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COMPARISON OF A MODEL OF JUPITER'S MAGNETOSPHERE WITH PIONEER DATA

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ABSTRACT

The model of Jupiter's magnetosphere presented by Prakash at the 1974 Frascati symposium (see Prakash and Brice, 1975), in which there is a circum-Jovian outflow of plasma from an inner corotating magnetodisc, is compared with the observations of the Pioneer flybys.

From the plasma measurements of the Pioneer 10 flyby of Jupiter, Wolfe et al. (1974) found that the size of Jupiter's magnetosphere is much larger ($\sim 96R_J$) than the extent ($\sim 53R_J$) predicted by scaling the Earth's magnetosphere (e.g., Brice and Ioannidis, 1971). In order to explain the 10 hr periodicities in the flux of energetic particles observed in the Jovian magnetosphere by Pioneer 10 (Fillius and McIlwain, 1974; McKibben et al., 1974; Trainer et al., 1974; Van Allen et al., 1974), Van Allen et al. invoked a rigidly corotating magnetodisc with particles concentrated in the equatorial plane. From their magnetic field data, Smith et al. (1974) concluded that the magnetodisc was warped toward the equator, although there exists some controversy with the University of Iowa interpretation of little warping (e.g., Van Allen et al., 1975). In the model of Jupiter's magnetosphere presented by Prakash at the 1974 Frascati symposium (see Prakash and Brice, 1975), the rigidly corotating magnetodisc is envisaged to be of limited extent ($L_c R_J$) and from its edges there is a centrifugally driven outflow of thermal plasma. Although the model is similar to the independently proposed model of Hill et al. (1974), the two pictures of the magnetosphere have significant differences. Whereas Hill et al. confine the outflow into the magneto-tail, the model presented by Prakash has circum-Jovian outflow. Moreover, the model explicitly takes into account the effect of the tilt of the dipole on the outflow which gives the outflowing plasma the appearance of a wavy disc, as shown schematically in Fig. 1. Also, the model envisaged the possibility that the outflow may be intermittent, perhaps in the form of blobs of plasma, and that the radius of the corotating region ($L_c R_J$) was a time dependent parameter, owing to fluctuations in the (thermal) plasma density distribution inside the magnetosphere, arising from auroral precipitation etc.

Since the Pioneer 10 and 11 plasma detectors are in no position to directly detect the outflow predicted by the model, we here point out the indirect evidence from the Pioneer data which would be consistent with the model. A more up to date version of some of the features of the model is also included.

McDonough et al. (1975) have recently obtained a revised version of the Ioannidis and Brice (1971) diffusive equilibrium curve of plasma density in the inner Jovian magnetosphere, resulting from the photoelectron escape flux from the ionosphere as calculated by Swartz et al. (1975). Using this result, we draw Fig. 2 which updates the Fig. 5 of Prakash and Brice (1975). The main rationale of the model is that since Jupiter is surrounded by an insulating atmosphere, interchange motions of the field lines are capable of causing an $\sim L^{-4}$ density drop, which, on the assumption of a maximum (thermal) plasma density of ~ 100 cm^{-3} (before interchange motions become dominant), intersects the $\sim L^{-8}$ Alfvénic limit curve (Ioannidis and Brice, 1971; Michel and Sturrock, 1974) inside the Jovian plasmasphere, at L_c. The Alfvénic limit for density is the density for which the local Alfvén speed becomes equal to the corotation speed. The model postulates that from L_c there is a circum-Jovian outflow of plasma, with frozen-in field lines. L_c is identified as the edge of the corotating magnetodisc and the plasma flow is taken to be tangential to the magnetodisc, as an approximation. The dashed Alfvén limit of Fig. 2 has been drawn for a dipole field with a surface (L=1) value $B_o = 8$ gauss, rather than the actual value of $B_o \sim 4$ gauss of Smith's D_2 model, in order to make the magnitude of the magnetic field in the outer magnetosphere close to the actual value observed there. The value of L_c so obtained is ~50. However, because the exact density distribution within the Jovian magnetosphere is unknown, the model takes L_c to be a time dependent parameter to be deduced from spacecraft data. The tilt of the dipole results in a wavy disc of outflowing plasma. The equation of the surface of this disc can be written as

