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A Dawn to Dusk Electric Field in The Jovian Magnetosphere

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INTRODUCTION

Recently, Ip and Goertz (1983), hereafter referred to as paper I, have suggested that the observed local time asymmetry of the UV emission from the Io torus (Sandel and Shemansky, 1982) could be accounted for if there exists a dawn to dusk electric field at the orbit of Io. The magnitude of this field was estimated as 1.5 mV/m. Even though this field may seem small it is not easy to understand that such a field can exist at all. As mentioned in paper I the usual solar wind induced polar cap electric field (if it exists) would correspond to a dusk to dawn electric field inside the Jovian magnetosphere, i.e., opposite to the solar wind induced convection field at the earth. This is simply due to the fact that the direction of the magnetic dipole at Jupiter is opposite to that at the earth. On the other hand, it seems very difficult to imagine a local time asymmetry without a solar influence (solar wind induced or otherwise). A possible mechanism for maintaining a dawn to dusk electric field is described in this paper. In essence this electric field is due to the fact that in the outer magnetosphere the centrifugal current caused by the rotation of magnetospheric plasma flows across a density gradient and is, hence, not divergence free.

A Birkeland current system results with currents into the ionosphere at dawn and away from the ionosphere at dusk. The current closure in the ionosphere sets up a dawn to dusk resistive electric field which is mapped out into the magnetosphere. How big can such a field be?

It has been suggested by Krimigis et al. (1981) that the presumably Io injected plasma is confined to a disk whose equatorial cross section is not circular but resembles an ellipse. This can be understood when one considers the solar wind induced distortion of the Jovian magnetic field. On the front side, field lines are compressed and they are extended on the night side. The corotation induced electric field is then also asymmetric (Goertz, 1978). The equipotential contours come closer to the planet on the day side. Since the flux tube content is constant along the drift path (Hill et al., 1981), constant flux tube contours must also be quasi-elliptical.

Krimigis et al. (1981) and others before them (Michel and Sturrock, 1974; Kennel and Coroniti, 1975, 1977; Hill et al., 1974; Hill and Michel, 1976) have suggested that as the plasma convects into the night side field lines extending beyond a certain critical distance may break open (Vasyliunas, 1983) and a rotationally driven antisunward directed plasma wind should flow in the tail. In paper I we have suggested a direct connection between this wind and the dawn to dusk electric field. However, it is not clear that the wind occurs on "closed" field lines or "reconnected" open field lines as suggested by Vasyliunas (1983), in which case the electric field inside the boundary between the rotational flow and the wind would be dusk to dawn corresponding to a sunward flow. However, it is plausible that flux tubes which cannot enforce rotation in the tail and from which plasma is lost will have a significantly reduced flux tube content. This is implied in plate 1 of Krimigis et al. (1982). This flux tube content gradient will also exist in the front side if the filling by outward radial diffusion is not fast enough.

This model suggests that there exists a fairly well defined boundary between the full and empty flux tubes. The equatorial trace of the "last" full flux tube is elliptical, as shown in Figure 1. In order to simplify the problem we will treat this boundary as infinitely thin. Inside the boundary the full flux tubes move on equipotential contours which must be calculated self-consistently. Outside, the empty flux tubes move on equipotentials which are given by the solar wind induced magnetic field distortion and the corresponding electric field. We also make the simplifying assumption that near this boundary the ionosphere cannot exert a torque on the plasma, i.e., that $\Omega \propto 1/r^2$. Hill (1979) has shown that this is a good approximation beyond a distance $L_o R_J$ where $L_o \approx 20$ is a critical L-shell parameter related to the mass injection from the Io torus. There is, however, an azimuthal current j_φ at the boundary due to the difference of the polarization drifts of low energy ions and electrons.

This current has a component towards the dense regions on the dusk side and towards the empty regions on the dawn side (see Figure 1). There is also a current due to the pressure gradient. The component of the pressure gradient, normal to the boundary, drives a current along the boundary which does not require a field-aligned current. There is, however, a component of the pressure gradient along the boundary because the plasma adiabatically cools as it convects into the decreasing magnetic field of the tail. This component drives a current normal to the boundary which has the same sign as the normal component of the centrifugal current. However, the plasma flow velocity (rotation) is most likely supersonic and the pressure gradient current is small compared to the centrifugal current. We shall neglect it and treat only the cold plasma case.

The polarization current has to be fed by a Birkeland current system with a field-aligned current out of the ionosphere and into the equatorial plane on the dusk side and in the opposite direction on the dawn side. The closure of this current in the ionosphere requires a dawn to dusk Pederson current and hence a dawn to dusk electric field. This self-consistent electric field distorts the drift orbits of the full flux tubes in a way to be calculated below (Fejer, 1964; Vasyliunas, 1970). The expected result is that in the night side, flux tubes move radially outwards and on the day side they move inwards. When this motion is superimposed on the rotational motion a dawnward displacement of the drift path results.

