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OF JUPITER'S MAGNETOSPHERE IN THE LIGHT OF
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CURRENT STATUS OF MODELS OF JUPITER'S MAGNETOSPHERE IN THE LIGHT OF PIONEER DATA

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ABSTRACT

The salient features of the various models of Jupiter's magnetosphere are compared with each other and with the major findings of Pioneer 10 and 11. No single model is able to explain all the major phenomena detected by the Pioneers. We propose a unified model of Jupiter's magnetosphere, as a step in the evolution of our understanding of the magnetospheric environment of the giant planet.

The large size of the Jovian magnetosphere measured by the magnetic field and plasma detectors during the Pioneer 10 flyby of Jupiter showed that the magnetosphere of Jupiter cannot be explained merely by scaling the magnetosphere of Earth for the planetary magnetic field and solar wind parameters at Jupiter. In addition, the Pioneer flybys revealed the existence of 10 hour periodicities in energetic particle flux and magnetic field data along the spacecraft trajectory within the magnetosphere. Several models of the Jovian magnetosphere have been proposed to explain these and other phenomena discovered by the Pioneer missions. However, it can be safely said that no single model proposed so far has been successful in explaining, even qualitatively, all the major features of Jupiter's magnetosphere as detected by the Pioneer flybys. The purpose of this short paper is to explore the possibility of a reconciliation of the various models with each other and with the Pioneer 10 and 11 data.

It appears that Van Allen's proposal of a wobbling, flattened magnetodisc (Van Allen et al., 1974), based on earlier theoretical studies (Gold, 1962; Piddington, 1967, 1969; Melrose, 1967; Gledhill, 1967), as an explanation of some of the 10 hr periodicities observed by Pioneer 10, is here to stay in one form or another. However, the extent and the precise shape of the magnetodisc remain subjects of controversy. Hill et al. (1974) calculated that the 10.6° tilt of the Jovian dipole with respect to the spin axis (Smith et al., 1974) would result in a warping of the magnetodisc toward the spin equator by the action of the centrifugal force such that the rim of the magnetodisc would never be farther than $5R_J$ from the spin equatorial plane. Independently, Smith et al. (1974) analysed their magnetic field data to discover a current sheet which corresponded to a magnetodisc warped parallel to the spin equatorial plane in the outer region. However, since the outbound trajectory of Pioneer 10 was substantially more than $5R_J$ above the equatorial plane well inside the magnetosphere, the theoretical calculation of the magnitude of warping (Hill et al., 1974) is in disagreement with the results of Smith et al. Moreover, Goertz (1975) has recently interpreted the Pioneer 10 outbound data as indicating an almost negligible warping out to $86R_J$. In another recent paper, Axford and Gleeson (1975) have analysed the formation of a magnetodisc from first principles, under simplifying assumptions. However, more theoretical and experimental work is required to obtain a full understanding of the nature of the magnetodisc. In a paper presented in May, 1974, it was pointed out by Prakash (see Prakash and Brice, 1975) that the existence of a magnetopause at $96R_J$, as detected by Pioneer 10 in December, 1973, implied (see Fig. 1, an updated version of Fig. 4 of Prakash and Brice) that a L^{-4} density drop due to interchange motions outwards from the vicinity of the orbit of Io would intersect (at L_c) the density limit ($\propto L^{-8}$) based on the criterion (Ioannidis and Brice, 1971; Michel and Sturrock, 1974) that the speed of corotation cannot exceed the local Alfvén speed, such that L_c lies within the plasmasphere. (Previously, Ioannidis and Brice had proceeded from the assumption that L_c was at the magnetopause.) Here L is the equatorial distance in units of Jupiter radius, R_J. It may be noted that the diffusive equilibrium curve of plasma density distribution in the inner magnetosphere that we have drawn in Fig. 1 is an empirical curve obtained by using the shape of the Ioannidis and Brice (1971) curve and shifting it vertically upwards on the logarithmic scale so that the number density at the orbit of Io is $\sim 30\ \mathrm{cm}^{-3}$, the value deduced by Frank et al. (1975) from the Ames plasma analyser data of Pioneer 10. The diffusive equilibrium density obtained from