$$z(x,y,t) = \frac{L_c \sin\theta_0 \cos\left(\omega t - \sqrt{\frac{x^2+y^2}{L_c^2} - 1} - \phi_0\right)}{1 - \sin^2\theta_0 \sin^2\left(\omega t - \sqrt{\frac{x^2+y^2}{L_c^2} - 1} - \phi_0\right)}$$

where $$\phi_0 = \cos^{-1}\left(\frac{y\sqrt{x^2+y^2-L_c^2} + L_c x}{x^2+y^2}\right)$$

and $$x^2+y^2 > L_c^2 .$$

Here ω is the angular speed of Jovian rotation, θ_0 is the tilt of the dipole axis with respect to the rotation axis ($\theta_0 = 10.6^\circ$ if Smith's D_2 model is used), L_c the radius of the corotating inner magnetodisc, and $V_A = \omega L_c$ is the Alfven speed at L_c. For a given (x,y), the equation gives the variation of z as a function time t. The coordinate system used is the Jovicentric system with the z-axis along the spin vector, x-axis towards the Sun, and the y-axis pointing west to give a right hand coordinate system. It is essentially the Jovicentric solar ecliptic coordinate system. It should be noted that the equation of the outflowing wavy plasma disc given above assumes that the equatorward warping of the inner corotating magnetodisc is negligible. The field spiral angle is given by

$$\phi(x,y) = \frac{\pi}{2} - \sin^{-1}\left(L_c/(x^2+y^2)^{1/2}\right) .$$

The outflow of the plasma, carrying frozen-in field lines, leads to a spiral field in the region beyond L_c. Fig. 3 shows this spiraling as a function of L_c. In the outbound pass of Pioneer 10, Smith et al. (1974) obtained a field 'lag' of $\sim 35^\circ$ at $\sim 96R_J$. This would require an L_c of 74. The model so fitted to the data is shown in Fig. 4. According to the model, the dynamic pressure of the outflowing plasma contributes to the observed (e.g., Wolfe et al., 1974) distention of the magnetospheric boundary of the scaled magnetosphere. The distention is expected to have a morning-evening asymmetry (see Fig. 7 of Prakash and Brice, 1975) and the dashed curve in Fig. 4 is a schematic representation of the boundary.

Fillius and McIlwain (1974) plotted the positions of their energetic particle flux minima as a function of System III (1957) longitude (see their Fig. 10) and pointed out that the locking-in of the phase of the inbound minima at $\sim 50R_J$ could be an indication of a boundary that separates two different regions of the magnetosphere. In their outbound data, such a boundary is indicated at about $75R_J$, which is in agreement with Fig. 4(in the outbound region) according to which $L_c = 74$. The indication of an inbound boundary at $L \sim 50$ in Fillius' data could be interpreted as due to the time dependence of L_c or due to a compression of L_c by the solar wind on the dayside. The disorderliness of the magnetic field data in the Pioneer 10 inbound traversal of the outer magnetosphere (Smith et al., 1974) is interpreted as due to the effects of compression by the solar wind which enhances magnetic merging of the oppositely directed spiral field lines (e.g., Gold, 1974; Simpson et al., 1974; Prakash and Brice, 1975).

The Pioneer 10 data of McKibben et al. (1974), (see their Fig. 2), can also be interpreted to indicate a boundary at

$L \sim 40$ inbound and at $L \sim 60$ outbound, the distances upto which the particle flux minima indicate rigid corotation. Since the magnetodisc need not be ' at the edges, the data of McKibben et al.(1974) are not inco stent with the above interpretation of $L_c \sim 50$ inbound and $L_c \sim 75$ outbound. However, this interpretation encounters a difficulty in the light of a preliminary interpretation of their Pioneer 11 data by Simpson et a'. (1975) who state that the periodicities in the energetic particle flux are synchronous throughout the sunward side of the Jovian magnetosphere. However, it appears that a clarification of the conclusions of Simpson et al. in harmony with the Pioneer 11 magnetic field data and the energetic particle data of other experimenters (e.g., Fillius et al., 1975) is needed before the situation is considered settled. In any case, the high latitude periodicities of Pioneer 11 present difficulties to the model discussed here, as they do to other models.

