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ELECTRODYNAMIC EFFECTS OF JUPITER'S SATELLITE IO

by

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1. Introduction

Jupiter's satellite Io has attracted attention for its remarkable control of Jovian decametric radio emission (recently reviewed)[1,2] and also for optical peculiarities in the form of a very high and possibly varying albedo.[3,4]

Io's orbit is approximately 6 R_J (Jovian radii), while the magnetosphere itself probably extends for several tens of planetary radii.[5] The radiation belt responsible for the decimetric radio synchrotron emission extends[6] to about 6 R_J so that Io moves in the inner magnetosphere and inside or just outside the radiation belt. Jupiter's magnetosphere rotates with the planet, presumably at or very near the rate determined by the decametric radio observations, whose Longitude System III was adopted by the IAU in 1962. The net result of this rotation and of Io's motion is that the satellite moves westward through the magnetosphere at a speed of about 56 km sec^{-1}. This motion may cause an electromagnetic disturbance which contributes to the radio emission. On the other hand tidal control by Io seems unlikely in view of the absence of any control by the other satellites.

The possible form of the electromagnetic disturbance has been discussed by a number of workers. There is little doubt that the Alfvén velocity near Io greatly exceeds 56 km sec^{-1}, from which

Warwick[1] concluded that the disturbance would be minor; however, Ellis[7] has suggested that the low-velocity hydromagnetic mode will, for certain directions of propagation, have a lower velocity and so a strong disturbance may develop. There is little likelihood of a long fan shaped proboscis[8] or of the direct stimulation of plasma waves[9] because ionospheric ambient plasma cannot reach Io, being stopped by a gravitational potential barrier.[10] In any case, as shown below, the interaction between Io and the magnetosphere appears to take a form quite different to these models.

2. Io's Hydromagnetic Disturbance

If Io's electrical conductivity were very small, then it would cause only a minor disturbance. The magnetic field lines would pass through the solid body and the plasma would be deposited in the body where all electric charges would be neutralized. This is the situation found near the moon,[11] whose electrical conductivity so determined is less than 10^{-16} emu.

Irrespective of Io's electrical conductivity, long immersion of the satellite in the steady magnetospheric field must ensure its magnetization. If the field strength in its orbit is 0.05 gauss,[1] then it will have a magnetic flux of about 4×10^{15} gauss cm^2 (some 7 percent of the flux in a section of the earth's magnetic tail). The demagnetization of Io would require a system of electric currents flowing on its surface in directions everywhere perpendicular to the undisturbed field. These would require a corresponding electric field $\underline{E}$ given by Maxwell's equation $\underline{\nabla} \times \underline{E} = -\frac{\partial \underline{B}}{\partial t}$ and this would, in general, require a flow of field lines into Io. The only way to provide $\underline{E}$ continually, and so to demagnetize Io permanently, would be to rotate it about an axis perpendicular to the undisturbed field.

If Io is magnetized and is conducting, then its relative motion through the magnetosphere ($\underline{V}$) will have drastic results. Field lines passing through Io cannot follow the motion of the external plasma since this would induce excessive electric field $\underline{V} \times \underline{B}$ and excessive current in the satellite and in the plasma. Sufficient current ($\underline{j}$) flows to deform the external field and to provide a force $\underline{j} \times \underline{B}$ which slows down the plasma and accelerates Io in its eastward motion. The deformation of the field near Io will propagate away as a set of hydromagnetic waves. The situation is shown in Fig. 1a, plasma and field is compressed at the left and the field gradient causes a diffusion into Io; field lines diffuse out from the satellite to the right at the same rate. The effectiveness of Io in creating a disturbance depends on its conductivity σ according to the well-known relationship

$$t_o \sim \sigma \ell^2 \quad , \qquad (1)$$

where t_o and ℓ are characteristic time and dimension. Putting $\ell = 3.2 \times 10^8$ cm (Io's diameter) and t_o equal to this distance divided by the relative speed, that is about 57 sec, we find the required conductivity (emu) $\gtrsim 6 \times 10^{-16}$. If the conductivity is of this value or higher then the field lines are effectively frozen into Io.