Fig. 1 >

the photoelectron escape flux alone is ~ 2 orders of magnitude smaller (Scarf, 1975). However, the observed distention of the field lines in the Jovian magnetosphere (e.g., Smith et al., 1974) implies significant plasma loading of the field lines. This fact, together with the measured number density at the orbit of Io (see also Hill et al, 1975), is indicative of (thermal) plasma sources other than photoelectron escape flux, e.g., secondary electron production resulting from auroral precipitation (Prakash and Brice, 1975), which are presumably included in the empirical diffusive equilibrium curve labelled "photo+auroral" in Fig. 1. Alternatively, the dashed curve marked "photo+Io" attributes the large plasma density t effective sources near Io. In Fig. 1 we have also assumed that the maximum plasma density in the Jovian magnetosphere is ~ 60 cm^{-3}, the value detected by Frank et al. (1975). Interchange motions beyond this point give $L_c \simeq 70$, which is inside the observed magnetopause at $L \sim 96$. Based on this result, Prakash's 1974 model magnetosphere (see Prakash and Brice, 1975) envisaged a magnetodisc, whether warped or not, of limited extent ($L_c \doteq 50$ to 75) and a circum-Jovian outflow of plasma into the outer magnetosphere from the edges of the corotating magnetodisc. This model has similarities with the independently developed models of Hill et al. (1974), Kennel and Coroniti (1975), and Eviatar and Ershkovich (1975). The significant difference from the model of Hill et al. is that they confine the outflow into the night side in order to blow open magneto-tail, whereas Prakash's model has a thin belt of outflowing plasma all around Jupiter. In Prakash's model the outflow can take the form of discrete blobs or an intermittent wind and L_c was developed as a time dependent and azimuthally variable parameter, determined largely by internal processes, e.g., auroral precipitation (Prakash, 1975), and other conditions, e.g., offset of the dipole (Prakash and Brice, 1975). Even a steady outflow in the thin (albeit wavy) plasma disc of Prakash's model is not to be thought of as "blowing open" the magnetosphere on the dayside, not only because of the thinness of the outflowing plasma disc but because the flow returns downstream as a boundary layer flow (Dryer, private communication, 1974) along the magnetopause, as illustrated below. The Kennel-Coroniti-Eviatar-Ershkovich model is the application of the Weber-Davis (1967) two-dimentional solution for stellar winds and, therefore, has the constraint that the Jovian dipole is assumed to be aligned with the spin axis. In order to take the tilt of the dipole into account, Prakash assumed, as a zeroth order approximation, that the plasma comes off, at the Alfvén speed, tangentially to the corotating inner magnetodisc and carries with it spiraling field lines. The outflowing plasma thus attains the appearance of a thin wavy plasma disc (see Fig. 9 of Prakash and Brice, 1975). The equation of the surface of this disc can be written as

$$z(x,y,t) = \frac{L_c \sin\theta_0 \cos(\omega t - \chi)}{1 - \sin^2\theta_0 \sin^2(\omega t - \chi)}$$

where $\chi(x,y,L_c) = \sqrt{\zeta^2 - 1} + \cos^{-1}\left(\frac{\eta\sqrt{\zeta^2-1} + \xi}{\zeta^2}\right)$,

and $\xi = x/L_c$, $\eta = y/L_c$, $\zeta = \sqrt{\xi^2 + \eta^2}$.

Here θ_0 is the tilt of the dipole ($\theta_0 = 10.6°$ in Smith's D_2 model), ω the angular velocity of Jovian rotation, L_c the radius of the inner corotating magnetodisc ($V_A = \omega L_c$ is the Alfvén speed at L_c). The Jovicentric coordinate system has the z-axis along the spin vector and the x-axis towards the Sun. The above equation assumes negligible warping of the inner magnetodisc. The field spiral angle (the acute angle between $\vec{B}(x,y)$ and the radius vector) is $\phi_s(x,y) = \sec^{-1}\zeta$.

