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Jupiter's Magnetosphere*

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ABSTRACT

Alternative types of Jupiter upper atmospheres are discussed and it is shown that a hot extensive ionosphere and dense magnetosphere may result from electromagnetic heating which also accounts for an apparent excess of thermal radiation. The heating will result from interchange motions and other hydromagnetic motions in the magnetosphere caused by rotation and transmitted along field lines to the ionosphere. These involve a ring current and plasma moved outward by centrifugal force until it no longer corotates, but forms a wrapped-around tail. Neutral sheets and particle accelerations are introduced in the geomagnetic tail.

The disturbance caused by the satellite Io through the magnetosphere may be far more violent than previous estimates, if the satellite has finite electrical conductivity. It will then carry field lines frozen into its body and cause a disturbance (a forced interchange motion) extending to the ionosphere in both hemispheres. There is evidence that this model accounts for all the Io related decametric radiation in terms of a single complex source lying near longitude λ_{III} 200° and radiating in more than one direction.

In the vicinity of the earth many interesting phenomena, notably trapped energetic particles and the geomagnetic tail, are caused by the solar wind and have provided ample rewards for investigations made by spacecraft. The present study indicates that near Jupiter there will be an even richer field of particles and magnetic phenomena, caused mainly by the planet's rotation.

I. INTRODUCTION

Following the detection of strong, intermittent radio signals from Jupiter by Burke and Franklin [1955], numerous studies, both observational (radio and optical) and theoretical, have been made. The results have been reviewed by Roberts [1963], Franklin [1964], Ellis [1965], Kraus [1966], Warwick [1967], and Drake [1967].

In addition to the anticipated thermal emission, there is a broad spectrum of decimeter and decameter radio emissions. The former have been interpreted as synchrotron radiation by electrons of energies in the range 10-100 MeV moving in a magnetic field of strength about 1 gauss and extent about 3 planetary radii. These correspond to the belt of energetic particles near the earth, except that they are about 1000 times as dense and in addition the magnetic fields are much stronger, having a value of about 15-20 gauss near the poles. Subsequently, it has been shown that the longitudes (relative to the direction of the earth) of the plane of the tilted dipole and also of the satellite Io both exercise a control over the radiation received.

To further develop theories of radio emission and other Jovian phenomena, a hydromagnetic model of Jupiter's surroundings is required. This will involve a determination of particles and fields in this region and of their motions and interactions. A key parameter is the temperature (and hence the scale height) of the ionosphere. If low ($\lesssim 10^3$ °k), then the ionosphere is confined far below the region where centrifugal force equals gravitational force. If high ($\gtrsim 10^4$ °k), then the plasma density in the magnetosphere is high and many interesting effects must follow, such as field deformation by a ring current, interchange motions, departure from corotation near the magnetopause, acceleration of particles to high energy and so on. Such motions must heat the ionosphere and so help determine its scale height; thus particle and field models are interdependent and must be determined simultaneously.

Another phenomenon requiring investigation is the effect of Io in its motion relative to the magnetosphere. Previous investigations have considered effects of the motion <u>through</u> the magnetized plasma; since this motion is much slower than the Alfvén velocity, its effects should be small. However, if Io is slightly electrically conducting, then field lines are frozen into its body and are dragged along with Io. This is a "forced interchange motion" and may have some remarkable results.

It seems most important that the various phenomena discussed below should be further evaluated before a space probe is sent to the vicinity of Jupiter.

II. MODEL JOVIAN ATMOSPHERES

The distribution of plasma in Jupiter's plasmasphere results from upward diffusion of protons and electrons. These are produced by dissociation and ionization from the molecular hydrogen that consitutes the bulk of Jupiter's atmosphere. The extent of the plasmasphere depends critically on the supply of energy available to ionize and heat the ionosphere because if the latter extends to sufficient height, it tends to move further out under the influence of centrifugal force.

2.1 Model Ionospheres

Early estimates of ionospheric peak electron density [Zhelezniakov, 1958; Rishbeth, 1959] were based on the simplest of model Chapman regions and gave values $\sim 10^6$ cm^{-3} -10^7 cm^{-3}. Gross and Rasool [1964] made a much more detailed study of the major properties of the upper atmosphere, based on the assumption of radiative equilibrium and determined electron density and temperature distributions. The peak electron density found was $\sim 10^6$ cm^{-3} and the scale height of order 100 km.

Ellis [1965] and Warwick [1967] have made indirect estimates of ionospheric temperature and scale height, based on radio data and its interpretation. Ellis' theory of decametric emission requires a high plasma density at several Jovian radii (R_J) and in support of the theory he postulates a temperature in the upper ionosphere of $\sim 5000\ ^\circ K$, which provides electron densities in the vicinity of Io $\sim 10^4\ cm^{-3} - 10^5\ cm^{-3}$ as required. Warwick, on the other hand, argues in favor of a low ionospheric temperature; his Cerenkov emission theory requires a very low electron density in the upper ionosphere in order that radiation may cross the region where electrons gyrate with the wave frequency. However, such escape seems improbable even with minimum density estimates, and so the radio emission theory does not favor any plasmasphere model. Warwick also cites his failure to observe Faraday rotation in Jupiter's radio emission as evidence of low plasma densities ($\gtrsim 10\ cm^{-3}$) beyond about 1 R_J. However, it is not clear from his argument that the same result would not be obtained if one polarization mode originated high in the plasmasphere, rather than near the surface of the planet as he assumes.

Summing up, it seems that there is no direct evidence of either a small close-in plasmasphere or a hot, extended model. If the energy input were limited to solar radiation, then the former would probably result. As shown below, however, it is probable that there are other sources of energy for heating and ionizing the Jovian ionosphere, notably hydromagnetic motions.

2.2 The Plasmasphere

While the terms plasmasphere and magnetosphere may refer to identical regions, we use the former in discussing a body of plasma which may possibly be confined to a limited part of a magnetic configuration, where the field is a simple unperturbed (although perhaps tilted) dipole field. It is generally recognized that the plasma surrounding a magnetized cosmical object rotates with the object. We may equally well visualize the magnetic field lines frozen into the object and rotating with it, or that the lines remain at rest and an electric field $\underline{E}$ is generated, such that

$$\underline{E} + \underline{v} \times \underline{B} = 0 \quad , \quad \underline{v} = \underline{\Omega} \times \underline{R}, \tag{1}$$

where $\underline{v}$ and $\underline{\Omega}$ are the velocity and rotational vectors and B the magnetic field [Hones and Bergeson, 1965].

