Inertial Limit on Corotation

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Corotation of a planetary magnetosphere with the rotation frequency of the planet is maintained by the viscous torque exerted by ion-neutral collisions in the planetary atmosphere, this torque being transmitted to the magnetosphere by Birkeland currents. In a steady state this torque balances the inertial drag associated with the production and/or outward transport of magnetospheric plasma. The viscous torque in the atmosphere requires some departure from rigid corotation, i.e., some difference between the average rotation velocities of the ionospheric plasma and of the un-ionized atmosphere. In this paper we calculate the inertial corotation lag as a function of radial distance in the magnetosphere, the solution being parameterized in terms of the Pedersen conductivity of the atmosphere and the rate at which plasma mass is produced and transported outward in the magnetosphere. Although insignificant in the case of earth's magnetosphere, the calculated inertial corotation lag is significant in the case of Jupiter's magnetosphere, where the rotation frequency may decrease by a factor of the order of 2 between the planetary surface and the magnetopause. One interesting consequence is that the active sector of Jupiter's magnetosphere (which is associated with a longitudinally restricted sector of enhanced ionospheric conductivity) should rotate faster, at a given distance, than adjacent longitude sectors and should therefore sweep up plasma from adjacent longitudes, thus amplifying the preexisting enhancement of plasma concentration in the active longitude sector.

INTRODUCTION

Planets that have both atmospheres and magnetospheres (earth and Jupiter for example) are expected, and observed, to exhibit the phenomenon of corotation, whereby the magnetospheric plasma rotates with essentially the angular velocity of planetary rotation. The role of the atmosphere is to provide a viscous transfer of momentum from the rotating surface of the planet up into the ionosphere, where the plasma is set into corotation by the collisional friction between the ions and the neutral particles (see, for example, *Hines* [1960]). The rotating ionospheric plasma polarizes so as to produce a corotation electric field

$$\mathbf{E} = -(\omega \times \mathbf{r}) \times \mathbf{B} \tag{1}$$

where ω and $\mathbf{B}$ are the planetary spin frequency and magnetic field vectors, respectively, and $\mathbf{r}$ is the radius vector from the spin axis. This electric field is then transmitted outward to enforce the corotation of the magnetospheric plasma, under the assumption that the magnetic field lines are perfect conductors [*Ferraro*, 1937]. (One often refers to the magnetic field lines themselves as corotating, although this description is ill defined for an axially symmetric field and is, in any case, unnecessary to the physical description.) In the absence of a significant neutral atmosphere, corotation can be enforced by the surface itself if the surface electrical conductivity is sufficient to impose the frozen-in-flux condition (1); this is expected to be the case in neutron star magnetospheres wherein corotation plays an essential role in most pulsar theories [e.g., *Gold*, 1968; *Michel and Tucker*, 1969; *Sturrock;* 1971].

If an electrically insulating atmosphere is present, there are two additional properties it must possess in order to enforce corotation: (1) it must have sufficient viscosity to transport planetary angular momentum upward to the Pedersen-conducting layer of the ionosphere, and (2) the Pedersen conductivity must itself be large enough to impose equation (1) (equivalently, the ion-neutral collision frequency must be large enough to drive the ions into corotation).

The first requirement has been discussed in connection with earth's atmosphere by, for example, *Hines* [1960] and in connection with Jupiter's atmosphere by *Coroniti* [1974] and *Kennel and Coroniti* [1975, 1977]. Although there remains some doubt in the case of Jupiter [*Kennel and Coroniti*, 1977], we will assume in the following discussion that the atmospheric viscosity is sufficient and that the rate of upward momentum transport from surface to ionosphere is limited chiefly by the second factor, the ionospheric conductivity.

Corotation cannot extend to arbitrarily large distances from the planet but must ultimately break down as the result either of external forces or of the inertia of the corotating plasma itself. In the case of earth's magnetosphere, external stresses imposed by the solar wind impede corotation beyond the plasmapause at about 5 earth radii distance [e.g., *Brice*, 1967]. In the prototypical pulsar model, corotation is presumed to be limited by relativistic inertial effects, which become important near the light cylinder at which $\omega r = c$, the speed of light. In the case of Jupiter's magnetosphere, corotation is generally considered to break down beyond the 'Alfvén point' or 'critical radius' at which $\omega r = v_A$, the local Alfvén speed [e.g., *Michel and Sturrock*, 1974; *Hill et al.*, 1974]. Beyond this point the magnetic field would be too weak to transmit the centripetal force necessary to contain the corotating plasma.