In the model of Kennel et al., the outflow is radial and super-Alfvénic. The outflow vectors in Prakash's model would not differ much from radial direction at an appreciable distance from the inner magnetodisc; however, the field spiral is less tightly wound than $\phi_s = \tan^{-1}\zeta$ of the radial outflow models and that facilitates agreement with the modest (~35°) spiraling observed near the magnetopause in Pioneer 10 data. Also, because of the decrease in the magnetic field with distance, the local Alfvén velocity will be smaller the larger the distance from the inner magnetodisc so that the outflow (which is at a constant speed equal to the Alfvén speed at the edge of the corotating inner magnetodisc) becomes super-Alfvénic as it proceeds towards the magnetopause. As has been discussed in detail by Kennel and Coroniti (1974) and by Eviatar and Ershkovich (1975), the super-Alfvénic outflow, interacting with the high Mach number solar wind, would lead to the formation of a fast internal shock, in addition to the bow shock. Dryer (private communication, 1974) has further pointed out that the interaction would also lead to a boundary layer flow of the magnetospheric plasma back along the magnetopause and we suggest that the magnetosheath flow seen by the Pioneer plasma experiment to be preferentially in the eastward or westward direction (Mihalov et al., 1975b) could partly be the boundary layer flow. At a fixed point in space downstream, the boundary layer flow would show 10 hr (or higher harmonic) periodicities. An unambiguous identification of the subsolar inner shock or an <u>in situ</u> detection of the radial component of the circum-Jovian outflow by instruments aboard future spacecraft missions to Jupiter would be a conclusive test of the outflow type models of the Jovian magnetosphere. As for the extent of the rigidly corotating magnetodisc, Van Allen (1975) has inferred corotation, at least at one instant of time, out to $60R_J$. A direct detection of corotating (low energy) plasma at this and larger distances from the planet would require sensitive instrumentation, as indicated by the theoretical estimate of the maximum corotating

Fig.2> flux which we have plotted in Fig. 2, using the Alfvenic limit criterion.

One of the remarkable discoveries of Pioneer 10 was the detection of MeV energy electrons of Jovian origin upstream the bow shock (Chenette et al., 1974; Teegarden et al., 1974). Chenette et al. (1974) showed that this upstream flux of energetic electrons has 10 hr periodicities, synchronous with the energetic particle flux periodicities detected just inside the Jovian magnetosphere. According to Hill et al. (1975), the source of the upstream periodicities is the escape of magnetospheric energetic particles from the open magneto-tail of their model. To obtain a 10 hr period, they invoke the longitudinal asymmetry of the surface magnetic field as measured by Acuna and Ness (1975) during the Pioneer 11 encounter. As an alternative explanation, we suggest that in our circum-Jovian wavy plasma disc outflow model, the merging of the solar wind sector field with the Jovian spiral field at the nose of the magnetosphere is the source of the upstream energetic particles. The magnetic merging is illus-
Fig.3> trated in Fig. 3, where the Jovian spiral has been drawn for $L_c \sim 40$. The open arrows are the flow directions of the thermal plasma (including the solar wind). The inclined open arrows contain the boundary layer back-flow. The energetic magnetospheric electrons, which travel essentially along the field lines with the speed of light, are transferred into the solar wind magnetic field at the nose. The 10 hr upstream periodicities can arise not only by a 10 hr time variation throughout the outer magnetosphere (deduced by Simpson et al. (1975) from Pioneer 11 data) but also from the fact that the wavy form of the horizontally flowing thin plasma disc in our model magnetosphere (see Fig. 9 of Prakash and Brice, 1975) would imply

a vertical displacement of the plane of magnetic merging with a 10 hr periodicity, and this plane would intersect an upstream detector with a 10 hr periodicity (or higher harmonics).