The rotation of planetary plasmaspheres will add a centrifugal force term to the effects determining plasma distribution [Angerami and Thomas, 1964] and the effects of this term have been considered by Melrose [1967]. He determines a model Jupiter plasmasphere for a magnetic dipole aligned with the rotational axis and nowhere distorted by plasma forces (and the associated currents which provide the reverse Lorentz forces), so that the field lines satisfy

$$r \sin^2 \theta_i = \sin^2 \theta , \tag{2}$$

where θ is colatitude and θ_i its value where the line intersects the ionosphere. The potential energy Γ per unit plasma mass above its ionospheric value Γ_i is given, for plasma constrained to move along a rotating field line, by

$$\Gamma - \Gamma_i = gR_J(1 - r^{-1}) - 1/2\, \Omega^2 R_J^2 \,(r^2 \sin^2 \theta - \sin^2 \theta_i) , \tag{3}$$

where $-g\, R_J\, r^{-1}$ is the gravitational potential at distance $r\, R_J$ from the center of the planet. Above the ionosphere Γ at first increases to a maximum value at

$$r_m = (3/2\ \delta \sin^2 \theta_i)^{-1/4} \tag{4}$$

where $\delta = \Omega^2 R_J g^{-1} = 8.6 \times 10^{-2}$, and then decreases to a minimum value in the equatorial plane.

In Fig. 1 we show a plot of the potential energy function $(\Gamma - \Gamma_i)$, measured in units of the energy gR_J needed to lift the plasma from the ionosphere to infinity against gravitational force only. The curve applies for a value of $\theta_i \sim 66°$, corresponding to the orbit of Io, with r in the equatorial plane having a value of 5.9. The curve is drawn for a dipole field tilted at an angle of 10° to the rotational axis so that the potential energy peaks are asymmetrical. Plasma may be gravitationally trapped at levels below the energy peaks or centrifugally trapped between the peaks, while particles of sufficient energy may move over both peaks from one hemisphere to the other. Melrose suggests that particles streaming in this manner from opposite hemispheres would interact through the two-stream instability and so be trapped. However, in the presence of hot ambient plasma this mechanism is inoperative and so an efficient cooling process is required to allow such trapping.

In the outer potential trough of Fig. 1 there is net outward acceleration and an outwardly increasing pressure; this tends to cause a rapidly increasing density which cannot be limited by the solar wind and which Melrose finds unacceptable. He attempts to overcome this difficulty by assuming that the density falls towards zero at a rate determined by the condition that the magnetosphere remain stable against interchanges of the magnetic field lines.

Interchange motions of tubes of magnetic force are permitted when the lower atmosphere of the planet electrically insulates the magnetosphere and ionosphere from the planet itself, as in the case of the earth [Gold, 1959; Sonnerup and Laird, 1963]. Such motions involve changes in the energies of the plasma in the different tubes: the plasma thermal energy plus the potential energy Γ. When the net change is positive, then the motions are stable and this is the assumed condition in Melrose's model. It leads to a corotating magnetosphere limited to 7-8 radii.

Interchange motions, if they occur, do so against the <u>frictional forces</u> within the magnetosphere and ionosphere. Since these forces require the expenditure of energy outside the force tubes, it follows that only unstable interchange motions are possible. In fact, in the case of the earth, interchange motions to and from the tail of the magnetosphere are driven by external forces (friction with the solar wind) and dissipate frictional energy in the polar ionosphere as the DS current system [Piddington, 1960, 1962]. In Melrose's model unstable interchange motions are precluded and driving force is absent and so no motions will occur. The model is static, "cold" and the boundary is likely to occur inside 10 R_J.

2.3 An Active Magnetosphere

The existence of plasma in the outer potential energy trough of Fig. 1 will lead to unstable interchange motions, the field lines being moved outwards (and their feet to higher latitudes in the polar caps). Eventually, the field itself will become distorted from the dipole form and other effects will follow; these are discussed below. Such a dynamic magnetosphere will tend to be self-sustaining because the motions depend only on the presence of plasma in the trough and this depends only on heating of the plasmasphere, which, in turn, is provided by the motions themselves.

There are other ways in which the magnetosphere will be activated. Contrary to Melrose's conclusion, the corotating magnetosphere must extend to the magnetopause or boundary between Jupiter's field and the interplanetary medium. As shown below, there will be violent shearing motions in this region corresponding to velocity differences of about 1000 km sec^{-1}. A magnetic "tail" may form, which is wrapped around the inner magnetosphere. The magnetosphere may also be heated and disturbed by the relative motions of the satellites; these effects are discussed in Section V.

Finally we note the direct evidence of a hot magnetosphere in the form of energetic electrons (10-100 MeV) required to explain the powerful synchrotron radio emission. The flux of such electrons is some 10^3 times that of the earth's belt [Chang and Davis, 1962].

III. THE MAGNETOSPHERE

Even extremely low plasma density in Jupiter's distant magnetosphere, say orders of magnitude below 1 cm^{-3}, is sufficient to render it a conducting medium. We are forced, therefore, to consider the plasma (and also, in effect, the magnetic field lines) as rotating with the planet. If they do not corotate, then we must, alternatively, assume that they are distorted: probably wound onto a spiral surface. Also we must determine a magnetopause separating the magnetosphere and the interplanetary medium, otherwise the planetary field will extend indefinitely.

3.1 A Non-rotating Model

The characteristics of the solar wind in the vicinity of the earth are quite variable [Neugebauer and Snyder, 1966]. The wind velocity ranges (for average conditions) from about 300-700 km sec^{-1}, the density from < 1-70 protons cm^{-3} and the temperature from about 3×10^4 - 6×10^5 °K. We may only make a rough estimate of its characteristics outside Jupiter's magnetosphere, at about 5 A.U. from the sun. If the velocity is maintained at say 200 km sec^{-1}, then the density will be about 0.3 cm^{-3}; the temperature is taken as 1 x 10^5 °K, which may be compared with the 'temperature' corresponding to the translational motion, of about 100 eV or 10^6 °K. Balancing the thermal pressure alone against magnetic pressure leads to a magnetic field strength of about 1 γ; the magnetosphere would extend for about 100 R_J (for an equatorial surface field of 10 gauss). On the solar side of the magnetosphere the pressure would be greater and the extent limited to about 66 R_J. At the rear of the cavity the magnetosphere would extend somewhat beyond 100 R_J to form a rudimentary tail as shown in Fig. 2. For reasons given below the tail does not extend far to the rear of the planet like the geomagnetic tail, but some evidence of a tail of sorts has been given by Gruber [1965].

There is some observational evidence that geomagnetic field lines near the magnetopause break and become connected to the interplanetary lines [Dungey, 1961; Fairfield, 1967], the effect depending on the existence of a strong, southward directed field. A similar effect might be expected near Jupiter but, since the strength of the field component perpendicular to the ecliptic will be reduced by an average factor of five, the rate of reconnection per unit area should be smaller. On the other hand, the linear dimensions of the magnetosphere shown in Fig. 2 exceed those of the earth's field by a factor of about 100 and so the effect may be important.

3.2 Effects of Rotation

With the introduction of rotational effects a model magnetosphere becomes much more complex because neither plasma nor field distributions may be determined alone, even by approximate methods as used above. The problem is now hydromagnetic and an intuitive approach may be necessary. Melrose [1967] briefly mentions expected flattening towards a disk and stretching of the field lines by the rotating thermal plasma. Gledhill [1967] makes several simplifying assumptions leading to a grossly distorted plasmasphere at the orbit of Io (about 6 R_J). He assumes that corotating plasma must be thrown out to the extremities of the field lines; he then assumes that the plasma density N_{max} rises to, but does not exceed, the value which just fails to disrupt the magnetic field [his equation (1)]. Finally he assumes the plasma density at Io's orbit to be about 2×10^7 cm^{-3}, a value which might explain decametric radio emission as due to plasma oscillations created by the passage of Io.

