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CONVECTIVE MOTION AND THE STRUCTURE OF THE JUPITER MAGNETOSPHERE

by

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ABSTRACT

The convective motion and its relation to the electric field in the magnetosphere of Jupiter are investigated. It is shown that the electric field is induced in the Jovian ionosphere due to the corotating action of the ionospheric gases and further is communicated into the magnetosphere along the magnetic lines of force which connect between the ionosphere and the magnetosphere. This electric field drives the plasma to corotate with the planet in the magnetosphere. The distribution of the electric field and its effect on the plasma motion is estimated in the magnetosphere. The shape of the magnetosphere is then estimated considering the equilibrium condition.

Discussion is given on the equilibrium plasma distribution in the magnetosphere and on the condition for the excitation of wave-particle interaction at the Io orbit.

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1. INTRODUCTION

At present, it is thought that Jupiter has a magnetic field of dipole type from radio astronomical observation (e.g., Warwick, 1967, 1970; Carr and Gulkis, 1969). Since this field extends into the space around the planet, it seems natural that the magnetosphere is formed round the planet itself. This magnetosphere is perhaps influenced by the rapid rotation of Jupiter (e.g., Obayashi, 1970), and furthermore, by its interaction with solar wind which seems to be still flowing away at and beyond the Jupiter orbit.

In this paper, we will consider the influence of the Jovian rotation on the convective motion and the structure of the Jupiter magnetosphere, and estimate the electrodynamic processes occurring in the magnetosphere. Such processes seem to be effective on the modulation by the Io satellite on the decametric radio emission.

2. STEADY MOTION AND THE ELECTRIC FIELD IN THE MAGNETOSPHERE

The type of steady motion in the Jupiter magnetosphere will be considered. If we assume that the plasma in the magnetosphere consists of protons and electrons, fundamental equations appropriate to this problem are (e.g., Spitzer, 1962).

$$-\nabla P + \frac{1}{c}\vec{j} \times \vec{B} - \rho \nabla\varphi = 0 \qquad (1)$$

$$\vec{E} + \frac{1}{c}(\vec{\Omega} \times \vec{r}) \times \vec{B} - \frac{1}{nec}\vec{j} \times \vec{B} - \frac{1}{ne}\nabla P_e = 0 \qquad (2)$$

and

$$\nabla \times \vec{B} = \frac{4\pi}{c}\vec{j}, \qquad (3)$$

where ρ, n, $\vec{E}$, $\vec{B}$, P, r, $\vec{j}$, e, $\vec{\Omega}$ and c are the mass and number densities, electric and magnetic fields, pressure, position vector, electric current and charge, angular velocity and the speed of light, respectively. Here φ defines the gravitational potential in the rotating system as given by

$$\varphi = -\left[\frac{g_o r_J^2}{r} + \frac{1}{2} r^2 \Omega^2 \sin^2\theta\right], \qquad (4)$$

where g_o, r_J and θ are the gravitational acceleration at the surface ($r = r_J$), the Jupiter radius and the polar angle measured from the north polar axis (see Fig. 1). In deriving eqs. (1) and (2), we have assumed that the mean velocity of the plasma is given by $\vec{\Omega} \times \vec{r}$ on an average. Eq. (1) has been used by Parthasarathy, Whitten and Sims (1970) to study the plasma distribution in the Jupiter magnetosphere.

Since the electric current $\vec{j}$ is expressed as consisting of the terms proportional to ∇P, $\nabla\varphi$ and $\vec{B}$ (e.g., Sakurai, 1971) the third term in eq. (2) is neglected as far as the drift velocities due to ∇P and $\nabla \varphi$ are small compared to the rotating speed $|\vec{\Omega} \times \vec{r}|$ in any point in the magnetosphere. The fourth term does not influence the motion of magnetic field lines when spatial variation of n is negligible. Thus eq. (2) is reduced to

$$\vec{E} + \frac{1}{c} (\vec{\Omega} \times \vec{r}) \times \vec{B} = 0 \qquad (5)$$

This result gives the pattern of the convective motion in the magnetosphere. We, however, need consider the drifts due to the magnetic field gradient and curvature. If the energy $W_\perp$ of the plasma particles perpendicular to $\vec{B}_o$ satisfies the condition

$$W_\perp < W_\perp^* = 2.13 \; \frac{r}{r_J} \; |\vec{E}_\perp \text{ (volt/km)}| \text{ (Kev)}, \qquad (6)$$

all the particles satisfying this condition tend to corotate with the magnetic field lines by the drift $\frac{c}{B^2} (\vec{E} \times \vec{B})$. Since these particles take a part in the convection in the magnetosphere, in so far as they occupy the main part of the plasma in the magnetosphere, eq. (5) well represents the electrical condition in the magnetosphere; namely, the plasma motion is mainly controlled by the electric field as given in eq. (5). In deriving the result of eq. (6), we have assumed that the main field of Jupiter is expressed by the dipole field. This assumption will be used hereafter in this paper.