We now address ourselves to the problems encountered in regard to the questions of the shape of the boundary surface of Jupiter's magnetosphere and of the overall field line topology. From their Pioneer 10 and 11 measurements, Smith et al. (1974, 1975) have emphasized that the direction of the magnetic field just inside the magnetopause is preferentially southward and that this implies closed field lines. From their plasma measurements, Mihalov et al.(1975a)observed that the distances of the dayside magnetopause obtained during the high latitude outbound crossings of Pioneer 11 are somewhat smaller than the corresponding distances obtained from the low latitude inbound crossings.Mihalov et al. (1975a) interpret this as indicating that the magnetosphere is more extended near the equatorial plane, especially when the solar wind pressure is minimum. Beard and Jackson (1975) have also obtained a 20% flattening of the magnetospheric boundary from theoretical calculations which incorporate the effect of the current sheet associated with the magnetodisc. Although Prakash (see Prakash and Brice, 1975) had not explicitly given the field line topology in the region surrounding the wavy plasma disc, he had predicted that the flattening of the outer magnetosphere boundary on the dayside could result in a second high latitude shock surface, downstream the first bow shock at the nose. That prediction is independent of whether the outflow exists inside the magnetosphere. Starting out with an Earth-like ("classical") magnetospheric boundary, the ultimate cause of the flattening of the boundary surface of Jupiter's magnetosphere is distention of the "classical" magnetosphere due to the centrifugal force and the distention is going to be negligible at high latitudes. Consequently, at high latitudes we expect the boundary of the Jovian magnetosphere to be that obtained by scaling the (unflattened) magnetosphere of the Earth and that implies existence of a (hat-like) bulge in the high latitude region of the Jovian magnetosphere. Thus, although the subsolar magnetopause crossing at $96R_J$ by Pioneer 10 demolished the previously predicted classical magnetosphere (e.g., Brice and Ioannides, 1970) for Jupiter, the classical magnetosphere possibly still exists as a shadow magnetosphere which shows up as a real bulge at high latitudes in the centrifugally distended Jovian magnetosphere. The downstream magnetosheath flow over the flattened equatorial magnetosphere would reach supersonic speeds before encountering this high latitude bulge and a second high latitude shock would be formed. However, it is not clear whether the equatorial flattening in the actual Jovian magnetosphere is significant enough for this purpose, and the existence of the second high latitude shock (and hat-like bulge) must be regarded as an open question. Indications of the second shock might exist in the outbound Pioneer 10 shock crossings (Prakash, 1975) which, unlike the outbound Pioneer 11 trajectory, sampled flow downstream the polar cap.

How can one reconcile the relatively blunt outer magnetosphere consisting of closed field lines near the magnetopause, as deduced from Pioneer data (e.g., Smith et al., 1975), with the flattened magnetodisc deduced by Van Allen and others? And how does the intermittent circum-Jovian outflow predicted by Prakash and others fit into the picture? As an attempt to answer such questions, we propose a unified model of the topology of the Jovian magnetosphere shown in Fig. 4. In this picture, the innermost magnetosphere (upto $\sim 15R_J$) consists of rigidly

Fig. 4>

corotating undistorted field lines which contain intense trapped radiation. At larger distances, the distention of field lines in the magnetic equatorial plane starts to become appreciable, resulting in a flat corotating (skew) magnetodisc. Except near the edge, the warping of this disc toward the spin equator is small (Goertz, 1975). Associated with the magnetodisc is a current sheet (Smith et al., 1974). In the outer half of this disc, the field lines have a modest westward spiraling (Smith et al., 1975). (The spiraling of field lines has not been shown in Fig. 4, for the sake of simplicity.) The radius of the corotating magnetodisc region is a time dependent (Prakash and Brice, 1975) and azimuthally dependent (Prakash and Brice, 1975; Hill et al., 1975) parameter. (Pioneer 10 data, e.g., Fig. 10 of Fillius et al. (1974), Fig. 2 of McKibben et al. (1974), and Figures 4 and 5 of Trainer et al. (1974), are remarkably consistent with the hypothesis of $L_c \sim 50$ on the dayside and $L_c \sim 70$ on the pre-dawn side in that they all show a discontinuity at these distances.) From the edge of this inner magnetodisc there is an intermittent circum-Jovian outflow of (thermal) plasma which carries the field lines with it (Prakash and Brice, 1975); the flow is unimpeded in the tailward direction (Hill et al., 1974). This region is susceptible to magnetic merging which leads to formation of loops and neutral points. Fig. 4 shows an instantaneous picture of the topology (without including the spiraling). (The outflow can start out as discrete plasma blobs which get cut-off by reconnection (Gold, 1962; Prakash and Brice, 1975), in which case the loops in Fig. 4 represent such blobs.) For the particle density shown in Fig. 1, and the magnetic field measured by Smith et al. (1974), the conversion of magnetic energy into particle energy via field annihilation gives 500 keV per particle. This is the turbulent outer magnetosphere observed by Smith et al. (1975). Magnetic merging of the field lines in the outflowing plasma, before it reaches the magnetopause, leaves the outermost magnetosphere with the southward directed closed field lines, as shown in Fig. 4, in accord with the observations of Smith et al. (1975). The high latitude (polar cap) field lines are connected to the interplanetary field lines and if they are considered to have convected downstream from the nose via the reconnection process as it is generally believed to occur for the case of the Earth then the solar wind velocity being only $\sim 50R_J$ per 5 hours (which is half the Jovian rotation period), the corotation of the foot of such a field line would make the polar cap field lines twisted (Kennel and Coroniti, 1975; Piddington, 1967), as shown in Fig. 4.