We would then expect the plasma to be colder at dawn than at dusk, as described in paper I.

Before we proceed with the calculations, we would like to discuss some observational evidence which demonstrates the existence of the boundary postulated above. Figure 2 shows data obtained by the LECP instrument during the inbound path of Voyager 2 (Krimigis et al., 1981). Between the last magnetopause crossing at a distance of 63 R_J and about 45 R_J, the LECP density, i.e., the density of hot ions ($T_i \sim 30 - 40$ keV), balances practically all the electron density obtained from the plasma wave (PWS) data (Gurnett et al., 1981). The density of the lower energy ions, determined by the PLS instrument (Bridge et al., 1979a,b; Belcher et al., 1980; and McNutt et al., 1981), is quite low in this region. Inside of about 45 R_J the plasma density in the current sheet is an order of magnitude higher. Such a region of low density but high temperature plasma between the magnetopause and the fully developed (Gledhill) plasma disc can also be observed on the Voyager 1 and 2 outbound paths (Figure 3), as well as in the Saturnian magnetosphere (Goertz, 1983). It may be a characteristic feature of rapidly rotating magnetospheres in general (Goertz, 1983). The observation on the night side of a planetary wind by Krimigis et al. (1981) is obviously strong evidence for the existence of the boundary. In the region it was observed by Voyager 2 (between 140 and 160 R_J) the PSW total electron density was reduced by at least an order of magnitude, as compared to the density in the nightside Gledhill disc (see Figure 3).

I. GOVERNING EQUATIONS

In the magnetosphere the plasma is confined to a thin equatorial Gledhill disc across which neither the magnetic field ($\vec{B} = - B_o(r)\hat{e}_z$) nor the plasma velocity changes significantly. The mass density per unit magnetic flux η,

$$\eta = \int \frac{nm}{B} d z \quad , \tag{1}$$

is constant along the drift path (Hill et al., 1981)

$$\vec{V}_E \cdot \nabla\eta = (\frac{B \times \nabla\Phi}{B^2}) \cdot \nabla\eta = 0 \quad , \tag{2}$$

where the electric field $\vec{E}$ is expressed in terms of the electrostatic potential Φ. To first order the drift velocity V_E is in the azimuthal direction, i.e.,

$$\vec{E} = - \nabla\Phi = - \Omega R_J \sin \theta \; \hat{e}_\varphi \times \vec{B} - \nabla U \quad , \tag{3}$$

where U is a small "resistive" potential to be calculated below. Associated with the plasma drift is a polarization current which, when integrated across the Gledhill disc, is given by

$$\vec{J}_\perp = \eta\ \hat{b} \times (\vec{V}_E \cdot \nabla \vec{V}_E) \quad . \tag{4}$$

Note that we have assumed the plasma to be cold and consequently neglected the pressure gradient current. Since $\nabla \cdot \vec{J} = 0$ the divergence of $\vec{J}_\perp$ must be cancelled by a field-aligned current $j_{\parallel}^{\ e}$ (Vasyliunas, 1970),

$$j_{\parallel}^{\ e} = -\frac{1}{2} \nabla_\perp \cdot \vec{J}_\perp \quad . \tag{5}$$

This current maps into a field-aligned current into the ionosphere $j_{\parallel}^{\ i}$, which is given by

$$j_{\parallel}^{\ i} = \frac{|B^i|}{B_0} j_{\parallel}^{\ e} \quad , \tag{6}$$

where B^i is the magnetic field strength in the ionosphere. Current continuity in the ionosphere requires (superscript i refers to the ionosphere)

$$j_{\parallel}^{\ i} \sin \varkappa^i = \nabla_\perp{}^i [\underline{\underline{\Sigma}}^i (\vec{E} + \vec{v}_n \times \vec{B}^i)] \quad . \tag{7}$$

The magnetic field inclination is $\varkappa^i$ and $\underline{\underline{\Sigma}}^i$ is the height integrated conductivity tensor. The neutral gas velocity is $\vec{v}_n = \Omega_J R_J \sin\theta\ \hat{e}_\varphi$. In the equator the drift velocity is

$$\vec{V}_E = \Omega r\, \hat{e}_\varphi + \vec{w} \quad , \quad |w| \ll \Omega r \tag{8}$$

with

$$\vec{w} = \nabla U \times \hat{e}_z / B_o \quad ,$$

and hence neglecting terms which are quadratic in w.

$$\vec{J} = \eta\, \Omega^2 r\, \hat{e}_\varphi + \eta\{w_r(2\Omega + r\frac{\partial \Omega}{\partial r}) + \Omega \frac{\partial w_\varphi}{\partial \varphi}\}\, \hat{e}_r$$

$$+ \eta\{2\Omega w_\varphi - \Omega \frac{\partial w_r}{\partial \varphi}\}\, \hat{e}_\varphi \quad . \tag{9}$$

The first term is the well-known centrifugal current, the second term represents a radial current which exerts a torque on the radially drifting plasma, and the third term is a small correction to the first, which we shall neglect.

