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DAWN-DUSK ELECTRIC FIELD ASYMMETRY OF THE IO PLASMA TORUS

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ABSTRACT

We consider the effects of a combined convection and corotation electric field across the Io plasma torus. A dawn-to-dusk electric field E_c will modify the orbits of charged particles shifting them toward dawn. The radial drift imposed by the perturbed orbits implies a local time-dependent modulation of low-energy ion and electron temperatures with particles hotter at dusk than at dawn. With $E_c \simeq 4$ mV/m, the orbits near 6 R_J would be shifted by approximately 0.2 R_J. Then the electron temperature would be 20% higher at dusk than at dawn, an effect which could explain the local time asymmetry of EUV intensity found by the Voyager ultraviolet spectrometer. The source of the convection electric field is internal to the magnetosphere and is attributed to the tailward escape of Iogenic and Jovian plasma beyond the Alfven surface.

I. INTRODUCTION

Detailed observations at optical and ultraviolet wavelengths have revealed many new and puzzling features of the Io plasma torus. Most notably, Sandel and Broadfoot (1982) have reported on and analyzed a local time asymmetry (LTA) in electron temperature of the plasma. The maximum intensity of extreme ultraviolet (EUV) emissions from the warm torus ($5.7 < R < 7$ R_J) occurs most probably at 1900 L.T. Citing other evidence that the plasma density is uniform in azimuth, Sandel and Broadfoot conclude that the brightening at the dusk meridian is due to higher electron temperature there rather than increased ion density. In a companion paper Shemansky and Sandel (1982) put forward a model in which the plasma is heated by electron-electron collisions that transfer energy from an unspecified local time-dependent source centered at noon.

The observational result and its interpretation have stimulated a good deal of interest as it departs significantly from the conventional view of the torus energy source expressed by Broadfoot et al. (1979) after the discovery of the EUV torus by Voyager spacecraft. In the generally accepted picture of torus dynamics, electrons are heated by interacting with ions newly created out of a diffuse torus of Iogenic neutral sulfur and oxygen atoms. If the new ions are accelerated to full corotation speed, they gain comparable (thermal) energy in their gyromotion. Barbosa et al. (1983) have analyzed a model based on the above premise which demonstrates that Coulomb collisions between pickup ions and electrons can maintain the high rate of energy loss by the plasma to EUV radiation. However, that model by itself does not offer any obvious explanation for the EUV local time asymmetry and some additional process is needed to enforce dawn-dusk asymmetry on the torus dynamics.

The necessary ingredient could be a convection electric field oriented perpendicular to the Sun-Jupiter line. Such a field might be a natural consequence of the solar wind interaction with the Jovian magnetosphere, but its influence near the orbit of Io would be small. For example, Brice and Ioannidis (1970) considered an earth-like convection pattern induced at Jupiter directly by the solar wind. They concluded that the convection field would be dominated by the corotation field of Jupiter essentially throughout all of the Jovian magnetosphere and the solar wind influence would be peripheral. A thorough review of all theoretical considerations along these and related lines is given by Kennel and Coroniti (1979).

In this letter we present a new model for understanding the dawn-dusk EUV asymmetry. We explore the consequences of a larger convection electric field not arising from a direct solar wind interaction. We suggest that the convection electric field is the result of internal forces that derive from plasma flow down the tail giving rise to a residual effect that shows up at the orbit of Io. That is, specifically, the Sun-Jupiter line is a preferred direction in space resulting from the solar wind control over the shape of the magnetopause and magnetotail. The orientation and sense of the electric field (dawn-to-dusk) is dictated by the requirement that most of the plasma outflow be collimated and escape antisunward down the tail. We analyze the drift orbits of particles in this convection field combined with the corotation field. The EUV observations of the torus are then used to quantify the convection field strength.