In this picture, the periodicities observed in the energetic particle flux in the inner magnetosphere are from the spatial variations that arise from the rotation of the inner skew magnetodisc (e.g., Van Allen et al., 1974). The periodicities in energetic particle flux observed in the outermost magnetosphere arise either from longitudinal asymmetry or from some (unknown) time phenomenon which creates periodic bursts of particles in the entire outer magnetosphere (Simpson et al., 1975). The longitudinal asymmetry could be due to higher multipole surface fields (Hill et al., 1975) or localised field anomaly. But it is tentalizing to note (see Fig. 10 of Fillius et al., 1974) that from $\sim 80R_J$ upwards, the energetic particle minima occured when Pioneer 10 was at the System III longitude opposite to the dipole offset direction, for both inbound and outbound data. This is what would be expected if there were a substantial loss of trapped energetic particles by the greater engulfment of the field lines by the ionosphere for the anti-offset hemisphere. Unfortunately, it is hard to find a way to make such depletion of flux significant. One should, therefore, look for a mechanism which would generate bursts of energetic particles in the outer magnetosphere once every 10 hours. Escape of energetic electrons from such time controlled bursts would also explain the upstream periodicities. Perhaps, the annihilation of the loops shown in Fig. 4 somehow occurs once every 10 hours.

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FIGURE CAPTIONS

Fig. 1. An estimated (thermal) plasma density distribution within the Jovian magnetosphere. Unlike the Brice and Ioannides (1970) case, the density becomes equal to the limiting value for corotation well inside the plasmasphere and outflow of magnetospheric plasma results from the edge (L_c) of the magnetodisc (see also Prakash and Brice, 1975).

Fig. 2. An estimate of the maximum possible flux of corotating (cold) plasma in Jupiter's magnetosphere (based on the Alfvenic limit criterion) as a function of radial distance (LR_J) from the planet.

Fig. 3. Magnetic merging of the planetary wind spiral field with the solar wind spiral at the nose of Jupiter's magnetosphere, for times when intense outflow of magnetospheric plasma becomes possible. The view is from above the north pole.

Fig. 4. Our proposed unified model of the overall topology of the Jovian magnetosphere, seen in the noon-midnight meridional section. The spiraling of field lines at the edges of the inner magnetodisc and beyond has been omitted. Field lines on the night side have also been omitted for simplicity.