The radial current has been treated by Hill (1979) who has shown how it is related to the mass flux injected into the magnetosphere from the Io torus. We will use his solution of the equation

$$\nabla_\perp{}^i[\underline{\underline{\Sigma}}^i(\Omega_J - \Omega)R_J \sin\theta\, \hat{e}_\varphi \times \vec{B}^i] = \frac{\sin \kappa^i}{2} \frac{|B^i|}{B_o} \frac{1}{r} \frac{\partial}{\partial r}(r\, J_r) \quad , \tag{10}$$

which predicted quite accurately the observed (Bridge et al., 1979) decrease of Ω with radial distance. Hill has shown that beyond a certain distance, $r_o = L_o R_J$, the ionosphere cannot exert enough torque to maintain corotation. In fact, beyond r_o a very good approximation is given by $\Omega \propto 1/r^2$ in which case $J_r \approx 0$. Thus we write for the outer magnetosphere

$$\nabla_\perp{}^i (\underline{\underline{\Sigma}}^i \, \nabla^i \, U) \simeq \frac{\sin \varkappa^i}{2} \frac{|B^i|}{B_o} \Omega^2 \frac{\partial}{\partial \varphi}(\eta) \quad . \tag{11}$$

This equation is similar to equation 14 of Hill et al. (1981) who have used the same derivation albeit in a corotating frame of reference. In their work, φ is the longitude (e.g., System III) in a frame rotating with Jupiter. In our case, φ is the longitude in an inertial, sun-fixed coordinate system, i.e., local time.

Since $V_E \cdot \nabla\eta = 0$, the local time asymmetry of the flux tube content is related to the radial gradient

$$\Omega \frac{\partial}{\partial \varphi}(\eta) \approx - w_r \frac{\partial}{\partial r}(\eta) \quad . \tag{12}$$

To solve equation 11 we need to map its right hand side to the ionosphere. To do that, we note that the potential is constant along a field line which we label by its Euler potential α. In the equator the magnetic field is purely in the z-direction and given by

$$\vec{B}^e = \frac{1}{r} \frac{\partial \alpha}{\partial r} \times \hat{e}_\varphi = - B_o \, \hat{e}_z \quad . \tag{13}$$

In the ionosphere we approximate the magnetic field by a pure dipole field with the dipole axis along the z-axis (rotation axis). We then have

$$B_o \, r \, dr = - 2R_J^2 \sin\theta \cos\theta \, B_s \, d\theta \quad , \tag{14}$$

where B_s is the surface dipole magnetic field strength at the equator. Using the well-known equations for B^i and $\sin \varkappa^i$ for a dipole field and assuming, for simplicity, that $\underline{\underline{\Sigma}}$ is everywhere the same, we finally arrive at the equation

$$\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta \frac{\partial U}{\partial\theta}\right) + \frac{1}{\sin^2\theta}\frac{\partial^2 U}{\partial\varphi^2} + g(\theta)\frac{\partial U}{\partial\varphi} = 0$$

$$g(\theta) = \frac{1}{2\Sigma_p B_s \sin^7\theta}\, \Omega \frac{\partial}{\partial\theta}(\eta) \tag{15}$$

This equation must be solved subject to the boundary conditions to be discussed in the next section.

II. BOUNDARY CONDITIONS AND SOLUTIONS

Like other authors before (Hill, 1979; Hill et al., 1981), we will assume that within the plasmadisc plasma transport occurs via an adiabatic interchange diffusion which maintains a constant flux tube content η. Outside the boundary, η is much smaller and, for simplicity, we will set it equal to zero. The boundary field lines intersect the ionosphere at a latitude θ^*. The value of θ^* is not well known. We will treat this as a free parameter. Integrating equation 15 with respect to θ yields the first boundary condition

$$\left[\partial U/\partial\theta + \frac{\cos\theta}{\sin\theta} U - \frac{\Omega\ \eta\ \partial U/\partial\varphi}{2\Sigma_p B_s \sin^7\theta}\right]_{\theta=\theta^*} = 0 \quad , \tag{16}$$

where [ ] indicates the difference between the value of the bracketed quantity inside and outside the boundary. In addition, we require the potential to be continuous across the boundary

$$[U]_{\theta=\theta^*} = 0 \quad . \tag{17}$$

For $\theta < \theta^*$ we have $\eta \approx 0$ and it seems plausible that the ionosphere can enforce rigid corotation on the empty flux tubes at lower colatitudes as $\theta \to 0$. In fact, the apparent disagreement between the LECP observations of nearly exact corotation in the low density region (Krimigis et al., 1981 and Carbary et al., 1981), and the PLS observations of significantly reduced rotation rates in the high density regions (Bridge et al., 1979a,b; McNutt et al., 1981), indicates precisely this. Thus, in the low density region $U \to 0$ as $\theta \to 0$.