The nature of the external disturbance will depend principally on the ratio of the velocity V to the hydromagnetic velocity V_A. If this ratio is large, then the disturbance travels "down wind" and results in a well-defined tail or wake as for the earth. If the ratio is small, then a large proportion of the disturbance will travel as hydromagnetic twist or shear waves along the field lines. The velocity V_A near Io probably lies in the range 10^3 - 10^4 km sec^{-1},[1,7] and so is much larger than V and far from shock conditions. There will be little magnetic perturbation in Jupiter's equatorial plane and the main effect will result from the fact that a tube of magnetic force remains attached as Io moves, and the whole Io force tube moves approximately with Io. This result is illustrated in Fig. 1b which shows a meridian plane in Jupiter's magnetosphere and Io's force tube (IFT). The relative motion of Io is out from the plane of the paper, and if we regard the force tube as being rigid then it moves as a whole, executing "interchange motions" with surrounding force tubes. These motions resemble the motions discussed in connection with the earth's magnetosphere,[12] except that the former are driven by the satellite with its frozen-in field lines and are much more localized. The whole of IFT moves about the axis of rotation, more or less in meridian planes with the centre cutting Io and the ends dipping into the ionosphere at the appropriate latitudes (approximately 65° north and south). The foot of IFT in the northern hemisphere moves around the north magnetic pole N (Fig. 2a), and, because of the 10° tilt of the magnetic to the rotational axis, excentrically around the latter. Displacement of the foot of IFT from the meridian plane containing Io itself is discussed below.

3. Propagation to the Ionosphere

If the relative motion V commenced abruptly, then Io would become polarized as shown in Fig. 1b. Electrons from the plasma would flow to neutralize the positive charge and ions to neutralize the negative charge (since Io cannot emit electrons). Currents ($\underline{j}$) would flow up and down the sides of IFT and hydromagnetic waves would propagate to the ionosphere in each hemisphere, or lower if the lower atmosphere were conducting. For maximum effect, Io's electrical conductivity must be such that t_o in equation (1) exceeds the time for the wave to propagate to the ionosphere.

The velocity of the wave is not evident. If it were a twist wave (caused by Io rotating about an axis parallel to $\underline{B}$) then it would travel with the Alfvén velocity.[13] However, it is a more complicated disturbance, and will contain elements of the slow hydromagnetic mode which will be radiated away from IFT in directions away from the lines of force. Since even the velocity of the fast mode is not known (because of lack of knowledge of plasma density) we will for the present assume a velocity of propagation along IFT of 1000 km $\sec^{-1}$. The disturbance reaches the ionosphere (in each hemisphere) in about 10 minutes and the required conductivity of Io is about 6×10^{-15} emu.

If Io has this conductivity, then its whole force tube, extending from ionosphere to ionosphere, will swing westward relative to the magnetosphere itself. The cross-sectional area of the force tube perpendicular to the direction of motion is about 200 times that of Io and so the disturbance in the magnetosphere caused by its passage is correspondingly large. The disturbance must leave a wake of turbulence and fast particles extending eastward from IFT. The bending of the force tube means that the feet are displaced eastward of Io, the above time delay of 10 minutes corresponding to a longitude difference of about 5 degrees. If we add to this the displacement of the wake of IFT, any Io related electromagnetic phenomena should be found at longitudes displaced eastward of Io by amounts varying from zero to more than 5 degrees.

IFT dips into northern and southern ionospheres and rotates around the two poles (rotational and magnetic) as shown in Fig. 2a. The dimensions of the feet, in latitude and longitude, are about 150 km and the speed through the ionosphere about 5 km $\sec^{-1}$. Collisions between ions carried by the force tube and stationary neutral atoms will heat the ionosphere to a temperature exceeding 1000° K., considerably above the undisturbed value of about 200°K.[14] The tube motion is also likely to cause a shock wave outside the tube and to generate an extensive disturbance. The electric field projected into the ionosphere by IFT will give rise to Pedersen currents which are responsible for the frictional drag. They will also drive Hall currents which will change the whole electric field pattern,[15] not only in the ionosphere but along the force tube.