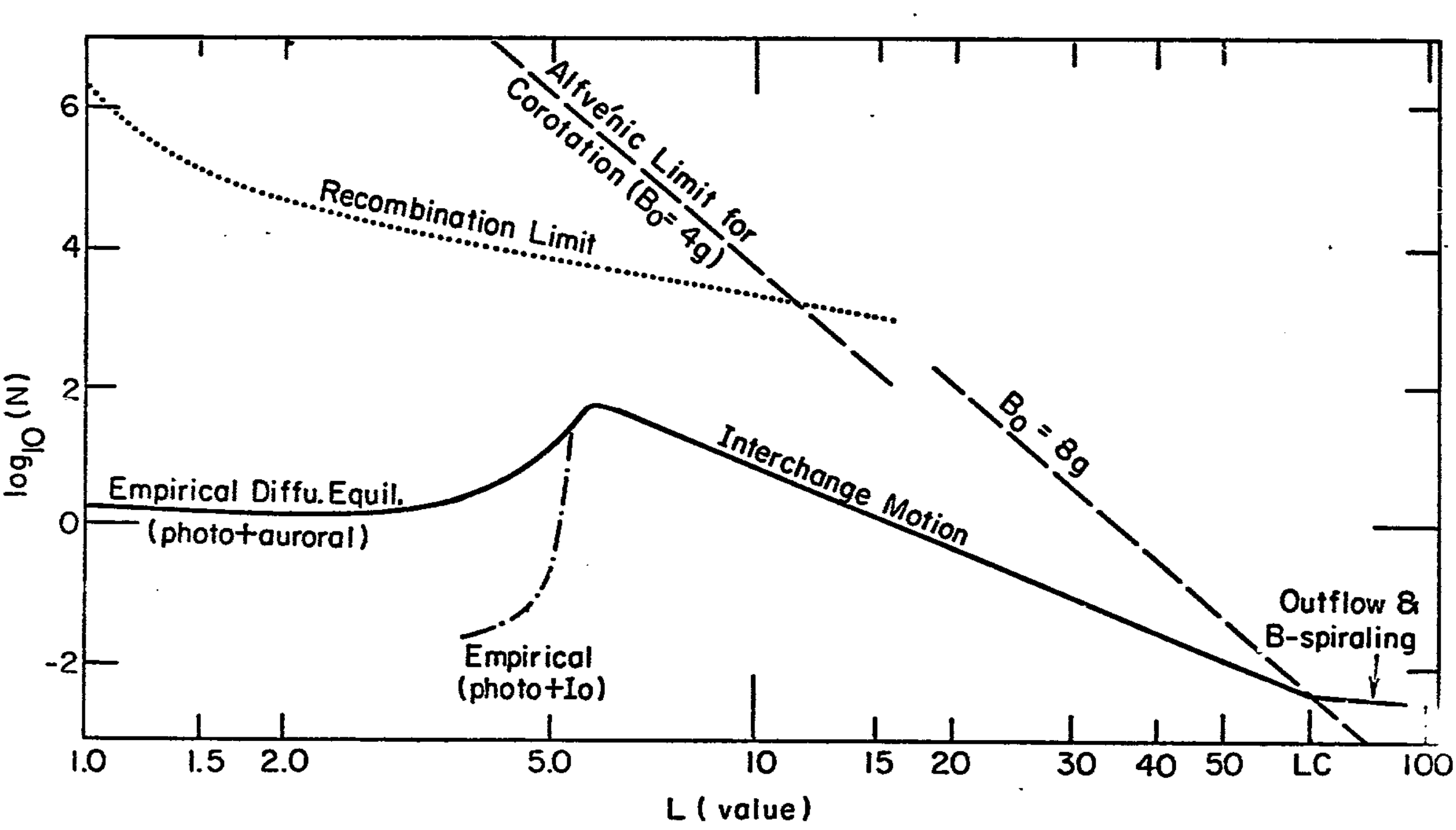

Fig. 1

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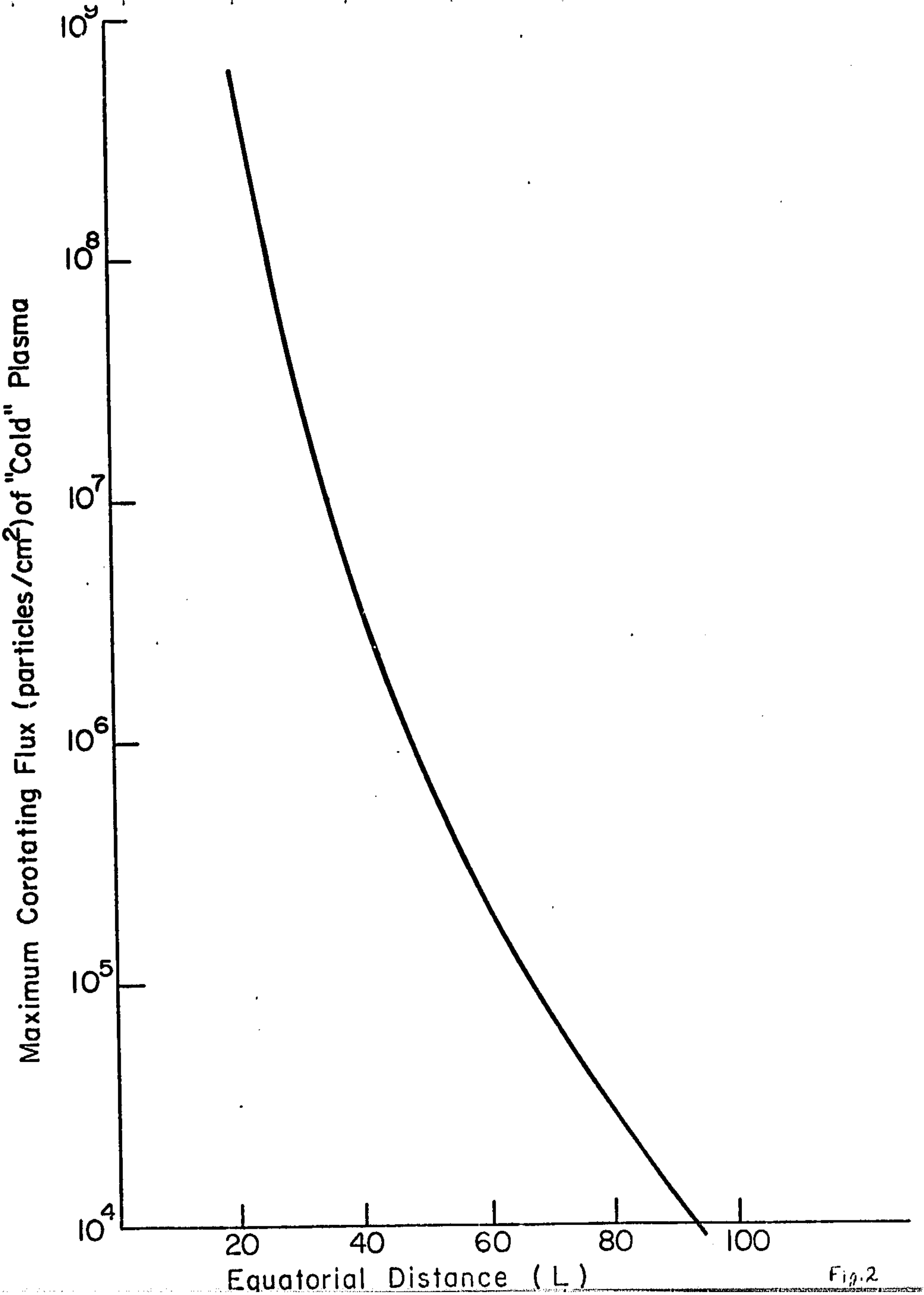

10^9
10^8
10^7
10^6
10^5