Trainer et al. (1974), in their Fig. 4 and Fig. 5, plot the Pioneer 10 differential energy spectra of electrons at different radial distances from the planet for the inbound and outbound trajectories. Their data show a boundary within the magnetosphere such that the spectrum goes as E^{-2} inside the boundary and as $E^{-1.5}$ outside the boundary. Their data are remarkably consistent with $L \sim 50$ for the boundary in the inbound case and $L \sim 74$ in the outbound case, and give added support to our interpretation.

From the detection of a current sheet with energetic particle flux maxima in the inbound pass of Pioneer 11, a feature that was not observable in Pioneer 10 data, Simpson et al. (1975) conclude that the "spatial distribution of particles changes with time over a period of many days." This is in accord with the time dependent nature of L_c expected in the model discussed here. An unresolved difficulty with the model is that if the inner magnetodisc is warped as much as deduced theoretically by Hill et al. (1974), then the wavy outflow is confined to an amplitude less than $5R_J$ and this makes it unlikely that the periodicities seen in the outer magnetosphere could represent periodic immersion of the spacecraft in the outflow.

According to the model, the "sponginess" of the outer magnetosphere observed by the Ames plasma detectors on Pioneer 10 and 11 (Wolfe et al., 1974; Mihalov et al., 1975) is to attributed in part to fluctuations in L_c, although variations in the solar wind pressure undoubtedly are a factor. The fact that the inbound Pioneer 11 flyby showed approximately the same magnetopause crossings as the inbound pass of Pioneer 10 (Mihalov et al., 1975), may not merely be a fortuitous coincidence but an evidence for the distention of the magnetopause resulting from outflow of plasma from the inner magnetosphere. Some of the multiple boundary crossings detected by the Ames plasma analyser show ~5 or ~10 hr intervals and these could also be interpreted (Prakash, 1975) as supporting the picture given by Prakash and Brice (1975). The outflow is also expected to give rise to a double shock at the nose (e.g., Kennel et al. 1975; Dryer, private communication to Prakash, 1974). Since the Ames plasma detectors on Pioneer 10 and 11 were mounted facing the sun, it is difficult to identify the second internal shock at the nose or to directly detect the outflowing plasma. It appears that only future spacecraft missions, equipped with a (low energy) plasma detector facing Jupiter, could provide conclusive evidence for or against the outflow model of Jupiter's magnetosphere considered here.

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FIGURE CAPTIONS

Fig. 1. Schematic representation of the noon-midnight meridional section of Jupiter's model magnetosphere according to Prakash (Prakash and Brice, 1975). The waviness of the outflowing plasma disc has been exaggerated -- in actuality less than one wavelength would exist on the sunward side.

Fig. 2. An estimated plasma density distribution in Jupiter's equatorial plane shows that rigid corotation is unlikely to exist beyond a critical radial distance given by $L_c \sim 50$.

Fig. 3. Predicted spiraling of field lines as a function of L_c.

Fig. 4. Model magnetosphere of Jupiter (now viewed from above the N-pole) as fitted to the magnetic field spiraling observed in the Pioneer 10 outbound pass.