There is, however, another factor that can limit the extent of corotation independently of the above effects, namely, the inertial drag exerted by any local production and/or outward transport of plasma. If the magnetospheric plasma distribution were completely static (with no local production or transport), then no torque would be required to maintain the magnetosphere in corotation out to the Alfvén point. If such a static magnetosphere were not initially corotating, the differential rotation between atmosphere and ionosphere would produce an unbalanced torque that would ultimately drive the magnetosphere into corotation.

On the other hand, if plasma is continually produced or transported outward in the magnetosphere, then corotation (or even partial corotation) would imply that the total angular momentum of that plasma is steadily increasing in time, and this increase would require a net torque in the atmosphere to transfer planetary angular momentum outward into the mag-

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netosphere. In order to provide the required viscous torque the ionosphere must rotate somewhat more slowly than the un-ionized atmosphere. Thus corotation is necessarily incomplete in the presence of plasma production and/or outward transport. This self-limiting feature depends on the atmospheric conductivity and the rate of plasma production or transport and is quite independent of the effects that occur near the light cylinder or Alfvén point, which depend on the ability of the magnetic field to confine the plasma radially.

In the following section we calculate the inertial corotation lag as a function of distance in a magnetosphere characterized by the values of $\dot{M}$, the total rate of production and outward transport of plasma mass, and Σ, the height-integrated Pedersen conductivity of the atmosphere. We find that the corotation lag becomes significant at a distance L_0 (in units of planetary radii) given by

$$L_0 = (\pi \Sigma R_p^2 B_p^2 / \dot{M})^{1/4} \qquad (2)$$

where R_P is the planetary radius and B_p the planetary surface dipole magnetic field strength. Thus as one would expect, the corotation lag is most significant when the conductivity is small and the rate of mass addition is large.

The critical distance L_0 turns out to be too large to be of any consequence in earth's magnetosphere and in typical pulsar model magnetospheres. For Jupiter, on the other hand, we find $L_0 \sim 60$, i.e., well inside the magnetosphere (at least part of the time), so that the inertial corotation lag may have important consequences, on which we will comment briefly at the conclusion of the paper.

CALCULATION OF INERTIAL COROTATION LAG

In this section we first calculate the torque exerted on the ionosphere by the neutral atmosphere through ion-neutral particle collisions, this torque being proportional to the height-integrated Pedersen conductivity. We then calculate the rate of increase of angular momentum in the magnetosphere, this rate being proportional to the rate of outward mass transport. Upon combining these two results we obtain a differential equation whose solution gives the corotation lag as a function of distance in the magnetosphere.

Figure 1 illustrates the Birkeland current geometry and the coordinate system used here. For simplicity we treat the case of a spin-aligned dipole magnetic field, aligned with the axis of our spherical (r, θ, ϕ) coordinate system. Note in Figure 1 that the $\mathbf{j} \times \mathbf{B}$ force is directed so as to increase the angular momentum of the outer magnetosphere at the expense of the angular momentum of the atmosphere.

Atmospheric torque. Ion-neutral collisions exert a drag force F_ϕ per unit volume that is balanced, in a steady state, by the $\mathbf{j} \times \mathbf{B}$ force:

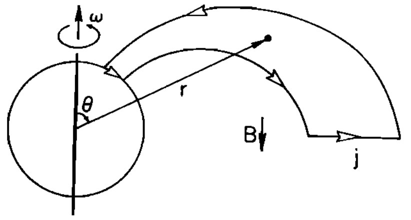

Fig. 1. Illustration of the coordinate system and field geometry employed in the calculation. The sense of the electric current flow is indicated by open arrowheads.

$$F_\phi = j_\theta B_r = \sigma B_r^2 \, \delta v \qquad (3)$$

where σ is the Pedersen conductivity and

$$\delta v = r \delta\omega \sin\theta \qquad (4)$$

is the rotational drift speed of the ions relative to the neutral gas. The torque per unit magnetic flux is thus

$$\frac{dT}{d\Phi} = \int \frac{dh}{B_r} F_\phi r \sin\theta \qquad (5)$$

where T, Φ, and h denote torque, magnetic flux, and altitude, respectively. If we define the height-integrated conductivity

$$\Sigma = \int \sigma \, dh \qquad (6)$$

and assume that all other quantities in the integrand of (5) are approximately constant through the Pedersen-conducting layer of the ionosphere, we can combine (3)–(6) to obtain