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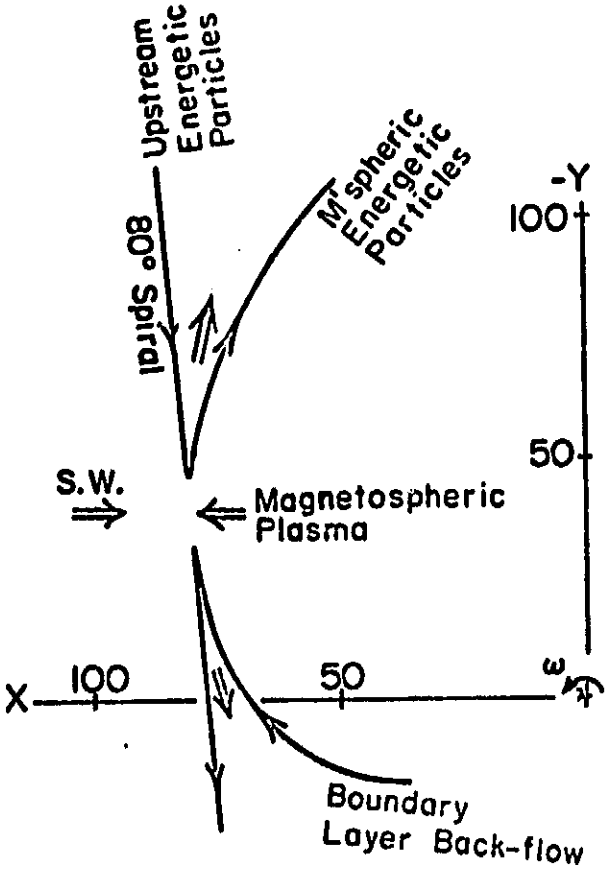
Maximum Corotating Flux (particles/cm²) of "Cold" Plasma
20
40
60
80
100
Equatorial Distance (L)

