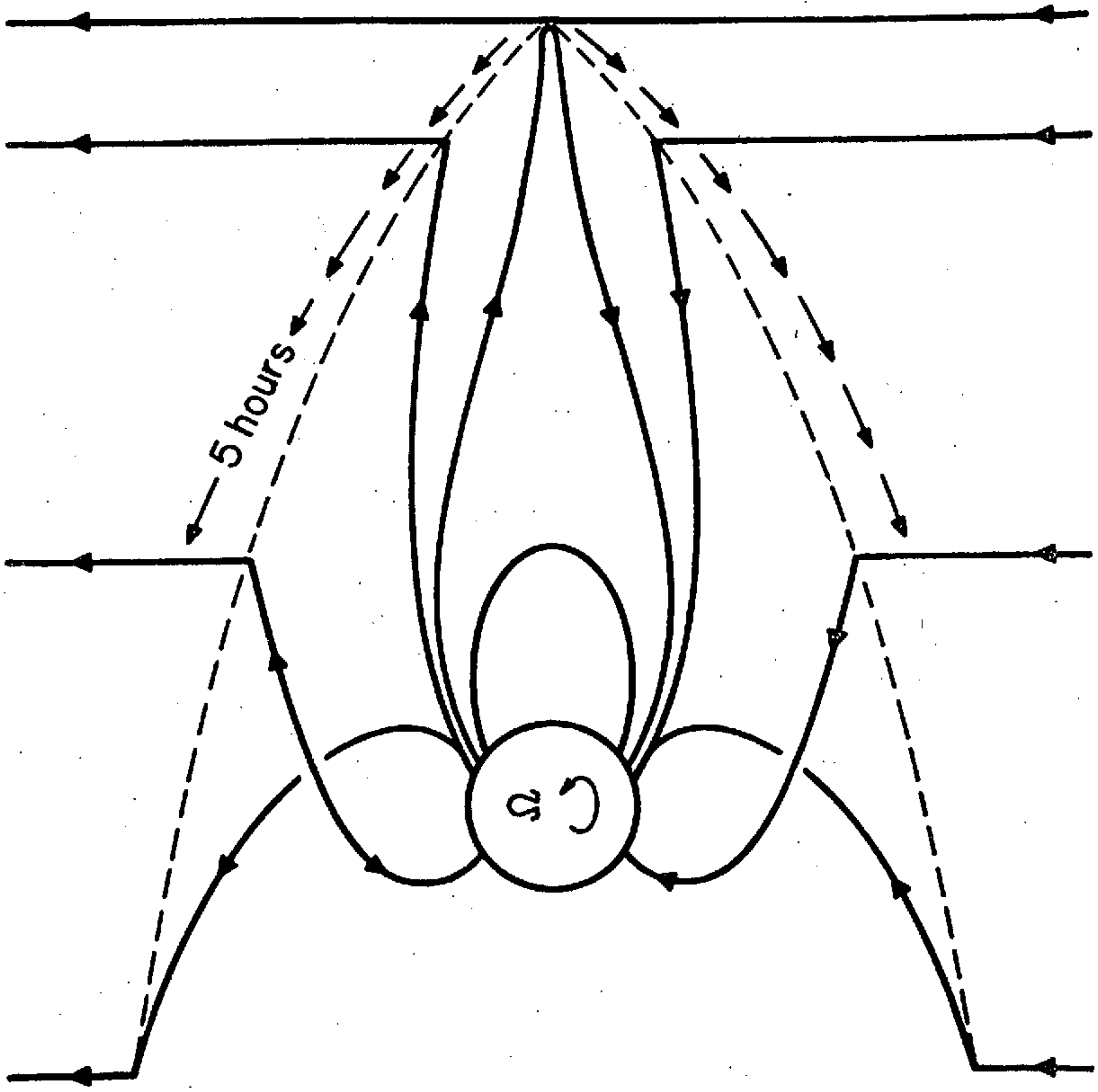


Total field intensity during the period of magnetopause crossing on June 8-9, 1965.



ALIGNED ROTATOR

SPINDOWN


5 hours

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