There are objections to each of these three assumptions. In the first place there is a gravitational potential barrier between the ionosphere and Io's orbit, as shown in Fig. 1, so that plasma is not thrown out to the equatorial plane. However, if we assume that the plasma density near 6 R_J does attain these enormous values then, as Melrose has shown, the density must continue to increase outwards and the whole magnetosphere is quite unstable. Finally, apart from these dynamical difficulties, the electron density adopted at 6 R_E is an order of magnitude larger than that estimated for the ionosphere itself [Gross and Rasool, 1964] and requires magnetic energy density near the surface of the planet (a field of 30 gauss) an order of magnitude larger than previous estimates [Drake, 1967].

Rotation of the model Jovian magnetosphere shown in Fig. 2 will lead to surface speeds of about 1200 km sec^{-1} near the dawn-dusk meridian plane and higher in the tail. The shearing velocity on the dawn side will then be 1400 km sec^{-1} and on the dusk side 1000 km sec^{-1}. Such large shearing motions, even though the field lines generally lie in the shear planes, will result in some type of frictional interaction and distortion of the field lines. Again, plasma moving into the tail must be speeded up to attain the higher surface speed. In each of these cases there will be deformation of the field lines as shown schematically by the line Q. In the extreme case, discussed below, some plasma is ejected from the magnetosphere carrying with it grossly distorted field lines, in the manner first suggested for the formation of a geomagnetic tail [Piddington 1960a].

In the following sub-section we consider rotational effects at distances from Jupiter ranging from a few radii to some tens of radii. Here a ring current must form as a result of diamagnetism of energetic particles and the centrifugal force of cold plasma trapped in the potential well of Fig. 1.

3.3 The Jovian Ring Current

The combined gravitational and centrifugal force per unit mass of plasma in a direction perpendicular to the magnetic field line (and inwards) is found from the geometry of Angerami and Thomas [1964] to be

$$f'(r,\theta) = \frac{g}{r^2}(1 + 4\cot^2\theta)^{-1/2} - \Omega^2 r R_J \sin\theta \left\{1 - \frac{9\cos^2\theta}{1+4\cot^2\theta}\right\}, \quad (5)$$

where, as before, g is the gravitational force at the surface, r the distance in planetary radii and θ the colatitude. In regions near the equatorial plane and beyond ~4 planetary radii this reduces $f' \sim -\Omega^2 r R_J$ and the outward force density is given by

$$f \sim \rho\Omega^2 \; r \; R_J \tag{6}$$

This force must be effectively balanced by a magnetic force (or a Lorentz force $\underline{j} \times \underline{B}$). Over limited distances the outward force may be balanced partly or wholly by an outward pressure gradient Δp, but this is not effective in balancing the total outward centrifugal force and must result in a larger Lorentz force further out. The total current $\int j(\varphi) \, d\theta \, dr$ is a ring current, reducing the dipole field inside its center of cross section and increasing it beyond that value of r.

For a given plasma distribution and a ring current which causes only a perturbation of the field, the Lorentz force is approximately $j \; B_o \; r^{-3}$ which, when equated to the centrifugal force, gives

$$j \sim \rho\Omega^2 \; r^4 \; R_J \; B_o^{-1} \; . \tag{7}$$

With increasing plasma density an unstable situation is reached when the field gradient caused by the ring current equals or exceeds the normal gradient of a dipole field. The gradients are given by the equations $(R = rR_J)$

$$\left|\frac{\partial B}{\partial R}\right| \sim \text{curl } \underline{B} = 4\pi \underline{j} \; ; \qquad \left|\frac{\partial B}{\partial R}\right| = \frac{3B_o R_J^2}{R^4} \quad . \tag{8}$$

The instability condition is then found from equations (7) and (8)

$$\rho \gtrsim 3B_o^2 \left(4\pi \, \Omega^2 \, r^8 \, R_J^2\right)^{-1} , \tag{9}$$

or written in terms of the Alfvén velocity $V_A = B_o(4\pi \rho r^6)^{-1/2}$ and rotational velocity V_R

$$V_R > \sqrt{3}\, V_A \; . \tag{10}$$

For example, the maximum proton density consistent with a stable corotating magnetosphere at say 30 R_J is about 20 cm^{-3}; at 60 R_J it is about 0.1 cm^{-3}. Thus any significant amount of plasma which finds its way to the outer magnetosphere is likely to disrupt that part of the magnetosphere.

It seems likely that plasma will find its way outward under the influence of interchange motion, provided that when it has disrupted the magnetosphere, the erupted magnetic force tubes may then move back to lower latitudes thereby completing the interchange cycle. Such motions would be somewhat analogous to the motions of geomagnetic force tubes to and from the tail [Piddington, 1960b] and similarly would drive ionospheric current systems. It remains to investigate whether these current systems would help significantly in creating a "hot" ionosphere.

3.4 Departure from Corotation

There are two ways in which the more distant parts of Jupiter's field and plasma may not corotate with the planet. The first is the well-known isorotation effect, in which different magnetic shells have different velocities with the field lines lying in the shear planes. Such motion may require some initial field deformation but is not the cause of any cumulative deformation. The second pattern of differential rotation involves a component of magnetic field across the shear planes, and this leads to a steady increase in field deformation, to the creation of magnetic flux through certain surfaces and so to a further series of effects.

If there is sufficient frictional drag between the magnetopause of Fig. 2 and the external medium, then the outer shell of the magnetosphere will be slowed or stopped as shown in Fig. 3. In this schematic diagram the region between the magnetopause M and the magnetic shell defined by the curve S is at rest, or is rotating more slowly than the planet. The existence of such a region protects the magnetosphere from instability caused by the outward motion of ring-current plasma (by interchange motions). However, differential isorotation has other effects which are not as conducive to stability. The frictional interaction is now moved to an inner magnetic shell and here must create heating and smaller-scale hydromagnetic turbulent motions of a type discussed in connection with the earth's magnetosphere [Piddington, 1963]. In addition the isorotation must extend to the bottom of the ionosphere where the field lines enter a non-conducting atmosphere and their motion ceases to have any significance. The ionosphere moving across the field $\underline{B}_i$ with velocity $\underline{v}_i$ induces a field $\underline{E} = \underline{v}_i \times \underline{B}_i$ which is directed radially away from the poles. The Hall current driven by this field will flow in the direction of rotation of the planet along parallels of latitude.

These effects may be important in heating Jupiter's ionosphere and so increasing the magnetospheric plasma density. They may also be significant in connection with the observed differential rotation of Jupiter's atmosphere, since the non-rotating magnetospheric shell exercises a drag on the ionospheric rotation.