II. CONVECTION ELECTRIC FIELD

Perturbations of Particle Orbits

If a small convection electric field at the radius of Io is responsible for hotter electrons at dusk and the EUV asymmetry, it must be oriented from dawn-to-dusk. Our analysis will treat this effect as a small perturbation of both the orbits and the energy of particles near $R_o \sim 6$ R_J conveniently expressed in the parameter $\epsilon = E_c/E_o$ where E_c and E_o are the magnitudes of the (uniform) convection and corotation electric fields, respectively. A more complete analysis of particle trajectories has been given by Schield (1969) and a review of the topic for the Earth's magnetosphere has been given by Kivelson (1976).

For simplicity we assume a dipole magnetic field model oriented along the spin axis of Jupiter. The trajectories of particles with zero gyroenergy are the equipotential contours of the combined corotation and convection electric fields

$$\Phi(r,\phi) = \alpha/r + E_c r \sin\phi \qquad (1)$$

where the azimuthal angle ϕ is measured counterclockwise from midnight and $\alpha = \Omega B_J R_J^3/c$. If $\hat{y}$ is positive toward dusk, the total electric field is

$$\vec{E} = (\alpha/r^2)\,\hat{r} + E_c\,\hat{y} \qquad (2)$$

If $E_o = \alpha/R_o^2$, the solution of (1) for a particle that crosses the noon meridian at $r = R_o$ is simply

$$R = R_o\,[1 - (1 - 4\,\epsilon \sin\phi)^{1/2}]/2\,\epsilon \sin\phi \qquad (3)$$

For a dipole magnetic field, the stagnation point R_S of the Alfven surface separating closed from open orbits is from (2) $R_S = R_o/\epsilon^{1/2}$ and lies on the dawn meridian. To order ϵ^2 we obtain

$$R = R_o\,[1 + \epsilon \sin\phi + 2\,\epsilon^2 \sin^2\phi + 0(\epsilon^3)] \qquad (4)$$

Neglecting contributions quadratic in ϵ, the orbits are given by

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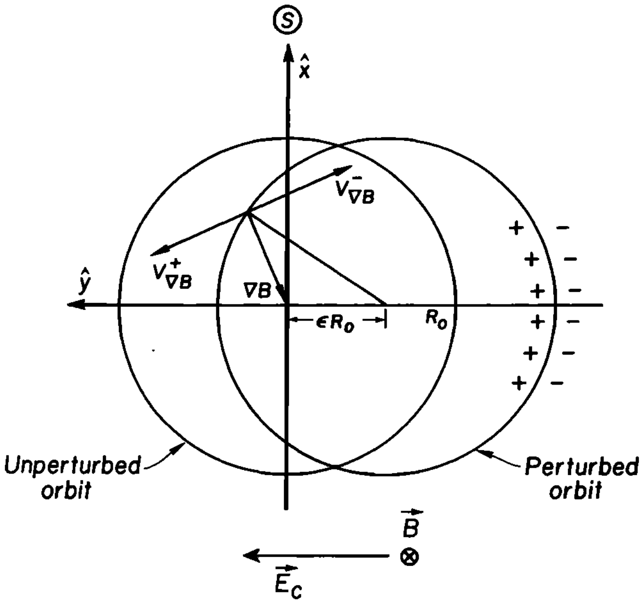

Figure 1: Schematic diagram of the displacement of charged particle orbits due to a dawn-to-dusk convection electric field.

$$x^2 + (y + \epsilon R_o)^2 = R_o^2 \tag{5}$$

and particles drift in circles whose centers are displaced ϵR_o toward dawn.

The particle drift velocity is $\vec{V} = c\,\vec{E}\times\vec{B}/B^2$ and if the magnetic field varies as $B \propto r^{-3}$, then from (2) and (4) we obtain

$$V \simeq V_{CR}\,[1 + \epsilon^2(1 - 3\sin^2\phi)/2] \tag{6}$$

for the drift speed around an orbit displaced by ϵR_o from R_o. Thus, to order ϵ the drift speed is a constant and equal to the rigid corotation speed $V_{CR} = \Omega R_o$ in the absence of the perturbation. A small departure from corotation occurs in quadratic order ϵ^2.