Since $g(\theta) = 0$ here the potential U must be of the form

$$U^{o} = \tan\frac{\theta}{2}\,(2A_1^{o}\cos\varphi + 2B_1^{o}\sin\varphi) + \sum_{m>1}\tan^{m}(\theta/2)(2^{m}A_m^{o}\cos m\varphi + 2^{m}B_m^{o}\sin m\varphi) \quad , \qquad (18)$$

we will regard only the first harmonic terms $(m = 1)$ because we do not expect the solar wind to cause higher harmonic distortions of the magnetic and electric field. We further note that the electrostatic potential Φ can be expressed as a function of the Euler potential α, say $\Phi = \int \Omega(\alpha')d\alpha'$. In that case, α is a constant along the drift contour and the form of α given by Stern (1967) together with equation (3) can be used to derive approximate values for the coefficients A_1^{o} and B_1^{o}. *Since the noon-midnight meridian is the symmetry* axis for the solar wind induced perturbations, we obtain $B_1^{o} = 0$. The remaining value of A_1^{o} depends on the magnitude of the solar wind induced compression of the magnetosphere, i.e., the solar wind stand-off distance, $r_s = L_s R_J$, or equivalently the colatitude $\sin\theta_s \approx L_s^{-1/2}$ of the polar cap. Using the relation of Stern (1967) based on the magnetic field model of Mead (1964), we obtain

$$A_1^o \simeq 0.27\, R_J^2\, B_o\, \Omega_J \sin\theta_s^6 \tag{19}$$

This corresponds to a very small poleward displacement of a field line by $\Delta\theta \sim 16\, L_s^{-3}$ degrees as it rotates from noon to midnight. Inside the boundary the solution for U is of the form

$$\begin{aligned} U^1 &= \tan(\theta/2)(2A_2^1 \cos\varphi + 2B_2^1 \sin\varphi) \\ &\quad + \tan^{-1}(\theta/2)(2C_2^1 \cos\varphi + 2D_2^1 \sin\varphi) \quad . \end{aligned} \tag{20}$$

Using the boundary conditions (16) and (17) we can solve for the potential U^1. A particularly simple form results when we approximate $\tan\theta/2$ by $\theta/2$, which should be good for high latitudes. In that case, we have

$$U^1 = A_1^o\, \theta \cos\varphi - \frac{\eta\Omega}{\sin^7\theta^*} \frac{A_1^o}{4\Sigma_p B_s}\, \theta \sin\varphi [1 - \frac{\theta^{*2}}{\theta^2}] \quad . \tag{21}$$

A sketch of this potential using an unrelatistically low value for η is shown in Figure 4. Near Io's colatitude (θ_{Io} = 26°) and with a realistic value for η, the contours given by equation (21) are indistinguishable on the scale of the drawing from those which result when the full function ($\tan \theta/2$), rather than its approximation, is used. The compression of the equipotential contours between θ^* and θ_{io} is very large for realistic values of η and it is difficult to show individual contours clearly. Two points are important.

(i) The electric field inside the boundary between full and empty flux tubes may be significantly larger than the original solar wind induced field. This depends on the value of the quantity

$$x = \frac{\eta\Omega}{4 \sin^7 \theta^*} \frac{1}{\Sigma_p B_s} [1 - \frac{\theta^{*2}}{\theta^2}] = x_o [1 - \frac{\theta^{*2}}{\theta^2}] \quad .$$

Whereas the potential difference (between noon and midnight) at θ^* is $A_1^o \theta^*$, it is $A_1^o \theta \sqrt{1 + x^2}$ at the colatitude θ. As we will see this may become quite large because $x_o = 65$. In Figure 4 we have used $x_o = 4$ to make the figure clearer.

(ii) The direction of the electric field changes as one goes to lower latitudes approaching a dawn to dusk direction, as θ becomes larger. The angle of rotation increases with increasing x.

At the inner edge of the torus we have again a steep radial gradient of η (Goertz and Ip, 1982) and the electric field will change direction and magnitude. Whereas in the dense regions of the torus the plasma flow has an antisunward component, it is mainly sunward inside the inner edge of the torus. We have shown schematically the equipotential contours inside the inner torus boundary by dashed lines in Figure 4. (These lines are not calculated exactly.)