Much more spectacular effects may result from differential rotation in which field lines cross the shear surfaces. The lines are then grossly distorted; a line is confined to a surface which was originally a meridian plane. Differential rotation distorts the sheet into a helical form as shown in Fig. 4(a) where three such planes are viewed from above the north pole. If the field is described in terms of its components in an r, θ, z system, with z coincident with the rotational axis, then B_r is not affected by the winding up but B_θ increases according to the equation

$$B_\theta = -B_r \, t \, r \frac{\partial \Omega}{\partial r} \, , \tag{11}$$

where t is time elapsed [Piddington, 1967b]. Hence the field strength continues to increase until some other motion is introduced. It is suggested below that the additional effect which must be introduced is magnetic field annihilation and reconnection as in the geomagnetic tail [Piddington, 1967a].

The nature of the frictional interaction responsible for bending the outer field lines is not known but may be a result of an interplanetary field which in the equatorial plane is oppositely directed to the magnetopause field as shown in Fig. 4(b). Planetary field lines then break and connect with interplanetary lines, as is thought to occur near the earth [Dungey, 1961]. This situation is shown schematically in Fig. 4(b); motion of rotation and of the solar wind will then distort the field shown.

Whatever the nature of the frictional interaction, field lines will be drawn out in the manner sketched in Fig. 5. However, instead of extending outwards as in the case of the geomagnetic tail, the lines of force are wrapped around the magnetosphere itself. In spite of this deformation we might expect similar phenomena to those observed in the tail: reconnection of field lines and shedding of the outer sections, acceleration of particle and contracting of the reconnected field lines to provide Jovian auroras and a belt of trapped energetic particles [Piddington, 1967a].

IV. DECAMETRIC RADIO EMISSION

Any discussion of Jupiter's magnetosphere is incomplete without reference to the decametric radio emission originating there or in the ionosphere below [Drake, 1967; Warwick, 1967]. The radiation received at the earth depends not only on System III ('radio') longitude, but also on the position of the Satellite Io [Bigg, 1964]. Reception is most probable and the radio frequency and power are maximum for longitude 200°, which corresponds to the position of the magnetic pole [Duncan, 1966]. In addition, radiation is enhanced when Io is at longitude 200°; in this case emission occurs in longitudes 110° and 250° which are respectively 90° eastward and 50° westward of the pole. Dulk [1965] finds a similar but not identical pattern and other workers find different patterns at lower frequencies [Drake, 1967]. It seems that both the magnetic field topology and the position of Io are important in determining the strength or direction, or both, of the emitted waves.

The control of Io might be exercised through a gravitational tidal effect on the ionosphere or more directly by the motion of Io through the much faster rotating magnetosphere. The former possibility seems remote in view of the absence of effects by the other satellites. In the absence of a resonance effect to enhance Io's tide, the other satellites should produce effects up to 10 per cent or more that of Io, yet no radio control has been detected.

Io moves westward relative to Jupiter's magnetosphere, with relative velocity of about 54 km sec^{-1}. Several models have been proposed for the disturbance created by this motion ranging from a shock hydromagnetic wave in the low-velocity mode [Ellis, 1965] or a fan shaped proboscis [Marshall and Libby, 1967] to a minor disturbance [Warwick, 1967]. We find an entirely different situation to any of these.

4.1 Io's Hydromagnetic Disturbance

Io has been exposed to Jupiter's magnetic field for a long time and whatever its electrical conductivity it must be permeated by this field, with an average strength of about 0.05 gauss and total flux of about 4×10^{15} gauss cm^2 (some 7 per cent of a section of the geomagnetic tail). If Io has finite electrical conductivity, then its motion across the field causes an increase in strength B ahead of Io and a decrease behind as shown in

Fig. 6(a). Lines of force diffuse into Io on the forward side and out the back and to a first approximation at least the flux does not change. The disturbance outside Io will radiate away as a hydromagnetic disturbance with velocity $V_A = B(4\pi\ \rho)^{-1/2}$, where ρ is the plasma mass density. Estimates of V_A range from as low as 700 km sec^{-1} [Ellis, 1965] to 10^5 km sec^{-1} [Warwick, 1967], but in any case are many times Io's velocity and will radiate away rapidly and not form a proboscis as suggested by Marshall and Libby [1967]. Their model depends on an unjustified comparison with the hypothetical lunar wake, where the speed is Mach 10 rather than Mach 0.1 or less in the case of Io.

In the case of Io the magnetic field lines are more or less frozen into the satellite body and are nearly rigid and the result is that the magnetic flux tube attached to Io is carried through the magnetosphere and ionosphere. The complete flux tube, extending from hemisphere to hemisphere must be carried bodily around the planet so that each point moves approximately in a circle, the feet of the flux tube moving in the ionosphere. This is an interchange motion, driven by the massive satellite moving relative to the (faster rotating) magnetosphere, and opposed by ionospheric collisions between moving plasma and stationary neutral particles. The essential feature is adequate electrical conductivity σ inside the satellite. The equation of diffusion of the field lines, and its solutions are

$$4\pi \sigma \frac{\partial \underline{B}}{\partial t} = \nabla^2 \underline{B} \quad , \qquad t_o \sim \sigma D^2 \quad , \tag{12}$$

where t_o is the characteristic time for readjustment of the field with a volume of diameter D. We must have t_o larger t_d, the time taken for the magnetic force tube to develop its maximum degree of deformation as described below.

The Io force tube, in relation to Jupiter's magnetosphere, is shown schematically in Fig. 6(b). Io's relative motion is out from the paper and it carries with it the parts of the connected field lines in its immediate vicinity. More distant parts of the force tube follow later, being delayed by the time taken for a complex hydromagnetic disturbance to reach them. In the case of a simple twist or rotation of circular cylindrical force tube, the disturbance would travel with velocity V_A [Piddington, 1960b]. For the interchange type of motion performed by Io's force tube, the velocity of propagation is likely to be much lower because the magnetic perturbation δB and the currents responsible (shown as j in Fig. 6(b)) must travel along the force tube, while the actual flow of plasma must extend beyond the tube. Propagation at a velocity of say 2000 km sec^{-1} would lead to a delay time of a few minutes and since we cannot determine the actual delay, we will assume that the longitude of the feet of Io's force tube (in the ionosphere) are 20° of longitude eastward of Io itself.

This deformation of the tube corresponds to a delay time t_d of about 40 minutes and an electrical conductivity of Io of at least 3×10^{-14} e.m.u., which is much less than that of dry earth or rock.

4.2 Ionospheric Effects

The force tube connected to Io projects into the ionosphere in each hemisphere at a longitude perhaps 20° eastward of Io itself, as shown in Fig. 7. The plane containing the axis of rotation and the magnetic dipole is at longitude λ III ~200°. The foot of the force tube follows the dashed line in a path corresponding approximately to magnetic latitude 66°, shown by the dashed circle.