The $\vec{E}\times\vec{B}$ drift orbits are appropriate for low-energy particles defined such that any competing single-particle drift speed V_{drift} is small compared with the corotation speed, $V_{drift} << V_{CR}$. This is particularly true for ions and electrons at thermal energies of the torus (< 50 eV). An increase or decrease in the particle gyroenergy is now associated with the conservation of the first invariant $\mu = mv_\perp{}^2/2B$ along the displaced orbit. Thus both ions and electrons will be hotter on the dusk side than the dawn side because of the offset of the orbit toward dawn when $\epsilon > 0$. Thus, to lowest order, the gyroenergy $W = mv_\perp{}^2/2$ along the orbit varies as

$$W/W_o = R_o^3/R^3 = 1 - 3\,\epsilon\sin\phi \tag{7}$$

A summary of these results is shown in Figure 1 where we have drawn an unperturbed and displaced equipotential contour. Note that the motion of the particles in the convection electric field by itself does not determine whether they gain or lose energy. For example, electrons passing from the dawn side to dusk might appear to give up energy to $\vec{E}_c$ when we know from conservation of μ that both ions and electrons must gain energy as they move radially inward. The actual gain or loss of gyroenergy is brought about by the curvature-gradient drift which displaces finite energy particles a very small distance across the equipotential contours of the total electric field. Thus, the grad B drift proportional to μ

$$\vec{V}_{\nabla B} = (\mu c/q)\,\vec{B}\times\nabla B/B^2 \tag{8}$$

moves ions (electrons) outwards (inwards) of the drift equipotential on the dusk side to enforce conservation of μ and tap the energy of the electric field. The opposite case occurs at dawn as illustrated in Figure 1. Since the electric potential at 6 R_J is ~62 Megavolts, particles need only be displaced 34 m in order to gain 5 eV of energy. This is also consistent with the statement that for 5 eV electrons, $V_{\nabla B} \simeq 2$ cm/s compared with $V_{CR} \simeq 75$ km/s.

Finally, we note that the inertial drift, $\vec{V}_g = (mc/q)\,\vec{g}\times\vec{B}/B^2$, where $\vec{g}$ is the inertial acceleration (equal to $V_{CR}{}^2/R_o$ for corotating particles) acts either to increase or decrease the drift energy (V_g is proportional to the corotational drift energy) along the orbit in a similar manner by displacing the particles perpendicular to contours of constant Φ. However, in the approximation of quasi-circular orbits $\vec{V}_g$ is tangent to the drift orbit in Figure 1 and the drift energy is not changed in linear order of ϵ, consistent with the result in (6).

Temperature Modulation

We now consider an electron gas at temperature T which is modulated by the convection electric field while simultaneously being heated and cooled by other processes. In particular we wish to solve

$$\frac{dT}{dt} = \frac{A}{T^a} - BT^b + CT\,\Omega\sin\Omega t \tag{9}$$

The first term may represent Coulomb heating by plasma ions for which a = 3/2 and the second term may represent electron cooling by impact excitation of EUV emitting ions (Barbosa et al., 1983). We will take b = 1 here in order to find a simple solution. The third term proportional to T [see equation (7)] represents the modulation by E_c and t = 0 corresponds to particles at 0600 L.T.

The solution of (9) for a + 1 ≡ 5/2 is given by

$$T(t) = [T_o^{5/2}\,e^{-5Bt/2} + \frac{5A}{2}\,F(t)]^{2/5}\,e^{-C\cos\Omega t} \tag{10}$$

where T_o is some initial temperature and the function

$$F(t) = \int_o^t dx\,\exp[-\frac{5Bx}{2} + \frac{5C}{2}\cos\Omega\,(t - x)] \tag{11}$$

In the limit t → ∞ F may be evaluated as

$$F(t) \underset{t\to\infty}{\longrightarrow} \sum_{k=0}^{\infty} \epsilon_k\,I_k\,(5C/2)\,\frac{(5B/2)\cos k\Omega t + k\Omega\sin k\Omega t}{(5B/2)^2 + (k\Omega)^2} \tag{12}$$

where I_k is a modified Bessel function and $\epsilon_k = 1$ if k = 0 and $\epsilon_k = 2$ otherwise.