4. The Decametric Emission

Decametric radio emission from Jupiter is associated with several System III Longitude regions and is controlled to a considerable extent by the position of Io in its orbit. The highest emission probabilities occur when the longitude of Io approximates that of the northern hemisphere magnetic pole and Io is in one of two preferred orientations.[1,2] The main features are illustrated in Fig. 2b where the two sectors marked Regions 1 and 2 are "apparent" regions of emission in the sense that stronger signals are received during their central meridian passage seen from the earth. This emission is Io controlled, being maximum when Io is near the longitude of the north magnetic pole ($\lambda_{111} \sim 200°$). In addition, there is a third region centred near $\lambda_{111}=200°$ which has the distinction that it appears to emit for all positions of Io. For none of these regions need we necessarily adhere to the assumption that emission is radially away from the centre of the planet, and so there is great flexibility in the interpretation of the data.

When Io is at $\lambda_{111}=200°$ the foot of its force tube intersects the ionosphere eastward of Io and the disturbance in its wake may place the maximum disturbance further eastward. We will suppose that this maximum, shown as a large dot, is at $\lambda_{111}=185°$ and also that radio emission originating there and leaving Jupiter in directions near the ecliptic plane, is in two beams directed at about 75° away from the meridian plane of the disturbance. Emission which appears to come from Regions 1 and 2 is now explained in terms of radiation from Io's disturbance region,[16] and does not meet the major difficulty of having to explain Io's control exercised from a distant part of the magnetosphere. The radiation from the hatched sector is presumably in meridian planes and may have a different source mechanism.

Some radiation is emitted from the vicinity of Io in the two preferred directions shown for nearly all longitudes of Io. We speculate that Io's force tube disturbance, either in the ionosphere or magnetosphere, may have the form of a bow wave directed westward. Radio emission from the wave front, in both the forward and reverse directions, might be expected, as for type II solar radio bursts.[17] The result would be two preferred directions as in Fig. 2b, one from the forward radiation and one from the backward radiation. If either the beaming or generation processes have increased efficiency at lower rotational latitudes, this would account for enhanced emission near the magnetic pole as may be seen from Fig. 2a.

Lack of influence of the other Jovian satellites on the decametric emission may be due to lack of adequate electrical conductivity or to rotation about an axis perpendicular to Jupiter's axis.

5. Magnetospheric Effects

The motion of IFT may account for the large flux of electrons of energy 10 - 100 MeV which populate Jupiter's radiation belt. In the region of hydromagnetic turbulence near the surface of IFT some particles will gain energy far in excess of $1/2\ MV^2$ (about 10 eV for protons). Interchange motions (magnetospheric convection) caused by Io or by interaction of the outer magnetosphere with the solar wind,[5] will carry some of these particles inwards from Io's orbit and give them higher energies.

A factor of possible importance is the ionospheric heating and disturbance, which will spread a sheet of plasma up the lines of magnetic force disturbed by Io. Plasma which attains the level where gravitational and centrifugal forces are equal will fall into a potential energy trough, oscillating back and forth across the equatorial plane. These trapped particles will provide a Jovian ring current and its attendant magnetic perturbations and auroral precipitation near latitude 66°. The accumulation of plasma in a magnetic shell of radius about six planetary radii will lead to interchange instability. This effect may determine conditions in the outer magnetosphere in a manner which will be discussed elsewhere.

New magnetic field lines enter Io as old ones leave, and the plasma on the new lines is absorbed by Io. This effect may be significant in connection with the remarkable optical properties of Io.[3, 4]

ACKNOWLEDGEMENTS

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CAPTIONS

FIGURE 1 The passage of the satellite Io through the magnetic field of Jupiter.

(a) Field lines (dashed) frozen into Io move with the satellite to create an external wave.

(b) The force tube C_I rotates with Io relative to the planet, as an interchange motion.

FIGURE 2 Two plots of Jupiter in Longitude System III.

(a) The high latitude ionosphere showing the rotational and magnetic axes and the path (dashed line) of the foot of Io's force tube.