The ionosphere moves eastward relative to Io's force tube with velocity $v_i \sim 4.8$ km sec^{-1}. If the magnetic field strength $B_i \sim 15$ gauss, then the induced electric field $\underline{E}_i = \underline{v}_i \times \underline{B}_i$ has a value of 7×10^6 e.m.u. or 0.07 volts cm^{-1} and is directed away from the pole. The north-south extent of the force tube is about 120 km and the total potential difference about 840 kilovolts. Such a field may cause a major ionospheric disturbance. Let the integrated electrical conductivity of a 1 cm wide strip of ionosphere have a value Σ (the Pedersen conductivity). The power dissipated per cm^2 is then given by $W_i = \Sigma \ E_i^2$, and if the conductivity is equal to that of the earth's ionosphere, about 10^{-8} e.m.u., then the power dissipated in and around Io's projection in the ionosphere is about 5×10^5 erg cm^{-2}. This is about 10^3 times the power incident on our ionosphere in the center of a major auroral precipitation event and is sufficient to heat the Jovian ionosphere substantially. Furthermore, electrons with free paths of a few meters will acquire energies of tens of electron volts and will ionize. It would seem that the feet of Io's force tube may kick up major distrubances in the ionosphere.

The disturbances so caused will lie eastward of Io itself, first because of the deformation of the force tube and second because of delay in the spreading and outward diffusion of the energized particles. We suggest that this disturbance provides the particles responsible for at least part of Jupiter's decametric radio emission. This emission will then be concentrated in a source about 20° eastward of Io.

In addition to ionospheric distrubances caused by Io, others are likely to occur at the feet of magnetic field lines in the non-rotating part of the magnetosphere (Fig. 4(a)). Here also, the field lines are prevented from moving with the ionosphere and an electric field develops, directed away from the pole. Reconnection of field lines in the wrapped around tail will also energize particles so that this magnetic shell may be a region of considerable activity.

4.3 Sources of Radio Emission

Decametric radio emission from Jupiter depends very much on the positions of both the magnetic pole ($\lambda_{III} \sim 200°$) and Io. If radiation were concentrated in meridian planes, then its sources would be in the planes $\lambda \sim 200°$ at all times, and $\lambda \sim 110°$ and 250° when Io itself is at 200°. If the longitude of the foot of Io's tube is significant, then the Io sources lie about 70° on either side of Io and are excited when the foot lies 20° eastward of the pole. The possibility appears, that most of the radiation comes from a source lying between longitudes 180° and 200°. Some radiation is emitted in the meridian plane and other preferentially at angles ± 70° to that plane.

The possibility of such oblique emission would remove a major difficulty met by the cyclotron theory of Ellis and McCullock [1965] according to which the emission is mainly in meridian planes. In order to account for emission at longitudes 110° and 250°, Ellis [1965] has suggested that slow-mode hydromagnetic waves originating near Io will travel preferentially to these regions. The amount of such radiation excited by Io is likely to be small and, like all shock radiation, emitted in a cone (or part of a cone) with axis pointed eastward. Only a small amount of radiation would be likely to reach the ionosphere in only one band of longitude. At the same time the Io force tube would be highly energized and so likely to radiate much more powerfully.

On the other hand, Warwick's [1967] theory which does invoke oblique emission, meets the major difficulty of explaining the escape of the extraordinary wave past the stop band $X + Y = 1$ [Ellis, 1965]. Warwick's suggestion of a "bounded plasma in a uniform field extending out into empty space" does not seem valid. One would hesitate to suggest a density as low as 0.1 to 1 cm^{-3} at say $2R_J$, and yet such a density seems adequate to provide a stop band.

V. CONCLUSIONS

1. Jupiter's ionosphere is hot and its scale height is several thousand kilometers. Heating and ionization are not limited to solar radiation, as assumed in previous models [Gross and Rosool, 1964], but are caused mainly by electric fields caused by motions of plasma and of the satellite Io.

2. The additional thermal energy seems capable of explaining an estimated deficit of about $\times 10^{25}$ erg sec^{-1} which must be supplied to the lower atmosphere to provide an energy balance [Gross and Rasool, 1964].

3. Jupiter's magnetosphere has a high plasma density, say $> 10^{4}$ cm^{-3} near Io's orbit. Centrifugal force causes plasma to move outwards and accumulate in an energy potential well (Fig. 1). The forces exerted by the plasma must be balanced by a ring current force (Fig. 3).

4. A model magnetosphere which might exist if the plasma density were very low (Fig. 2) is probably replaced by an unstable magnetosphere. Magnetic force tubes are pulled to increasingly large radial distances both by interchange motions and by deformation.

Eventually they cannot corotate and are drawn into a "wrapped-around tail" (Figs. 4 and 5). After being emptied of their plasma, the tubes reconnect and move again to lower latitudes.

5. These interchange motions seem capable of heating the ionosphere to the extent required to provide the hot, dynamic magnetosphere of which they are a part. They may also provide the energetic particles responsible for the observed synchrotron radiation -- a cold, static magnetosphere would fail in this respect.

6. Previous estimates of the possible electromagnetic effects of Io's motion relative to the magnetosphere may have been much too small. Io does not merely move through the medium but carries with it magnetic field lines frozen into its body. This not only increases the effective cross sectional area of the interaction by a factor of about 300, but also extends the interaction directly into the ionosphere where it causes a major heating and ionizing effect.

7. There is some evidence that the radio emission associated with Io and with the magnetic pole has its origin in a single region lying between longitudes $\lambda_{III} \sim 180° - 200°$. The multiplicity of apparent sources would then be explained in terms of a complex directional pattern of emission.

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FIGURE CAPTIONS

Figure 1 Potential energy per unit mass along a field line of magnetic latitude about 66°, plotted against radial distance in Jovian radii. Account is taken of the tilted dipole field.

Figure 2 A sketch of Jupiter and its magnetosphere from above the north pole showing a bulge in the anti-solar direction and a magnetic field line φ, distorted by frictional drag.

Figure 3 A meridian section of Jupiter with its corotating magnetosphere bounded by the shell S, its non-rotating magnetosphere extending to the magnetopause M, and a cross section of its ring current.

Figure 4 a. A view of the corotating and non-rotating parts of the magnetosphere, with distorted field lines.

b. A sketch of field lines breaking and connecting with interplanetary lines.

Figure 5 A stretched out field line and its neutral sheet; later the section shown is wrapped into a spiral.

Figure 6 The passage of the Satellite Io through the magnetic field of Jupiter.

a. Field lines (dashed) magnetize Io which otherwise causes no major distortion among the surrounding lines.

Figure 6 (Cont'd.) b. Io rotates relative to the planet carrying its frozen-in magnetic force tube ρ_I westward. The whole force tube, from ionosphere to ionosphere moves with Io but suffers considerable distortion.

Figure 7 A plan of the high-latitude ionosphere showing the foot of Io's magnetic force tube (moving westward), the north magnetic pole N surrounded by the area magnetically connected to the non-rotating shell of Fig. 3, and the axis of rotation A.