$$\frac{dT}{d\Phi} = \Sigma \delta\omega R_p^2 B_r \sin^2\theta_s \qquad (7)$$

where R_P is the planetary radius and θ_s the surface colatitude. Introducing the dipole field expressions,

$$B_r(R_p, \theta_s) = 2B_p \cos\theta_s \qquad \sin^2\theta_s = 1/L \qquad (8)$$

where B_p is the equatorial surface dipole field strength and L is the equatorial crossing distance of the field line in units of R_p, we have

$$\frac{dT}{d\Phi} = 2\Sigma\delta\omega R_p^2 B_p (1 - 1/L)^{1/2}/L \qquad (9)$$

It will prove convenient to express this result in terms of the torque per unit L (per unit equatorial crossing distance), i.e.,

$$\frac{dT}{dL} = \frac{dT}{d\Phi}\frac{d\Phi}{dL} \qquad (10)$$

For the dipole field we have

$$\frac{d\Phi}{dL} = 2\pi R_p^2 B_p / L^2 \qquad (11)$$

Combining (9)–(11), we obtain

$$\frac{dT}{dL} = 4\pi\Sigma\delta\omega R_p^4 B_p^2 (1 - 1/L)^{1/2}/L^3 \qquad (12)$$

Magnetospheric angular momentum. Let $\dot{M}$ be the total outward flux of plasma mass (in kilograms per second) crossing a given magnetic flux shell, and let l be the average angular momentum per unit mass of particles distributed along the flux shell. (A 'flux shell' is the surface of revolution of a field line about the magnetic axis.) The rate of increase of angular momentum per unit L (i.e., per unit normalized equatorial-crossing distance) is then

$$\frac{d\dot{\mathcal{L}}}{dL} = l\frac{d\dot{M}}{dL} + \dot{M}\frac{dl}{dL} \qquad (13)$$

On the right-hand side of (13) the first term represents the rate of increase (or decrease) of angular momentum due to a local source (or sink) of plasma, while the second term represents the rate of increase (or decrease) of angular momentum due to outward (or inward) transport. We shall neglect the local source/loss term and assume that the net transport is outward, i.e.,

$$\frac{1}{\dot{M}}\frac{d\dot{M}}{dL} \ll \frac{1}{l}\frac{dl}{dL} \tag{14a}$$

$$\dot{M} > 0 \tag{14b}$$

The justification for these assumptions will be discussed later. We thus approximate (13) by

$$\frac{d\dot{\mathscr{L}}}{dL} = \dot{M}\frac{dl}{dL} \tag{15}$$

The angular momentum per unit mass is just

$$l = (\omega_p - \delta\omega)\langle r^2 \sin^2\theta\rangle \tag{16a}$$

$$= (\omega_p - \delta\omega)R_p^2 L^2 \xi \tag{16b}$$

where ω_p is the planetary rotation frequency and $\xi \le 1$ is a geometrical factor of order unity which accounts for the latitudinal distribution of plasma along a field line.

For simplicity we shall assume that plasma is produced and transported outward within a thin equatorial disc as would be the case for plasma injected into Jupiter's magnetosphere by the satellite Io [*Hill and Michel,* 1976; *Siscoe,* 1977]. In this case, $\xi = 1$, and (16) yields

$$\frac{dl}{dL} = \omega_p R_p^2 \frac{d}{dL}[L^2(1 - \delta\omega/\omega_p)] \tag{17}$$

(For other latitudinal distributions of plasma the geometrical factor $\xi(L)$ would have to be included inside the brackets in (17).) Combining (15) and (17) gives

$$\frac{d\mathscr{L}}{dL} = \dot{M}\omega_p R_p^2 \frac{d}{dL}[L^2(1 - \delta\omega/\omega_p)] \tag{18}$$

Corotation lag. Combining the results (12) and (18) with the law of angular momentum conservation

$$T = \mathscr{L} \tag{19}$$

we obtain the differential equation

$$L^5\frac{df}{dL} + [2L^4 + 4L_0^4(1 - 1/L)^{1/2}]f(L) - 2L^4 = 0 \tag{20}$$

where

$$L_0^4 \equiv \pi\Sigma R_p^2 B_p^2/\dot{M} \tag{21}$$

and

$$f(L) \equiv \delta\omega(L)/\omega_p \tag{22}$$

Thus $f(L)$ is the corotation lag (i.e., the difference in angular velocity between the magnetosphere and the atmosphere), normalized to the planetary angular velocity.