(b) A schematic representation of the apparent emission regions of decametric radio bursts and the manner in which most emission may originate from one region.

G67 - 940(a)

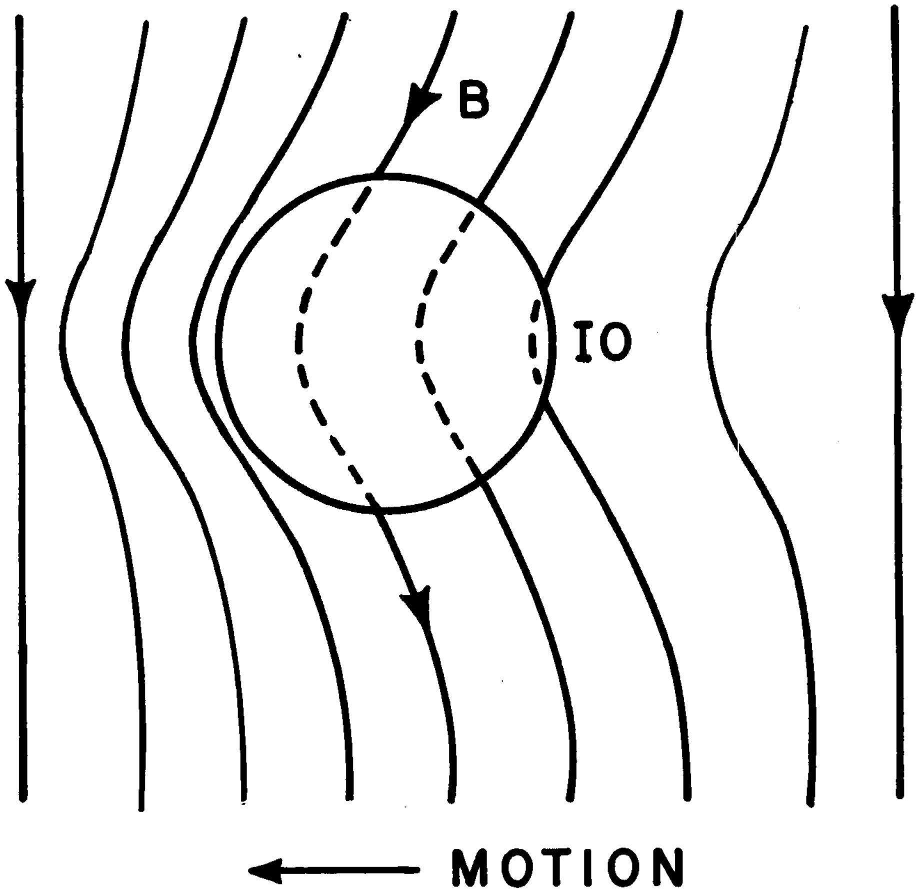

Fig. 1a

G67-940(b)