Fig. 2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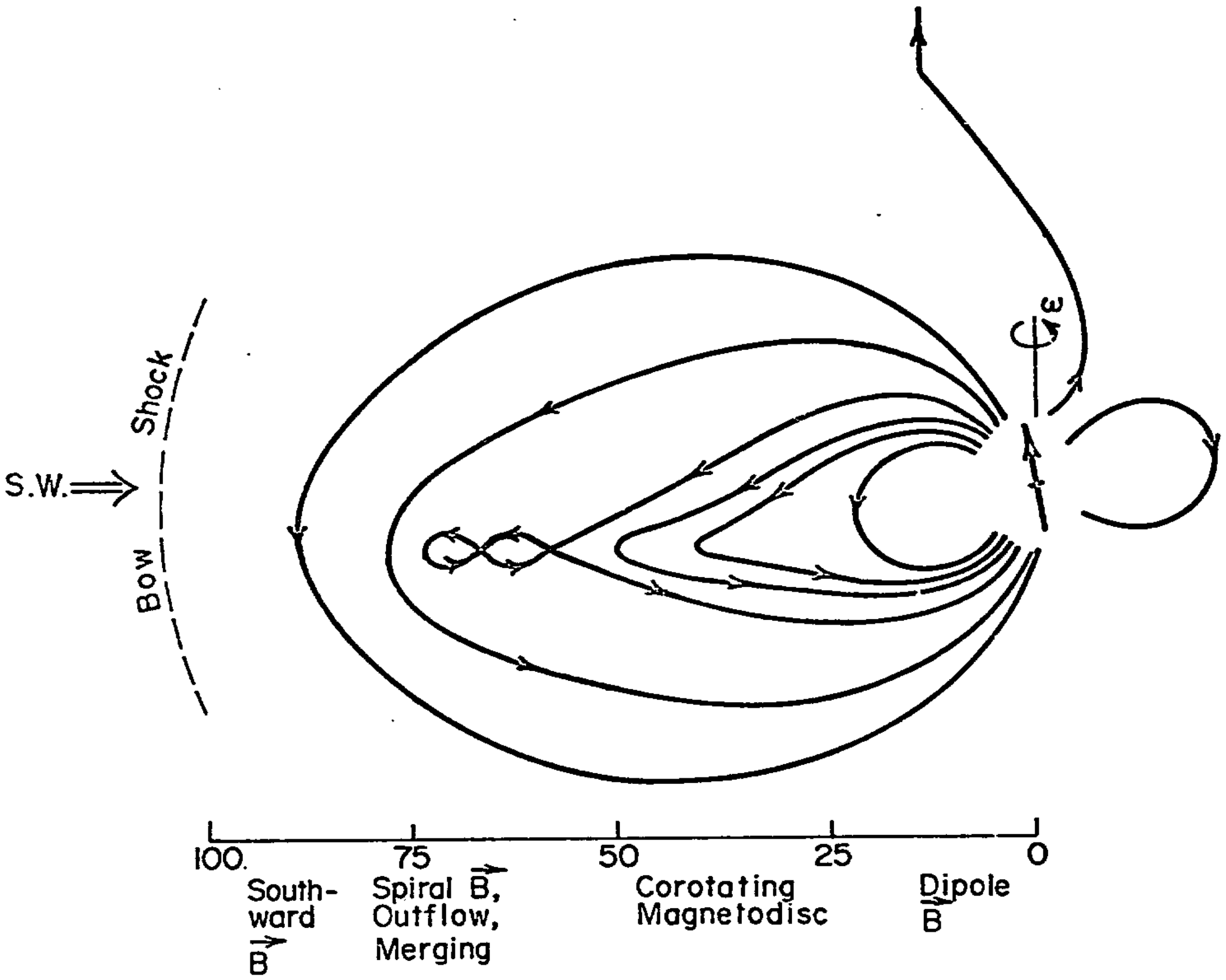
Boundary
Layer Back-flow

Fig. 3

S.W.
Bow
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75
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25
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South-ward $\vec{B}$
Spiral $\vec{B}$, Outflow, Merging
Corotating Magnetodisc
Dipole $\vec{B}$

Fig. 4