The solution to (20), subject to the boundary condition $f(1) = 0$, is

$$f(L) = \left[\int_1^L 2xg(x)\,dx\right]/[L^2 g(L)] \tag{23}$$

where

$$g(L) \equiv \exp\left[4L_0^4\int_1^L dx\,(1 - 1/x)^{1/2}/x^5\right] \tag{24}$$

The angular velocity $\omega/\omega_p \equiv 1 - f$ is plotted according to (23) in Figure 2 (solid line) for the case $L_0 = 64$, a value that appears to be appropriate for the Jovian magnetosphere (see the following section). As we noted in the introduction, the corotation lag becomes significant for $L \gtrsim L_0$. The functional form is essentially independent of the value of L_0 as long as $L_0 \gg 1$. The following approximation is useful for large distances:

$$g(L) \approx g(L_0)\exp(1 - L_0^4/L^4) \qquad (L \gg 1) \tag{25}$$

from which we obtain

$$f(L) \approx \frac{1}{L^2}e^{L_0^4/L^4}\int_1^L 2x\,e^{-L_0^4/x^4}\,dx \tag{26}$$

$$\equiv 1 - \frac{1}{L^2}\exp[-L_0^4(1 - 1/L^4)] + \pi^{1/2}(L_0/L)^2 \cdot \exp(L_0^4/L^4)[erf(L_0^2/L^2) - erf(L_0^2)] \tag{27}$$

$$\approx 1 - \pi^{1/2}(L_0/L)^2 \tag{28}$$

where the last result is correct to third order in L_0/L. Thus for large L,

$$\omega/\omega_p \equiv 1 - f \rightarrow \pi^{1/2}(L_0/L)^2 \tag{29}$$

Thus in the absence of external forces (like the solar wind) the plasma would asymptotically conserve its angular momentum at large distances where the ionospheric torque becomes increasingly ineffective. The asymptotic angular momentum carried away per unit mass is just

$$l_\infty = \lim_{L\to\infty} \omega r^2 \qquad l_\infty = \pi^{1/2}\omega_p R_p^2 L_0^2 \tag{30}$$

i.e., $\pi^{1/2}$ times the value that would obtain if the plasma were to corotate rigidly out to $L = L_0$ and strictly conserve its angular momentum beyond. The asymptotic form (29) is shown in Figure 2 as a dotted line.

APPLICATION

We propose that the model treated above is applicable to a significant portion of the magnetosphere of Jupiter. The three fundamental requirements for applicability of the model are that the net plasma transport be (1) outward and (2) suffi-

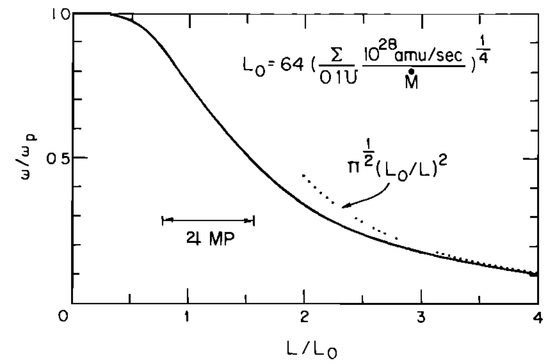

Fig. 2. The angular rotation frequency ω, normalized to the planetary value ω_p, is plotted versus the equatorial distance L, normalized to the value L_0 defined in (21). The solid line is plotted according to (23); the dotted line shows the asymptotic expression (29). The range of distances within which the Jovian magnetopause was observed by Pioneer 10 and 11 is indicated, according to the nominal scaling $L_0 \approx 64$ for Jupiter ($\omega/\omega_p = 1$ for rigid corotation).

ciently rapid to dominate local source and loss processes, and that (3) externally imposed forces be negligible in comparison with the inertial acceleration of this outward-moving plasma.

With regard to the first requirement we note that the two principal sources of plasma in the Jovian magnetosphere are widely considered to be the Jovian ionosphere [*Ioannidis and Brice*, 1971; *Hill et al.*, 1974; *Goertz*, 1976] and/or the innermost Galilean satellite Io [*Hill and Michel*, 1976; *Cloutier et al.*, 1978]; in either case the net plasma transport would be outward for $L \gtrsim 6$. (The external source of solar wind plasma is generally assumed to be negligible by comparison, although this assumption has not really been subjected to observational test.)