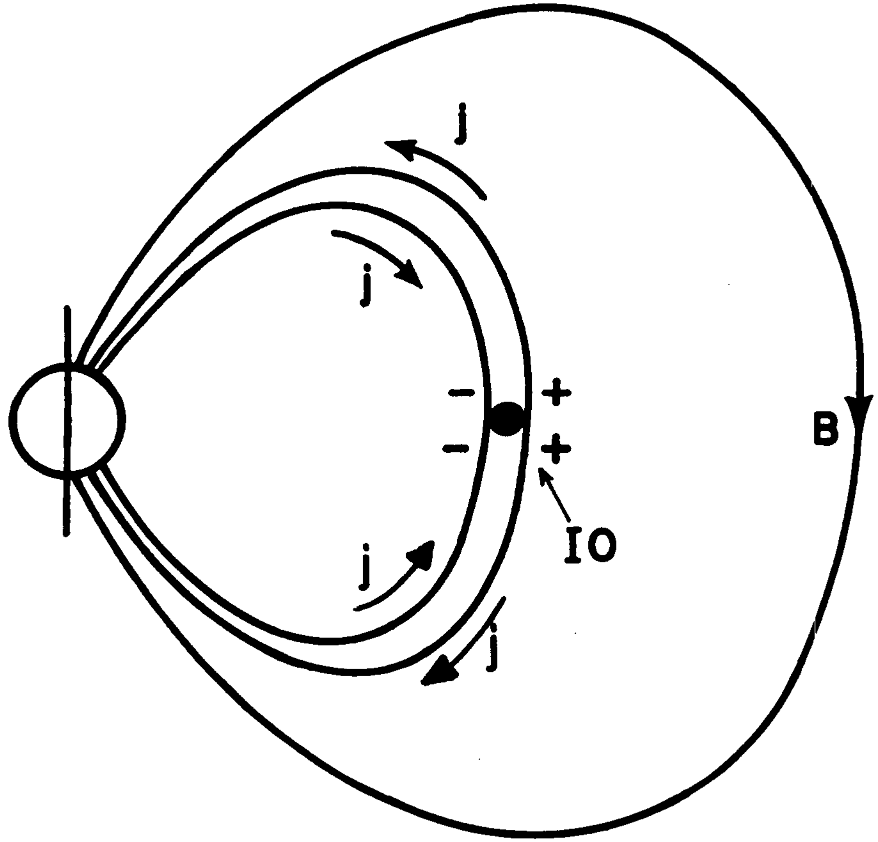

Fig. 1b

G67 - 941

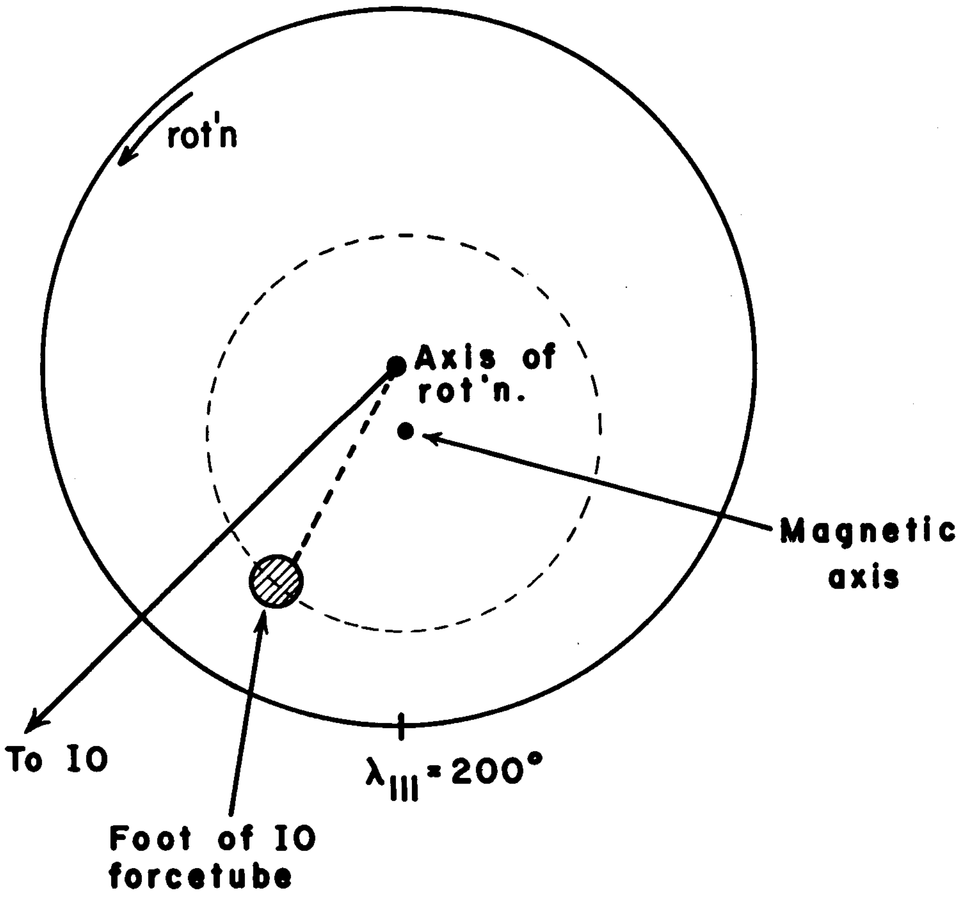