We can thus use eq. (5) to study the electric field in the magnetosphere. If the outer boundary of the magnetosphere results from the interaction of the magnetic fields of Jupiter with solar wind which is still flowing away at and beyond Jupiter's orbit, the size of this boundary is estimated as $\gtrsim 50\ r_J$ if the strength of the surface field is 10 gauss or more. In consequence, as far as the region within 10 or 15 r_J is concerned, we do not need consider the effect of the deformation of the magnetosphere due to the solar wind pressure.

From eq. (5), the electric field induced in the ionosphere is calculated as follows: by taking the spherical polar coordinate system (r, θ, φ) into consideration as shown in Fig. 1, we obtain

$$\left.\begin{aligned} E_r &= -\Omega\, r_J \frac{B_o}{c} \left(\frac{r_J}{r_1}\right)^2 \sin^2 \theta \\ E_\theta &= \Omega\, r_J \frac{B_o}{c} \left(\frac{r_J}{r_1}\right) \sin 2\theta \end{aligned}\right\}, \tag{7}$$

where B_o is the strength of the surface field at the equator. r_1 is the height of the ionosphere measured from the center of Jupiter. In the above equation, the direction of the magnetic moment is taken as the same as does the earth's dipole. If the situation is opposite to the case, the sign of $E\theta$ is only changed.

There exist some problems on the corotation of the magnetic field lines in the magnetosphere with the solid body of Jupiter because of the existence of the insulating neutral atmosphere near the Jupiter surface. This neutral atmosphere seems to be corotating with the planet as a result of the drag by viscosity of the atmospheric gas with the solid planet. This motion of the neutral atmosphere due to the drag induces the rotating motion of the plasma and magnetic field lines in the ionosphere which exists above the neutral atmosphere. The formation of the ionosphere is discussed by Gross and Rasool (1964) and others. Furthermore, it is certain that the rotating motion thus induced drives the motion of the magnetic field lines in the magnetosphere (e.g., Hines, 1963, 1964).

The time scale necessary for the ionosphere to begin to rotate with the corotating speed $|\vec{\Omega} \times \vec{r}|$ is theoretically given by $\tau_1 = \rho\, c^2/\sigma\, B^2$ (σ: electrical conductivity) and estimated as $\sim 6 \times 10^{-8}$ sec for the case of $n = 10^6$ cm^{-3} and $T = 200^{\circ}$K. Since the temperature in the ionosphere is perhaps more higher than the above value, it can be said that the corotating motion is instantaneously induced over the whole ionosphere.

In the ionosphere, the static potential S which gives rise to these electric fields is here taken 0 at $\theta = 0$. In this case, the potential is obtained as

$$S = - S_\Omega \sin^2 \theta, \tag{8}$$

where $S_\Omega = \Omega\, r_J^{\,2} \frac{B_o}{c} \left(\frac{r_J}{r_1}\right)$ (c.g.s.). Furthermore, the surface charge distribution is given as

$$\sigma = - \frac{\Omega\, r_J\, B_o}{4\pi c} \sin^2 \theta. \tag{9}$$

The electric conductivity in the magnetosphere seems to be very high along the magnetic field lines. Thus it seems that the state along a line of force is in equipotential in the magnetosphere since the potential obtained as in eq. (8) is immediately communicated along the line of force from the ionosphere.

Numerically, the potential S_Ω is given by

$$S_\Omega \cong 9.23 \times 10^4 \text{ volts.}$$

In calculating this, we have approximated as $r_1 \cong r_J$.