Combining expressions (14*a*), (16*b*), and (17) above, we find that the second requirement is

$$\frac{d\dot{M}}{dL} \ll 2\dot{M}/L \qquad (31)$$

i.e., the (outward) mass flux must be approximately conserved throughout the radial range of interest. In practice this means that the local production rate (e.g., through photoionization of neutral gas) and loss rate (e.g., through recombination) must be small in comparison with the diffusive flux. This condition is expected to be met within the range $6 \lessdot L \lessdot 50$ in Jupiter's magnetosphere (see, for example, *Siscoe* [1978]), but in situ measurements are again required to confirm the validity of this assumption.

The third requirement is equivalent to the condition that the solar wind induced convective motions be slow in comparison with the corotation speed; this condition is expected to be met at least within $L \lesssim 50$ in Jupiter's magnetosphere [*Brice and Ioannidis*, 1970].

Given these three fundamental assumptions, we can scale the results of Figure 2 to the Jovian magnetosphere using the scaling law (21):

$$L_0 = 64\,(\Sigma/0.1\ \text{mho})^{1/4}(\dot{M}/10^{28}\ \text{amu/s})^{-1/4} \qquad (32)$$

where we have used $R_p = 71{,}400$ km, $B_p = 4.2$ gauss, and the 'nominal' values $\Sigma \sim 0.1$ mho [*Dessler and Hill*, 1979, and references therein] and $\dot{M} \sim 10^{28}$ amu/s [*Kennel and Coroniti*, 1977; *Hill and Carbary*, 1978, and references therein]. Thus we expect Figure 2 to apply to Jupiter's magnetosphere in the range $L_0/10 \lesssim L \lesssim L_0$. By comparison, Jupiter's magnetopause has been found to lie at distances in the range $50 \lesssim L \lesssim 100$; this range is indicated by the arrow marked 'MP' in Figure 2. We see that the inertial corotation lag should be quite significant in the Jovian magnetosphere, the rotation frequency decreasing by a factor of the order of 2 between the planet and the magnetopause for the parameters quoted above. (The fact that our assumptions become invalid within $L \sim 6$ is of little consequence because the predicted corotation lag is negligible in this range anyway.)

We do not know whether any observational evidence exists either for or against a corotation lag of this magnitude. The Pioneer 10 and 11 spacecraft did not carry appropriate instruments to measure directly the flow velocity of magnetospheric plasma. Energetic proton measurements exhibited unidirectional anisotropies that were consistent with corotation out to $L \sim 50$ [*McDonald and Trainor*, 1976; *Simpson and McKibben*, 1976; *Van Allen*, 1976], but it is difficult in these measurements to separate the effects of corotation from those of field-aligned flow. Simpson and McKibben noted that the magnitude of the anisotropy just inside the magnetopause was 'much less than that expected for rigid corotation of the particles with the planet.'

The clear 10-hour periodicities observed in energetic particle fluxes in the outer magnetosphere do not necessarily imply rigid corotation because such periodicities may have been caused by latitudinal gradients coupled with the diurnal wobble of the tilted dipole, rather than by corotation of a longitudinally asymmetric particle distribution. Likewise the 10-hour periodicities in radio emission features do not contradict the possibility of a significant corotation lag in the outer magnetosphere because the emitting flux tubes are generally considered to be located in the inner magnetosphere ($L \sim 6$ for the sporadic 'decametric' emissions and $L \sim 2$ for the continuous 'decimetric' emissions).

Thus the results of our calculation (as illustrated in Figure 2) constitute a prediction that must be checked against future in situ plasma observations or, perhaps, against future detailed analysis of Pioneer energetic particle data.

For the sake of completeness we should point out that the corotation lag as predicted from the above analysis would be entirely negligible in the case of earth's magnetosphere and in the case of the typical pulsar model magnetosphere. For the earth, R_p and B_p are both about a factor of 10 less than they are for Jupiter, while Σ is about 2 orders of magnitude greater and the value of $\dot{M}$ (derived from a polar wind source) is at least 2 orders of magnitude smaller [e.g., *Hill*, 1974, and references therein] than it is for Jupiter. Thus (see (21) above) the value of L_0 should be about the same for earth as for Jupiter, i.e., $L_0 \sim 64$. The important difference is that solar wind induced convection overwhelms corotation for $L \gtrsim 5$ in earth's magnetosphere, so that a value $L_0 \sim 64$ renders the inertial corotation lag insignificant for earth (whereas the same value of L_0 produces a significant effect at Jupiter).