III. DISCUSSION

Whereas the general result of the previous section is quite encouraging, it is not clear that a 1.5 mV/m field results at the orbit of Io, because θ_s is probably quite small. However, Connerny et al. (1981) estimated the magnetic latitude θ_s of the auroral field lines to be about $\theta_s \simeq 18°$ which would correspond to a dipole L shell parameter of only 10. Previous estimates, not including the current sheet, put $\theta_s \simeq 10°$ corresponding to $L_s \simeq 33$. We will use the lower value for θ_s to be on the conservative side. A value for θ^* is equally difficult to estimate. Clearly, $\theta_s < \theta^* < \theta_{Io}$. One may argue that the value for θ_s, estimated by Connerny et al. (1981), really corresponds to θ^* because, in essence, Connerny et al. have determined the footprint in the ionosphere of the field lines bounding the current sheet which is filled with dense plasma. We thus take $\theta^* = 18°$. At this distance, the plasma rotation rate is reduced to something like 0.5 of its rigid value (McNutt et al., 1981). The flux tube content in the outer magnetosphere is at least $\eta = 2 \times 10^{-4}$ kg/W (Hill et al., 1981) but it may be as large as $\eta = 4 \times 10^{-3}$ kg/W, the value observed in the Io torus (Hill et al., 1981). In fact, using new results from Bagenal (private communication), one finds $\eta = 8 \times 10^{-3}$ kg/W in the torus. Thus, $\eta = 10^{-3}$ kg/W seems a reasonable value. The value for Σ_p is also not well known (see Hill et al., 1981 for a discussion), but $\Sigma_p = 0.25$ mho seems a reasonable number, even though values 10 times larger or smaller may also be realistic.

With these numbers we get $A_1^o = 2500$ V, $x_o \simeq 65$ and at the latitude of Io's flux tube, $x \simeq 35$. Thus, the maximum of the potential U occurs at a local time of 17:58, i.e., is almost exactly at dawn. The magnitude of the electric field at Io's orbit, however, is only 2×10^{-2} mV/m, i.e, a factor of 7 smaller than the field estimated in paper I. However, we do not regard this discrepancy as very serious because of the following two reasons:

1. The value of x may be too small. There are at least two reasons for this. The value for η used (10^{-3} kg/W) may quite possibly be too low by a factor of eight. In the Io torus, for example, η is certainly as large as 4×10^{-3} kg/W. In addition, we have neglected the contribution to the Birkeland current system driven by the pressure gradient along the boundary between full and empty flux tubes. This contribution would increase the right-hand side of equation (11) and, hence, lead to a larger $g(\theta)$ or, in turn, a proportionately larger value of x.
2. The value of A_1^o may also be an underestimate. If, as Connerny et al. (1981) have estimated, we take $\theta_s = 18°$, the value of A_1^o is increased by a factor of thirty.

The distortion of Jupiter's magnetic field may also be comparatively stronger than that of the earth's, which would yield a larger A_1^o. One may think that $2A_1^o\ \theta_s$ should, at least, be as large as the potential drop across the polar cap produced by field line merging or reconnection. Otherwise, the sunward directed convection resulting from such direct solar wind magnetosphere interaction would quench the antisunward directed planetary wind on closed field lines. The solar wind electric field at the orbit of Jupiter is 400 μV/m and if 10% of that penetrates the magnetosphere one would have about 100 keV between dusk and dawn even at $\theta_s = 18°$ (assuming no screening out of the field by drift induced charge separation fields). Our estimate of $A_1^o\ \theta_s$ of 1 keV may thus, indeed, be much too small. However, since very little is known about the occurrence or existence of an earth-type solar wind induced electric field, we will not pursue this line of reasoning. A more complete calculation of the equipotentials, including a possible direct solar wind induced dusk to dawn electric field at high latitudes will be left to future work.

Finally, we mention a number of possibly observable consequences of the convection pattern discussed above (assuming a field of 1.5 mV/m).

1. The antisunward drift at the orbit of Io is about 700 m/s increasing to 7 km/s at $L \simeq 15$. Such a drift may be observable either by in-situ spacecraft observations or by

ground-based observations of the optical emissions from the Io torus.

2. The oppositely directed flow in the cold inner torus may produce the opposite effect, namely hotter electrons in the morning. However, the effect is much reduced in magnitude.

3. Since the potential difference between dawn and dusk along contours of constant magnetic field is of the order of 1 MV at Io's orbit, one would expect a noticeable difference in energetic particle fluxes between the inbound and outbound paths of Pioneer 10, Voyager 1, and Voyager 2. Such an effect, corresponding to a drift contour displacement of about 0.1 R_J towards dawn, may have been observed in the Pioneer 10, 60 keV proton data (Randall, private communication). Similar effects should, by the way, occur also at Saturn, where the physics is almost identical, even though the value of η may be smaller. A search of the Pioneer 11 Saturn data for that effect is now being undertaken.

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FIGURE CAPTIONS

Figure 1. A sketch of the Jovian plasma disc configuration. Flux tubes are emptied through a planetary wind in the tail. There is a boundary between full and empty flux tubes whose cross section in the equatorial plane is quasi-elliptical. The azimuthal centrifugal current flows away from this boundary at dusk and towards it at dawn (large arrows). Birkeland currents close this current system (dark arrows).

Figure 2. Hot ion plasma densities in the front side magnetosphere according to Krimigis et al. (1981) and total electron densities according to Gurnett et al. (1981). The boundary between (relatively) empty flux tubes containing low density hot plasma and full flux tubes containing high density colder plasma is indicated.

Figure 3. Same as Figure 2 except that the data (Krimigis et al., 1981 and Gurnett et al., 1981) are obtained in the dawn side magnetosphere.