Fig. 2a

G67-1044

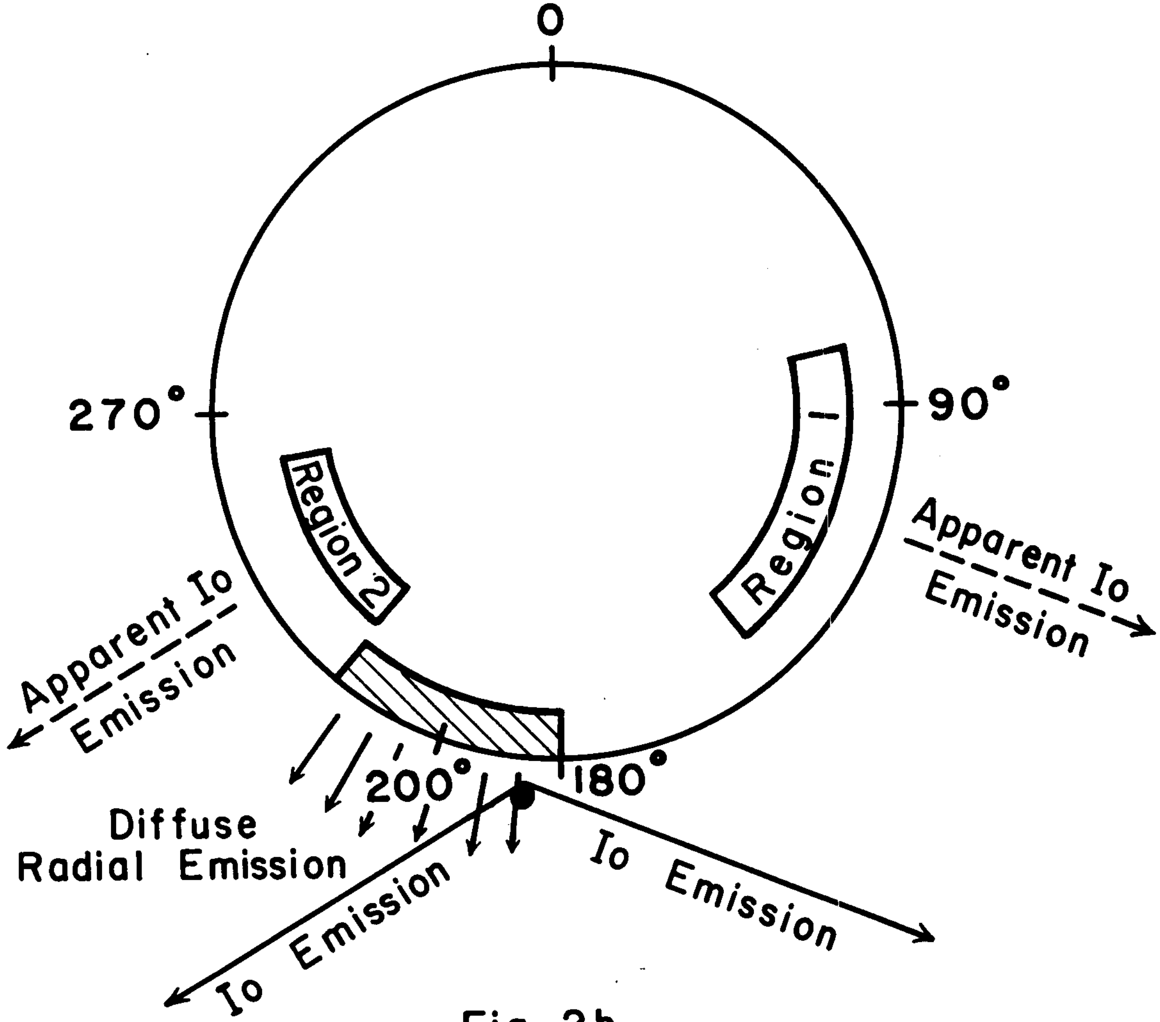

Fig. 2b