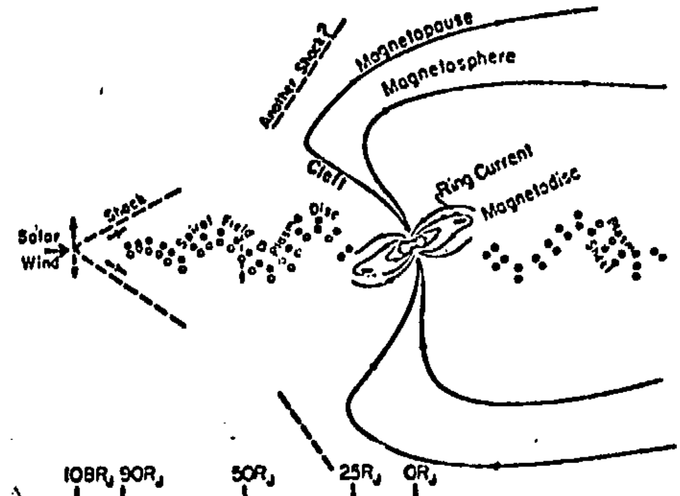
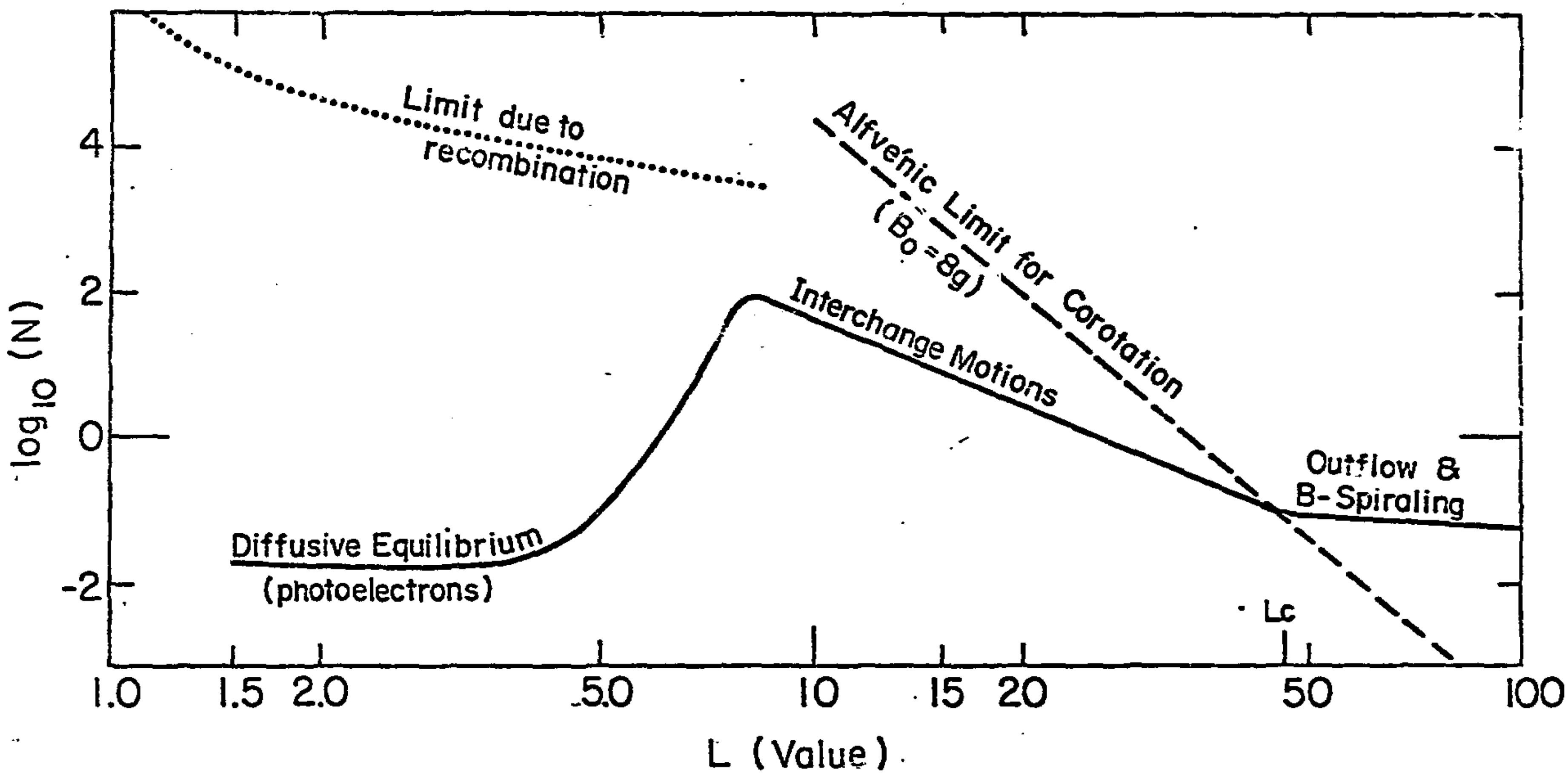
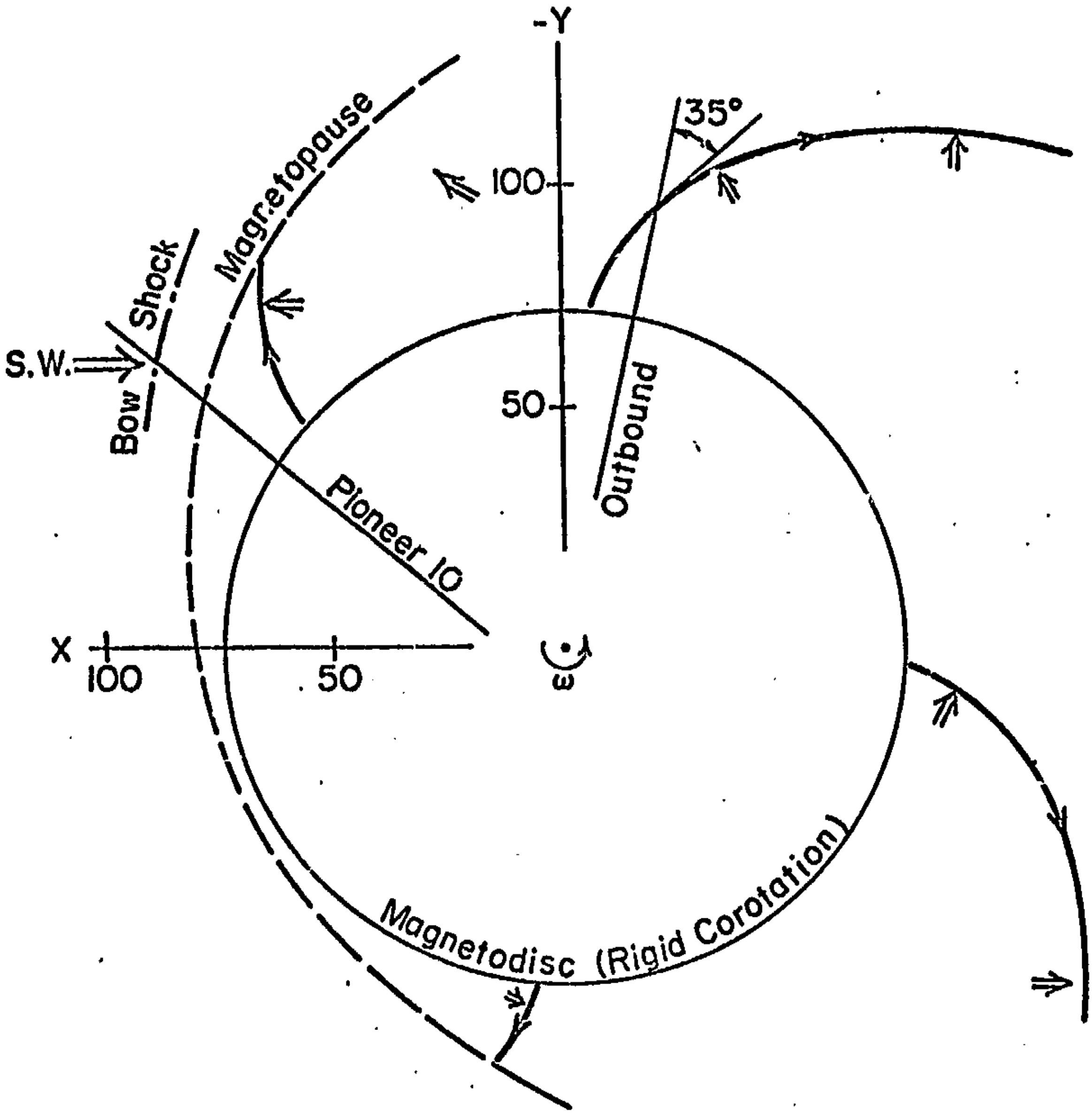

Magnetopause
Magnetosphere
Another Shock ?
Cleft
Ring Current
Magnetodisc
Shock
Solar
Wind
Spiral Field
Plasma Disc
108R$_J$
90R$_J$
50R$_J$
25R$_J$
0R$_J$

Fig 1



Limit due to recombination
Alfvénic Limit for Corotation
(B_o = 8g)
Interchange Motions
Outflow & B-Spiraling
Diffusive Equilibrium (photoelectrons)
Lc
4
2
0
-2
$\log_{10}$ (N)
1.0
1.5
2.0
5.0
10
15
20
50
100
L (Value)


-Y
35°
100
50
S.W.
Bow Shock
Magretopause
Outbound
Pioneer IO
X
100
50
ω
Magnetodisc (Rigid Corotation)