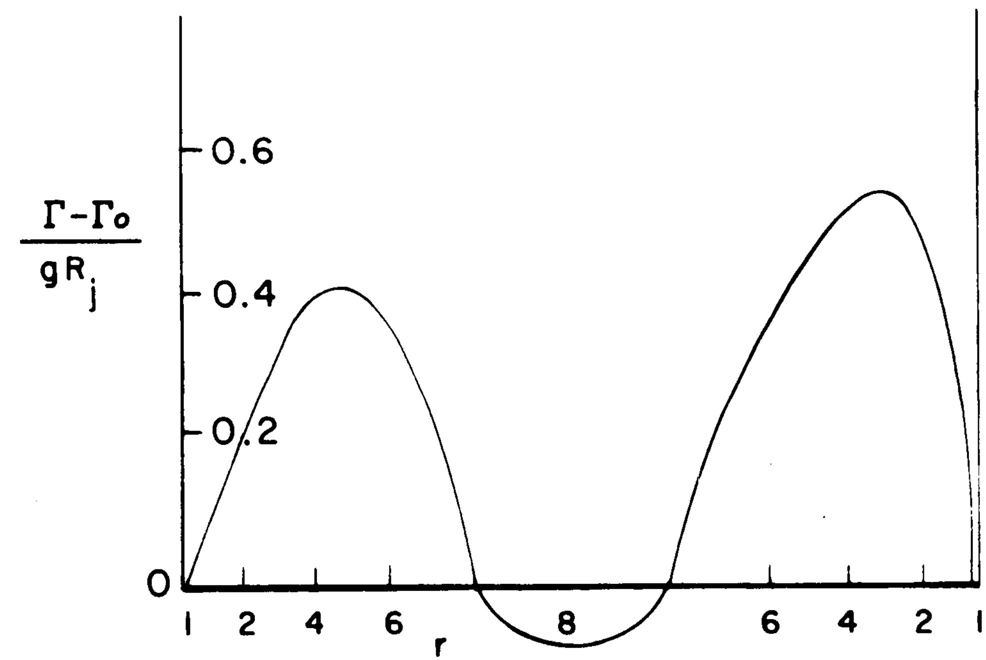

FIG. 1

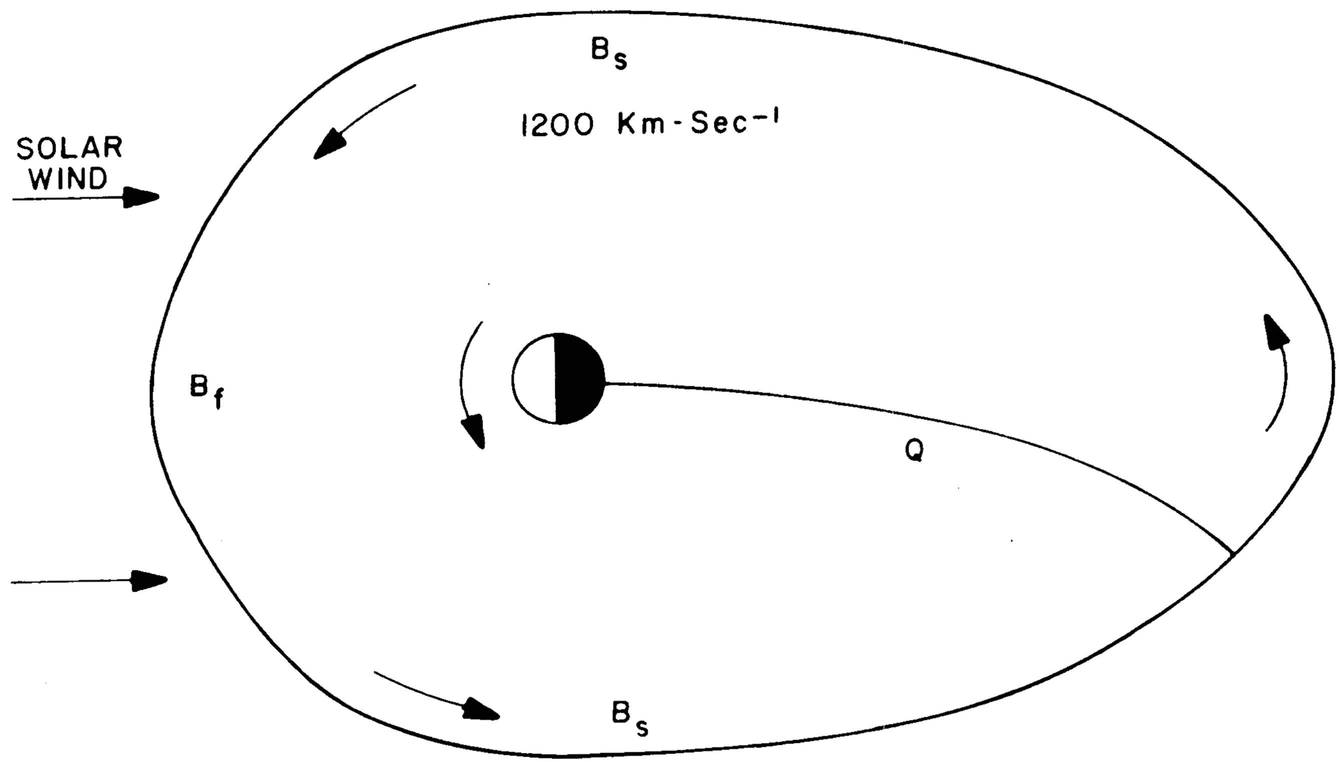

FIG. 2

G67-937

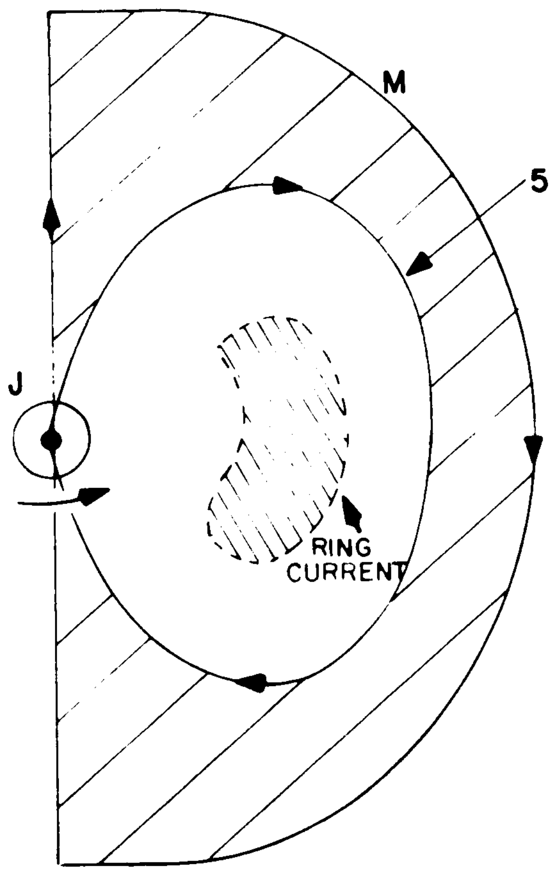

FIG. 3

G 67-939