Since the main part of the magnetic field seems to consist of the dipole field, we can write the equation of the magnetic field lines as $L = 1/\sin^2 \theta$. By using this relation, we are able to calculate the potential distribution in the equatorial plane in the magnetosphere since

$$S = -S_{\Omega} \frac{1}{L} . \tag{10}$$

It should be remarked, however, that this formula is only applicable to the region where the dipole field approximation is well satisfied. As has been discussed by Melrose (1967), the drag of the magnetic field lines in the magnetosphere by the rotating motion in the ionosphere does not work effectively in the region far distant from the planet because, in this region, we cannot neglect the influence of the centrifugal force. Melrose (1967) has estimated that such region begins with the distance 7 - 8 r_J or beyond in the equatorial plane.

It seems, however, that the potential S as given by eq. (10) well expresses the real circumstance in the region within 7 or 8 r_J. The calculated potential distribution is shown in Fig. 2. The value of the potential is 1.54×10^4 volts at the Io satellite orbit. Hence the electric field is calculated as $\sim 0.4 \times 10^{-6}$ volt cm^{-1} at this orbit. By applying the criterion (6), the energy of the corotating plasma particles is estimated to be lower than $\sim$ 0.5 Kev. The particles of energy higher than this value drift independently from the corotating motion of the magnetosphere. The definition of the criterion is, therefore, dependent on the energy of the particles being trapped in the magnetosphere. It should be noticed that the electric field as shown in Fig. 2 is not useful for the acceleration of particles (e.g., Hones and Bergeson, 1965).

3. OUTER BOUNDARY OF THE MAGNETOSPHERE

As the distance increases from the planet Jupiter, the influence of the centrifugal force becomes larger on the distribution of the plasmas and magnetic fields. The equilibrium state, however, seems to be still maintained by the electromotive and pressure forces as is evident from eq. (1). Since the contribution of the gravitational force seems negligible in the low and middle latitude regions in the outer portion of the magnetosphere, the equilibrium state is given by

$$-\nabla P + \frac{1}{c}\vec{j} \times \vec{B} - \rho(\vec{\Omega} \times (\vec{\Omega} \times \vec{r})) = 0 \tag{11}$$

By considering the balance among the components perpendicular to $\vec{B}$, we can estimate the size and shape of the outer boundary.

By neglecting the pressure force, we obtain

$$\frac{r}{r_J} = \left(\frac{3\, B_o^2}{4\pi\, \rho_J\, \Omega^2\, r_J^2}\right)^{1/8} \left(\frac{(1 + 7\cos^2\theta + 8\cos^4\theta)^{1/2}}{\sin^2\theta}\cos(\theta-\alpha)\right) \tag{12}$$

where ρ_J is the mass density at the boundary, and

$$\tan\theta = 2\tan\alpha.$$

When $\theta = \pi/2$, the radius of the outer boundary is estimated in the equatorial plane. In this case, a similar formula has already been used by Hines (1964) and Carr and Gulkis (1969) in order to estimate the outer limit of the corotating magnetosphere. It is clear that the radius is dependent on the mass density ρ_J, but this dependence does not influence so much the magnitude of the radius (e.g., Carr and Gulkis, 1969).

Except for the high latitude ($\gtrsim 65^{\circ}$), eq. (12) gives a spherically shaped magnetosphere. Over the polar regions, there are two possibilities on the configuration of the magnetic field lines as proposed by Dungey (1958). This is, however, not effective on the motion of the magnetospheric plasmas.

As is evident from eq. (12), the radius of the outer boundary is determined with B_o and ρ_J. We here show the result on this radius in the equatorial plane in Fig. 3. If we assume that ρ_J is 2×10^{-24} g cm^{-3} (1 protons cm^{-3}) and that B_o is 10 gauss, the radius of the outer boundary in the low latitude region is ~ 42 r_J. Although at present we do not know the plasma distribution in the magnetosphere, this estimated radius is by about 10 r_J shorter than the radius which is calculated from the interaction of the Jupiter field with solar wind. Since it seems reasonable that $\rho_J \simeq 2 \times 10^{-24}$ g cm^{-3} at $\sim 40\ r_J$, the result obtained above thus suggests that the Jupiter magnetosphere is confined within the region of spherical shape due to its own rapid rotation. In other words, the formation of the finite magnetosphere is only resulted from the interaction of the Jovian magnetic field lines with the centrifugal force due to its rapid rotation.