Figure 4. A sketch of the equipotential contours U in the ionosphere for $x_o = 4$, corresponding to a flux tube content of 6×10^{-5} kg/W. The contours inside of $\theta^* = 18°$ are parallel to the dawn dusk direction. If a solar wind induced sunward convection (driven for example by reconvection) would exist, the contours would have to be appropriately rotated.

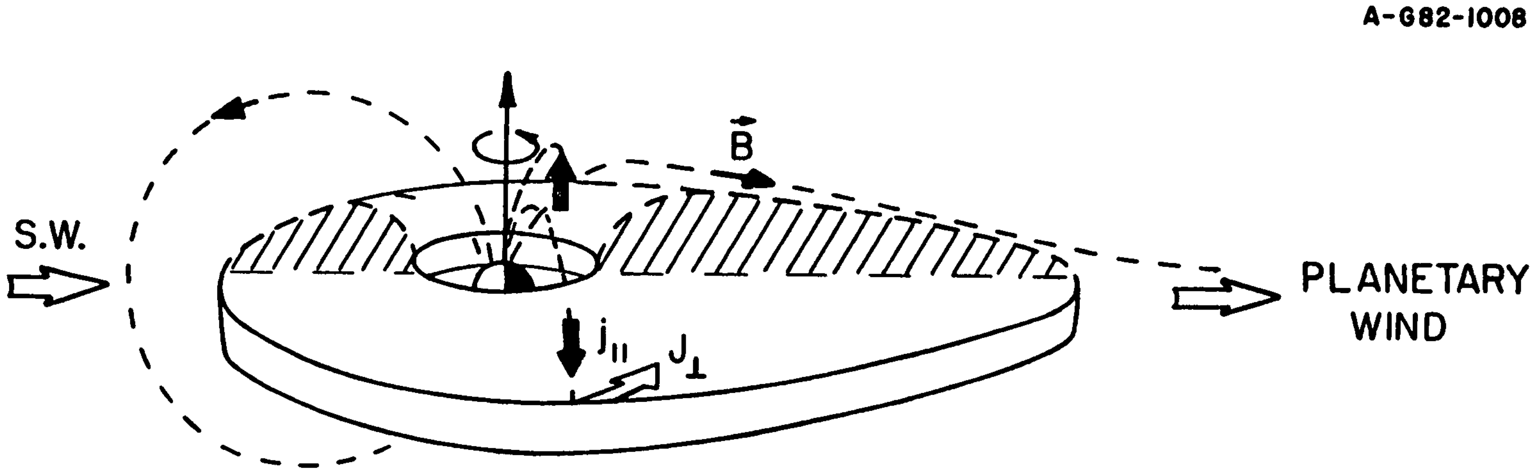

Figure 1.

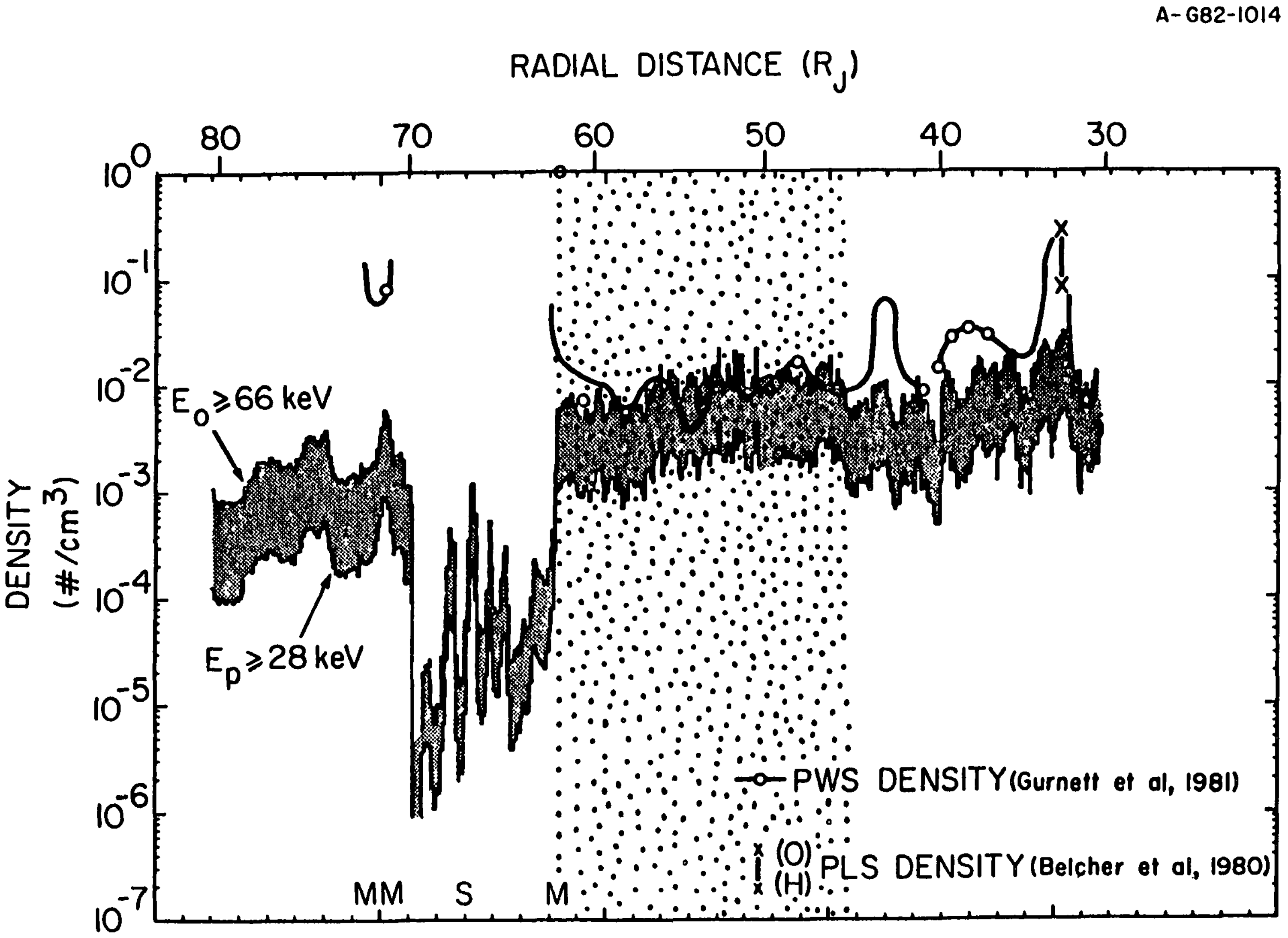
A-G82-1014
RADIAL DISTANCE (R_J)
80
70
60
50
40
30
DENSITY (#/cm^3)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$E_o \geq 66$ keV
$E_p \geq 28$ keV
MM
S
M
PWS DENSITY (Gurnett et al, 1981)
(O)
(H)
PLS DENSITY (Belcher et al, 1980)