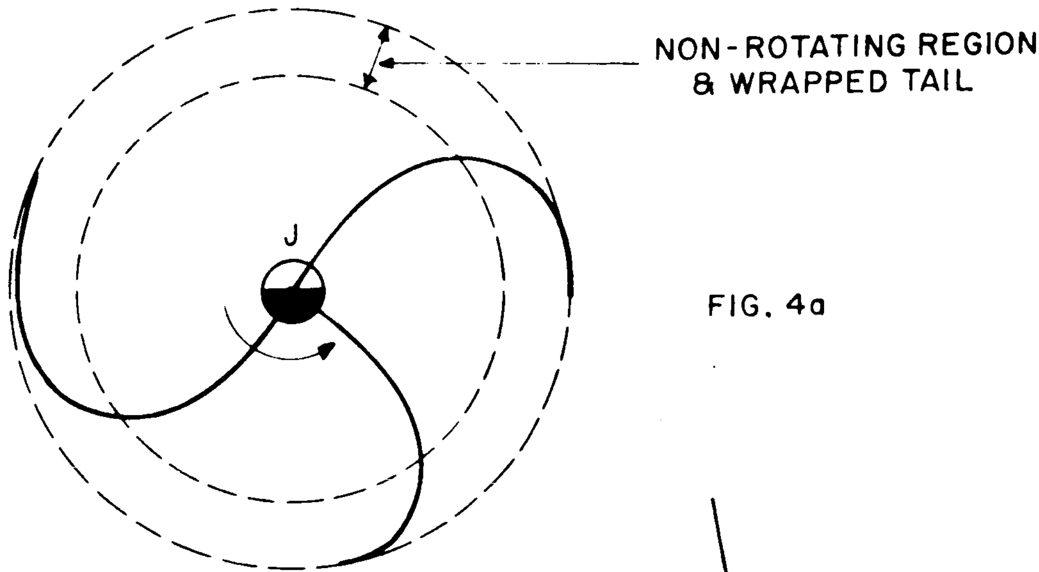

FIG. 4a

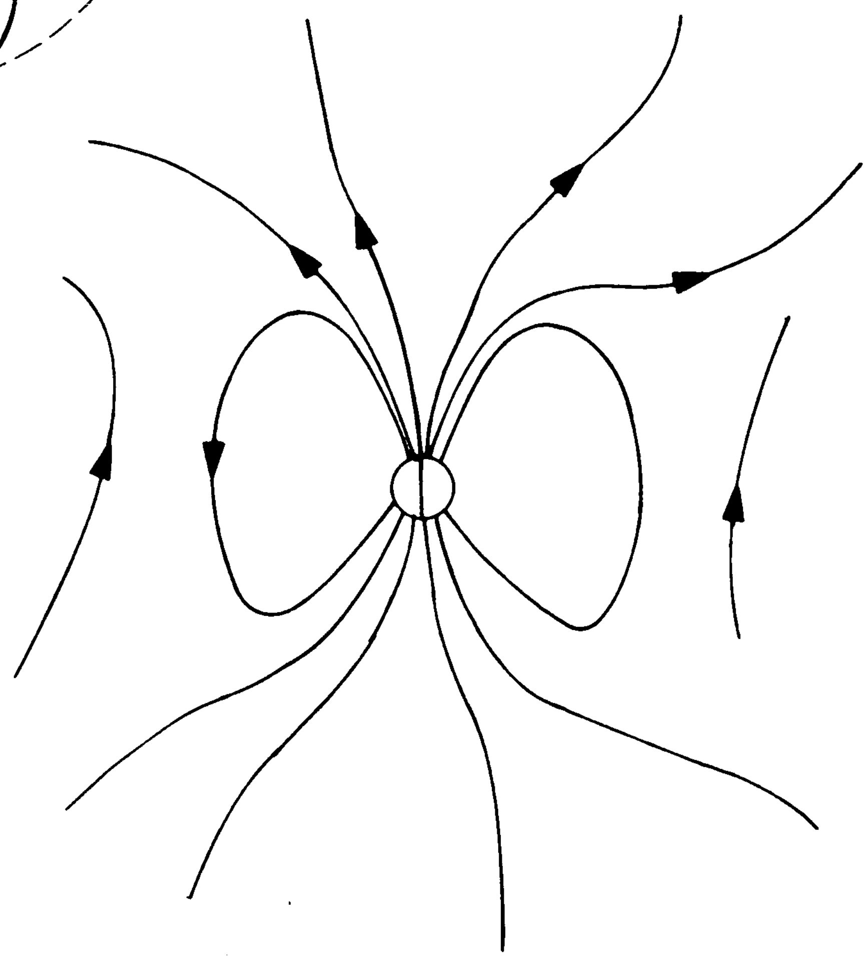

FIG. 4b

G 67-938

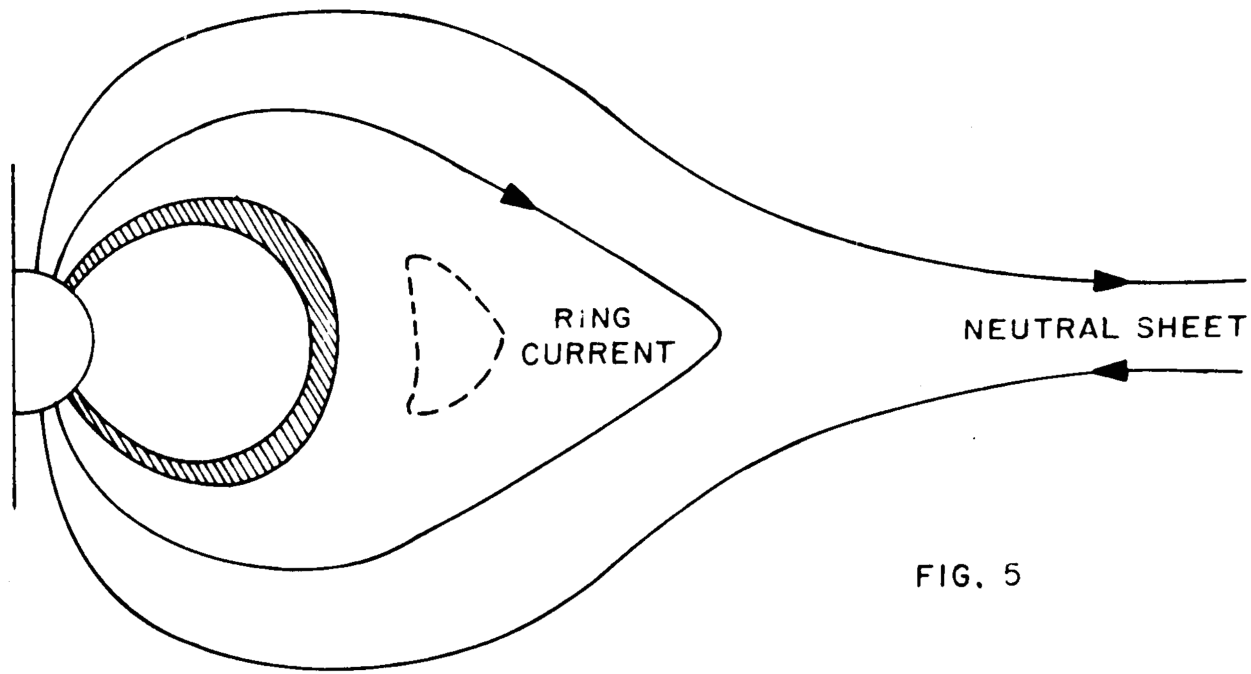

FIG. 5

G67 - 940(a)