In the outer portion of the magnetosphere, we cannot use eq. (17) to calculate the potential distribution in the equatorial plane, since the equation of a magnetic line of force is altered as a result of the confinement of the field lines in the magnetosphere. Because of the spherical shape of the magnetosphere, it is certain, however, that the equi-potential lines are still concentric in the equatorial plane. On account of the direct encounter with solar wind, the shape may be slightly deformed from the spherical one.

4. PLASMA DISTRIBUTION AND PERTURBATION OF EQUILIBRIUM

The distribution of the plasma in the magnetosphere is determined by eq. (10) (e.g., Melrose, 1967; Gledhill, 1967). Although we do not know as yet the exact form of the electric current $\vec{j}_o$, we are able to calculate the plasma distribution along a line of force. By multiplying scalarly eq. (10) with $\vec{B}_o$ and assuming the constant temperature, we obtain the equation to determine the plasma distribution along a line of force. This step was first taken by Gledhill (1967). Since, unfortunately, we do not know the plasma distribution in the ionosphere, we cannot determine the quantitative plasma distribution in the magnetosphere.

It is known, however, that, in so far as the magnetic energy density is much higher than the kinetic energy density at any point, the plasma motion is fully controlled by the motion of the magnetic lines of force and therefore the plasma can be strictly confined by the magnetic fields. Hence the upper limit of the plasma density in the equatorial plane is approximately estimated by using the inequality.

$$N_{U.L.} \lesssim 0.01 \frac{B_o^2}{8\pi kT} \left(\frac{r_J}{r}\right)^6 (\mathrm{cm}^{-3}). \tag{20}$$

If we assume that $T = 10^3$ ^{o}K, $N_{U.L.} \lesssim 2.8 \times 10^6$ cm^{-3} at the orbit of the I_o satellite ($r = 6\ r_J$).

As mentioned above, the magnetic field can confine the plasma of the number density less than 10^6 cm^{-3} at the I_o orbit when the temperature is 10^3 ^{o}K. Furthermore, the relative rotating speed of the I_o satellite is estimated as $\sim$ 60 km sec^{-1} since the magnetic field lines in the magnetosphere well corotate with Jupiter. This speed is lower than the fast mode hydromagnetic wave speed, but higher than the sound speed by about 10 times. It seems, therefore, that the I_o satellite can disturb the equilibrium plasma distribution along the I_o orbit.

If the plasma density is high as well as 10^4 - 10^6 cm^{-3} in the equatorial regions around 5 - $7r_J$ from the center, it follows that the gyrofrequency is much lower than the plasma frequency. In such a situation, various processes on wave-particle interaction would occur in the frequency range lower than the gyro-frequency. As a result, Kev electrons would be easily generated from the corotating plasma. If these processes could accelerate 10 - 100 Kev electrons along or near the I_o orbit, these electrons would possibly be the source for decametric radio emission. As we have mentioned in this section earlier, the existence of high density plasma is essential on the action of various wave-particle interactions (e.g., Hultquist, 1966; Kimura, 1967). In order to explain the I_o modulation on the decametric radio emission, we here propose the existence of high density plasma as 10^4 - 10^5 cm^{-3} around the I_o orbit in and near the equatorial plane in the magnetosphere. The meridianal distribution of the plasma in the magnetosphere seems to be similar to that which has been calculated by Gledhill (1967). The emission of the decametric waves seems to take place above the polar cap regions by gyrosynchrotron process since the accelerated electrons are injected into these regions along the magnetic lines of force passing through the I_o orbit or its neighborhood. In reality, the emissivity from individual electrons is highest at the reflecting point of their motion along the field lines.

5. CONCLUSIONS

By beginning with the fundamental equations of motion of the plasmas, we have developed the theory of the convective motion and its relation to the electric field in the magnetosphere. Although the plasma motion is controlled by the electric and magnetic fields, the gravity, the centrifugal force and the pressure gradient, the main body of the plasma of low energy moves in accordance with the condition (12). Thus the main body factually corotates with the planet Jupiter. This corotation induces the electric field in the ionosphere which is almost instantaneously communicated into the magnetosphere along the magnetic lines of force. Consequently, the equi-potential surface is formed for each of the magnetic shell which is defined by the third adiabatic invariant. The distribution of the electric potential in the equatorial plane has been shown in Fig. 2, and is concentric round the planet.