Figure 2

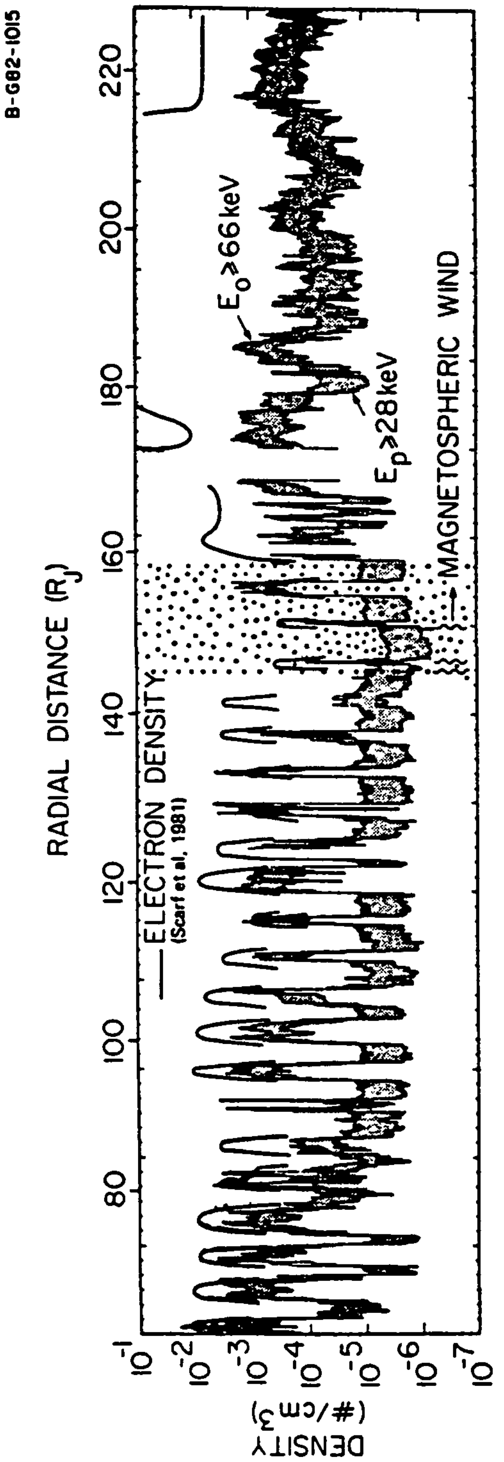
B-G82-1015
RADIAL DISTANCE (R_J)
80
100
120
140
160
180
200
220
DENSITY (#/cm^3)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
ELECTRON DENSITY
(Scarf et al, 1981)
$E_o \geq 66$ keV
$E_p \geq 28$ keV
MAGNETOSPHERIC WIND