Likewise, for the parameters of a typical neutron star magnetosphere [e.g., *Michel*, 1978], one can easily show that the characteristic distance L_0 (equation (21)) would exceed the radius of the velocity of light cylinder (and hence of the magnetosphere) by orders of magnitude, even if the neutron star conductivity were no better than that of Jupiter's atmosphere.

In our application to Jupiter's magnetosphere (equation (32)), we have used the nominal conductivity $\Sigma \sim 0.1$ mho that is applicable to the ambient ionosphere of Jupiter as produced by ionizing solar ultraviolet radiation. *Dessler and Hill* [1979] have proposed that electron impact ionization due to precipitation of magnetospheric radiation belt electrons may enhance the conductivity drastically within a longitudinally restricted sector of Jupiter's ionosphere. The effect of this enhanced conductivity would be to increase the characteristic distance L_0 (equation (32)) and hence to reduce the magnitude of the corotation lag at a given distance, within the favored longitude sector. For example, if Σ were locally enhanced by a factor of 20, as proposed by Dessler and Hill, then L_0 would increase by a factor $20^{1/4} \sim 2$. Referring to Figure 2, we conclude that the corotation lag would then be $\lesssim$10% within this enhanced longitude sector, but would approach 50% at other longitudes in the outer magnetosphere. We would then have the interesting possibility that Jupiter's 'active sector' (the longitude sector associated with enhanced ionospheric conductivity) corotates nearly rigidly with Jupiter, whereas the remaining longitudes do not. In this case the active sector would tend to overtake the more slowly rotating plasma in adjacent longitudinal sectors and to sweep up the plasma therein. In other words, a negative divergence of the plasma flux would occur at the leading edge of the active sector and would tend to increase the plasma concentration there. We would then have a positive feedback mechanism whereby the localized sector of enhanced conductivity produces an increase of the magnetospheric trapped plasma concentration, which in turn amplifies the conductivity enhancement (through precipitation), etc. This is not meant to imply that the frozen-in-flux condition is violated in the outer magnetosphere—rather, it is proposed that entire flux tubes from adjacent longitudes accumulate at the leading edge of the active sector, thus compressing the plasma therein. The region of enhanced conductivity is localized in longitude but extended in latitude; thus the accumulating flux tubes cannot detour around the enhanced conductivity region but must instead accumulate until the increasing plasma density drives an outward convective flow of the type described by V. M. Vasyliunas (private communication, 1978).

The longitudinal asymmetry of plasma density would thus be amplified as the plasma moves outward until it reaches the Alfvén radius, at which point the active sector plasma would force the magnetic field open to form a planetary wind. The plasma would be expelled once each rotation as the active sector rotates into the magnetospheric tail, as described by *Carbary et al.* [1976] and references therein.

CONCLUSIONS

We have found that the corotation lag due to the inertia of outward-moving magnetospheric plasma becomes significant at a distance L_0 which is proportional to the one-fourth power of the height-integrated ionospheric Pedersen conductivity and inversely proportional to the one-fourth power of the mass transport rate. For expected values of these parameters we find $L_0 \sim 64$ for Jupiter ((32) above), so that the inertial corotation lag should be readily observable in Jupiter's magnetosphere.

In the case of earth's magnetosphere we also find $L_0 \sim 64$, but in this case we do not expect the inertial lag to be significant because solar wind stresses become important for $L \ll L_0$. In the case of pulsar model magnetospheres the inertial lag is also unimportant because L_0 exceeds the size of the magnetosphere by a large factor.

In the case of Jupiter's magnetosphere the ionospheric conductivity, and hence the rotation speed at a given distance, may be a strong function of longitude. If this is true, then our results indicate that the active sector (the longitude sector associated with large ionospheric conductivity) may rotate faster at a given distance than other longitude sectors. The implication of this is that most of the magnetospheric plasma would tend to accumulate in the active longitude sector at and beyond $L \sim L_0$.

Note added in proof. Preliminary analysis of plasma flow measurements performed during the Voyager 1 Jupiter encounter indicates a significant departure from corotation in the magnetosphere beyond 12 R_J distance (H. S. Bridge and J. W. Belcher, private communication, 1979). The rotation velocity decreases to roughly three fourths of the corotational value at a distance of 20 R_J. With reference to Figure 2 above, this result is seen to be consistent with the above analysis if $L_0 \approx 20$ in (21) and (32) above, i.e., if the mass addition rate is as large as 10^{30} amu/s.

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