The shape of the magnetosphere has been estimated with the equilibrium condition. The shape seems to be spherical except for the high latitude regions, and its radius seems to be shorter than 50 Jupiter radii. Hence it is noticed that the size of the magnetosphere estimated here is smaller than that which is formed as a result of its interaction with solar wind. This suggests that the magnetosphere of Jupiter does not have its own magnetotail as does the earth's magnetosphere.

Due to the rapid rotation, the plasma is mainly distributed in the lower latitude region in the magnetosphere as shown by Melrose (1967) and Gledhill (1967). This plasma distribution necessarily gives rise to the situation that the gyrofrequency is much lower than the plasma frequency in this region, including the I_o orbit. Since it has been shown that the relative speed of the I_o motion is $\sim$ 60 Km sec^{-1}, there exists a possibility that I_o excites various types of wave-particle interaction along its orbit. These interaction may be the source of Kev electrons which are responsible for the decametric radio emission from Jupiter.

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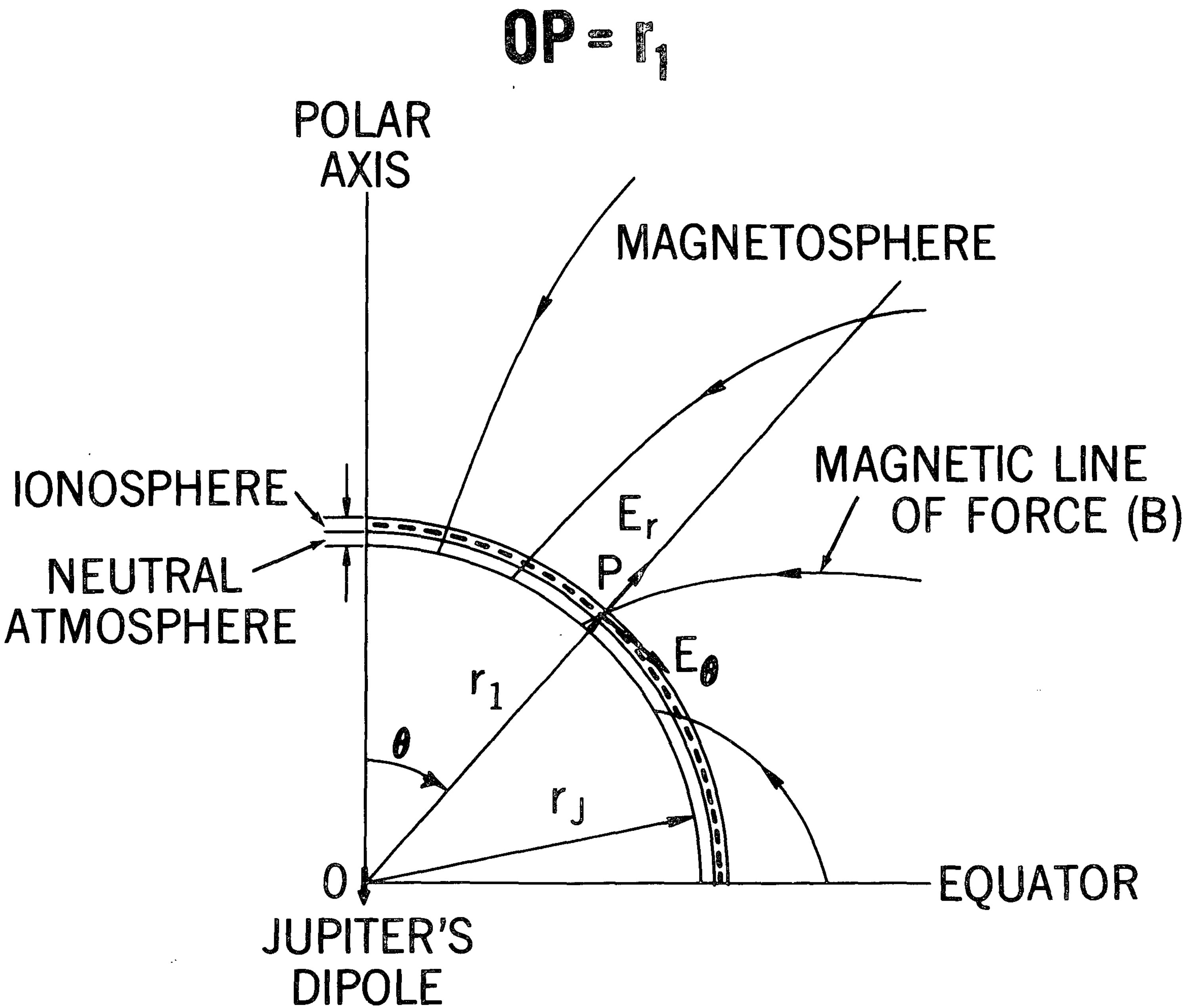

Fig. 1 The coordinate system and the constitution of the atmosphere of Jupiter.