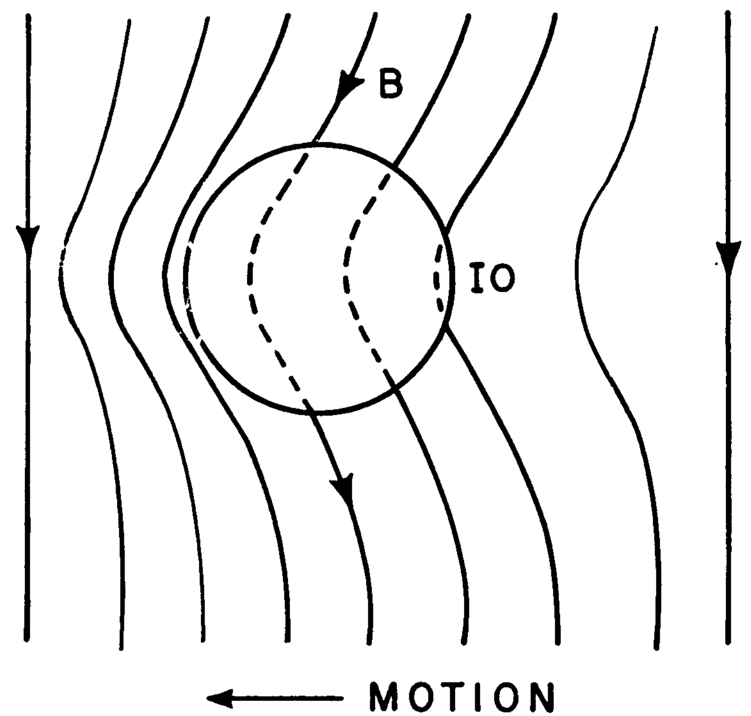

FIG. 6 (a)

G67 - 940(b)

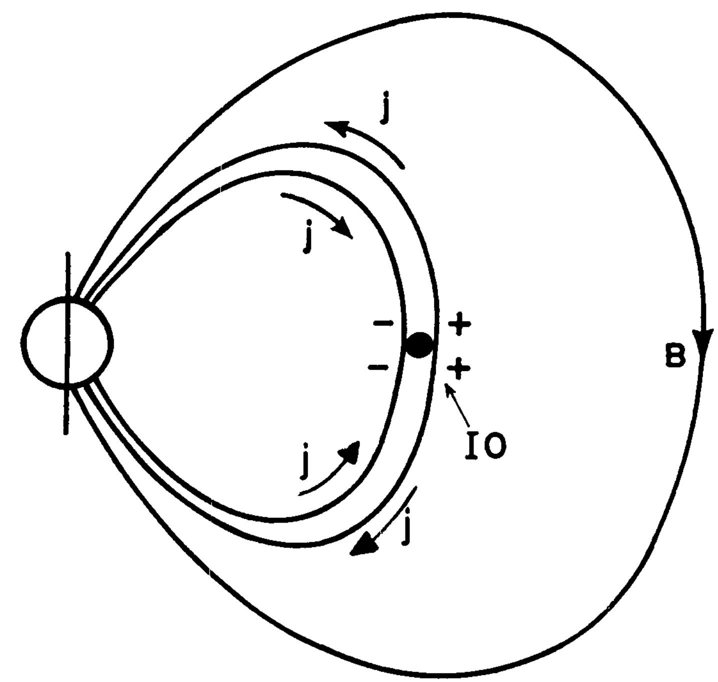

Fig. 6 (b)

G67 – 941

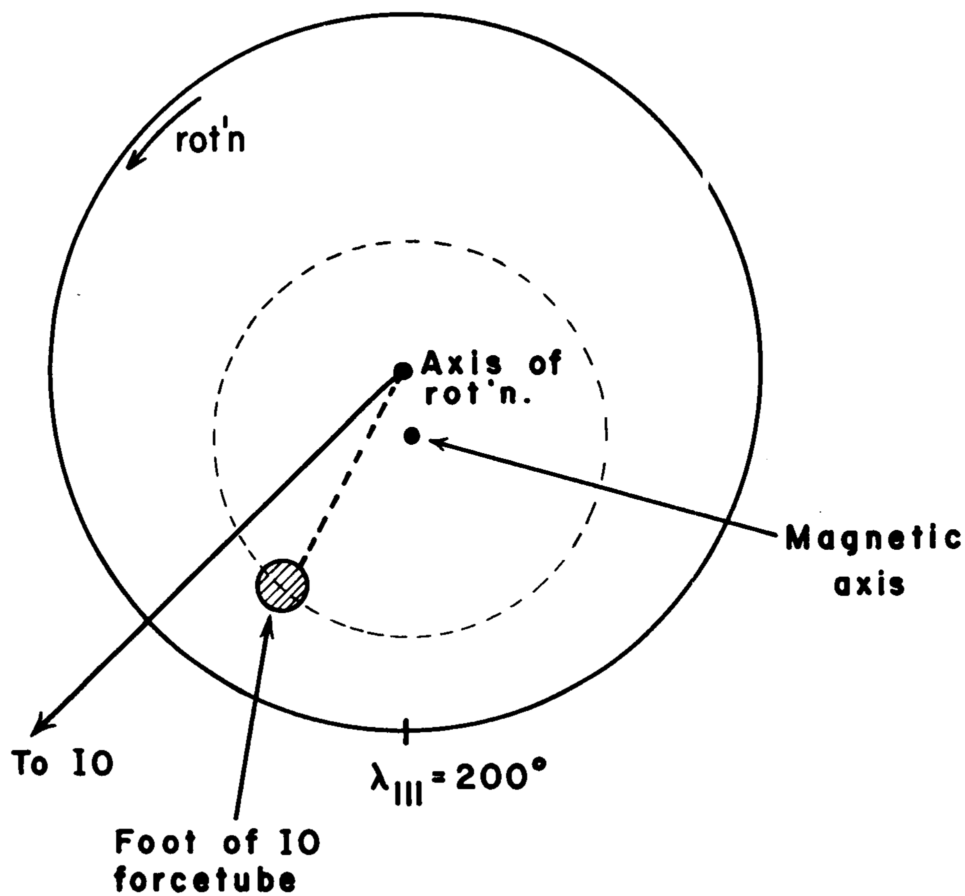
rot'n
Axis of rot'n.
Magnetic axis
To IO
Foot of IO forcetube
λ_{III} = 200°

Fig. 7