Figure 3

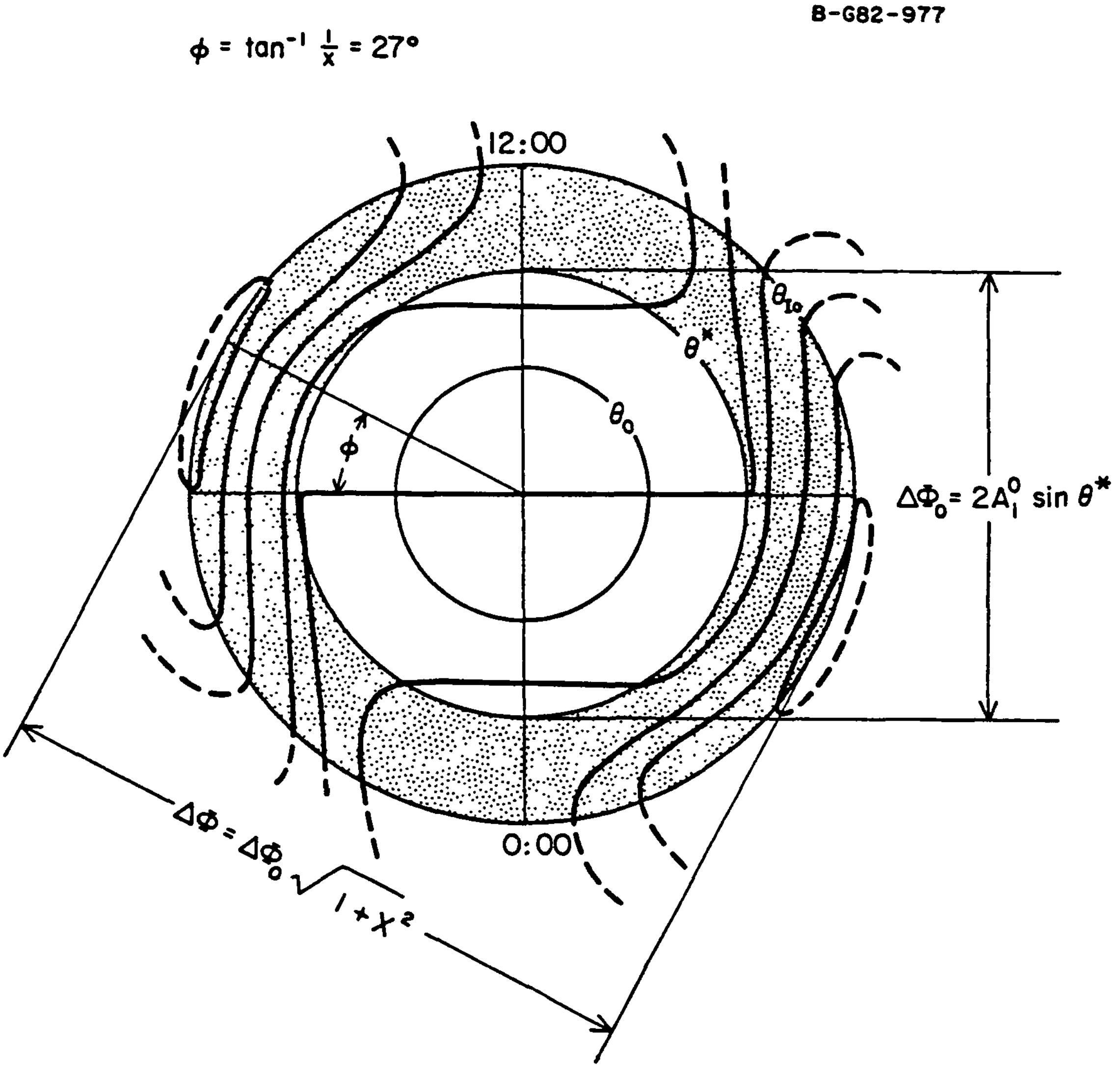
B-G82-977
$\phi = \tan^{-1}\frac{1}{x} = 27°$
12:00
θ_{1o}
θ^*
θ_0
ϕ
$\Delta\Phi_0 = 2A_1^0 \sin\theta^*$
0:00
$\Delta\Phi = \Delta\Phi_0\sqrt{1+X^2}$

Figure 4

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15. Supplementary Notes

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Moffett Field, CA 94035 FTS-8-448-6456 or 415-965-6456

16 Abstract

We show that if Io-injected plasma is lost via a planetary wind a sun-fixed Birkeland current system may result. This is due to the fact that the azimuthal centrifugal current flows across a density gradient produced by the loss of plasma through the planetary wind in the tail. The divergent centrifugal current is connected to field-aligned Birkeland currents which flow into the ionosphere at dawn and out of it at dusk. The closure currents in the ionosphere require a dawn to dusk electric field which at the orbit of Io is estimated to have a strength of 0.2 mV/m. However, the values of crucial parameters are now well known and the field at Io's orbit may well be significantly larger. Independent estimates derived from the local time asymmetry of the torus UV emission indicate a field of 1.5 mV/m.

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