THE EQUI-POTENTIAL LINES IN THE EQUATORIAL PLANE IN THE JUPITER MAGNETOSPHERE

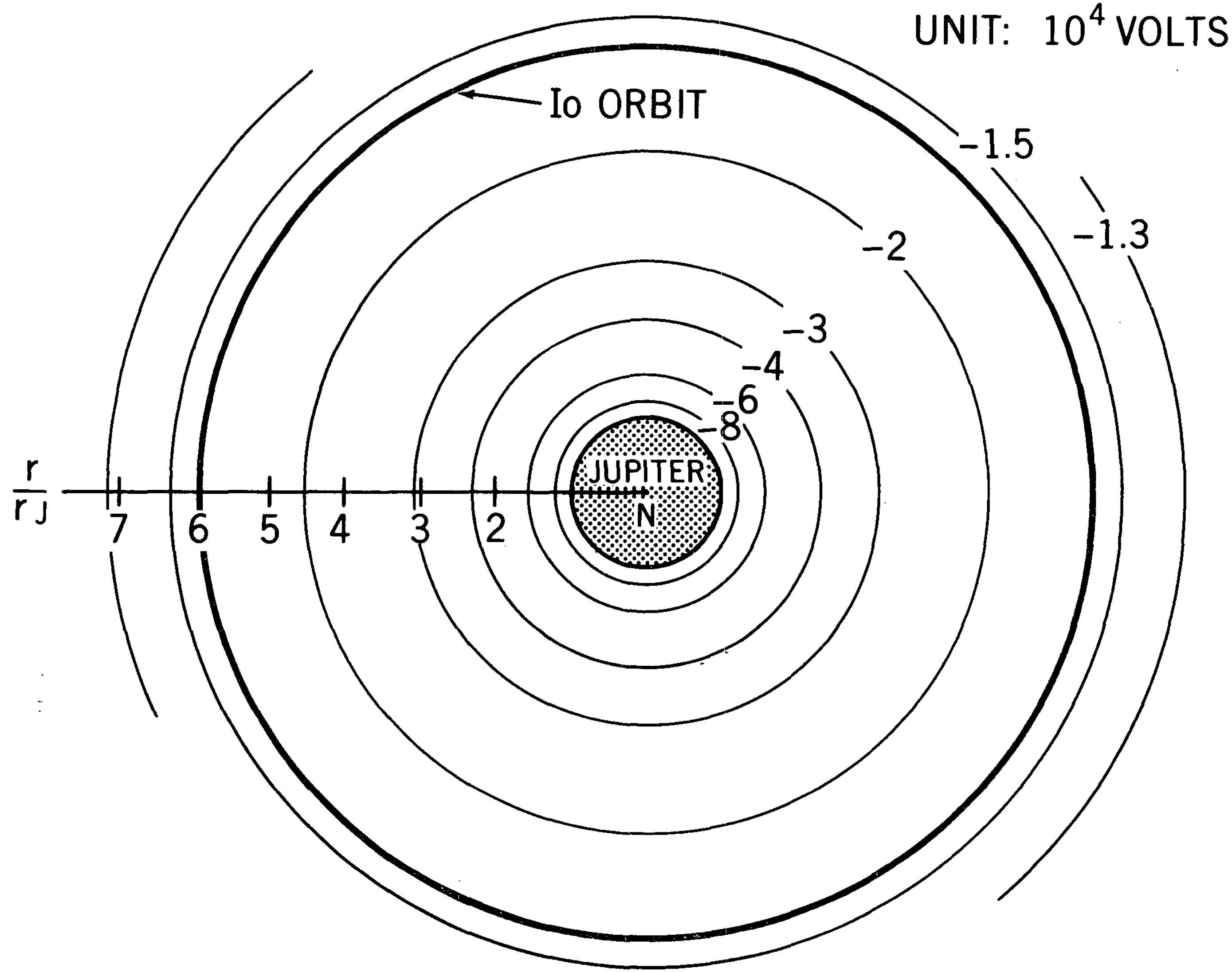

Fig. 2 The distribution of the electric field in the Jupiter magnetosphere. The equi-potential lines in the equatorial plane are shown.

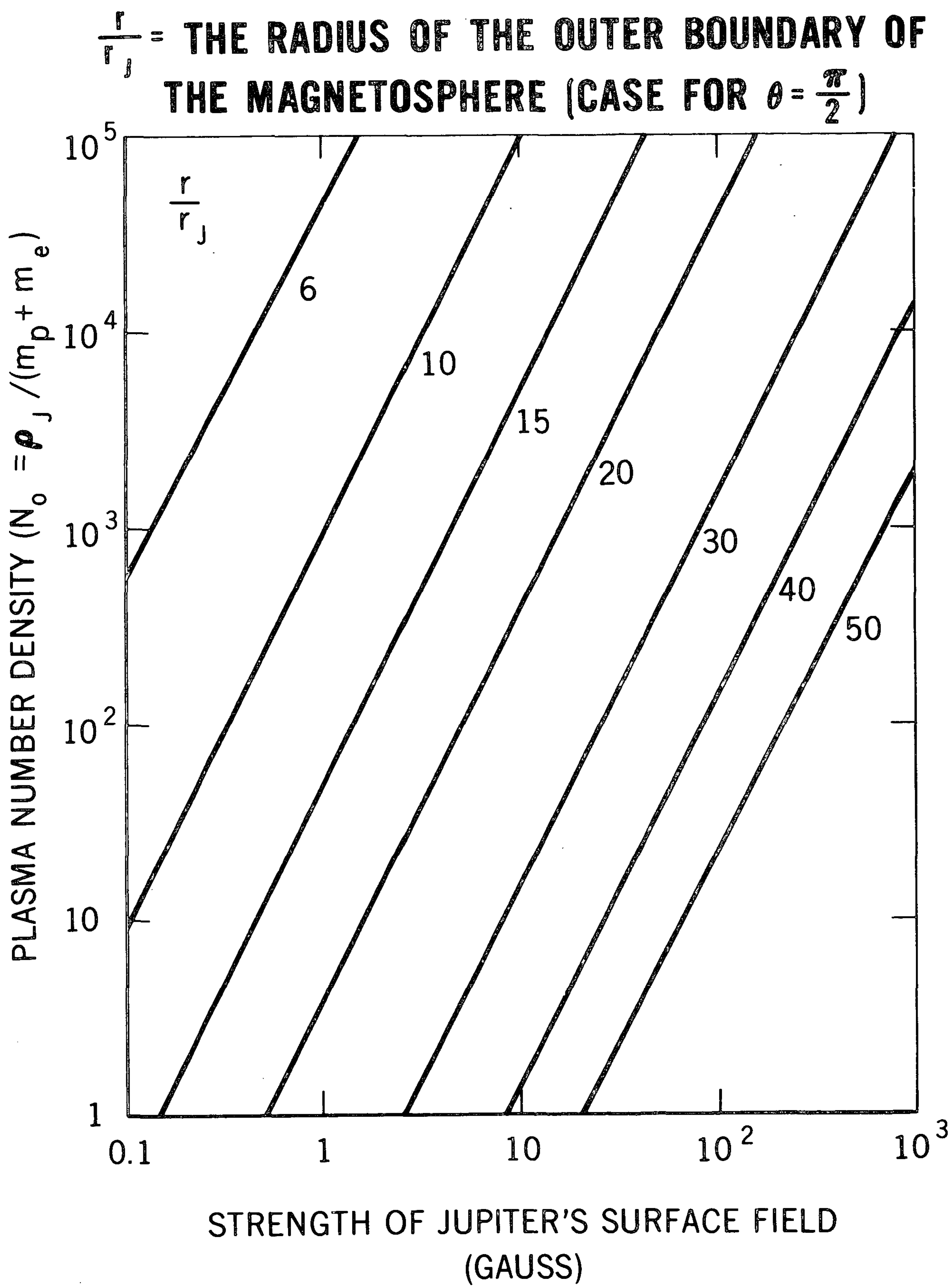

Fig. 3 Relation between B_o and ρ_J. The radius of the Jupiter magnetosphere boundary is parametrically indicated with B_o and ρ_J.