Three simple cases are noted: If C = 0 then

$$T(t) = [T_o^{5/2} + \frac{A}{B}(e^{5Bt/2} - 1)]^{2/5}\,e^{-Bt} \tag{13}$$

and the temperature approaches the steady state solution $(A/B)^{2/5}$. If A = 0 then

$$T(t) = T_o\,e^{-Bt-C\cos\Omega t} \tag{14}$$

representing a decay to zero temperature with a modulation superimposed. This case illustrates the point that in the absence of any external heating, the system will dissipate its energy to radiation irrespective of the forced modulation. No free energy for radiation is derived from the electrical sources of E_c or E_{CR}. Lastly, if C is very small, equations (10) and (12) can be expanded to linear order in C. Then in the limit t →∞, we have

$$T(t) \simeq (A/B)^{2/5}[1 - C(\frac{\cos\Omega t - \kappa\sin\Omega t}{1 + \kappa^2})] \tag{15}$$

representing forced modulation about the equilibrium solution due to heating and radiation alone. Here $\kappa = 5B/2\Omega = 5/2\Omega\tau_{rad}$ using the definition of τ_{rad} given by Barbosa et al. (1983). This may also be written as

$$T(t) \simeq (A/B)^{2/5}[1 - C \cos\psi \cos(\Omega t + \psi)] \quad (16)$$

where the radiative phase shift $\psi = \tan^{-1}\bar{\kappa}$

If τ_{rad} is small so that $\kappa >> 1$, then T_{max} occurs near noon where the heating rate $\dot{T}$ is maximum. However, if τ_{rad} is large $\simeq$ 22 hrs (Barbosa et al., 1983), then $\psi \simeq 10°$ and T_{max} occurs at 1720 L.T. If the maximum EUV intensity actually occurs after dusk at 1900 L.T. (Sandel and Broadfoot, 1982), this would suggest that the orientation of the convection electric field is not strictly dawn-to-dusk but pointed towards 1940 L.T. so that $\dot{T}$ maximizes at 1340 L.T. as EUV analysis has suggested (Shemansky and Sandel, 1982).

The offset of particle orbits and the dusk-dawn temperature ratio depend on radial distance through $\epsilon \propto R_o^2$. Thus, we expect from (7)

$$[T(\phi + \pi) - T(\phi)]/T_o \simeq 6\,\epsilon \sin\phi \quad (17)$$

In Figure 2 we show electron temperatures obtained by Shemansky and Sandel (1982). The solid curve is our theoretical prediction for T(2230 L.T.) using the observed values of T(1030). A value of $E_c \sin(157.5°) = 1.8$ mV/m was used to match the experimental result at 6 R_J. The theoretical result is fairly good inside of 6.5 R_J but does not conform with the dusk value at 7.2 R_J. If the slope of the dawn temperature continues to increase beyond the last data point at 7R_J, the theoretical curve may still lie within the error bars.

III. DISCUSSION

From (7) we see that a convection electric field will force a modulation of the electron temperature by an amount $\Delta T/T = \pm 3\epsilon$. The EUV asymmetry implies a change $\Delta T/T \simeq \pm 10\%$ near $R_o = 6$ R_J. Thus we require $\epsilon \simeq 3\%$ to account for the effect. The corotation electric field at $R_o = 6$ R_J is $E_o = 150$ mV/m and a convection electric field of the magnitude $E_c \sim 4$ mV/m is needed in the Io torus.

Although only a 3% effect, nevertheless a field of this size has not been considered easy to obtain in the Jovian magnetosphere. What are the possible sources? The solar wind electric field at Jupiter's orbit has been estimated to be ~ 400 μV/m and if we allow for 10% to penetrate into the system only 40 μV/m is available from the solar wind (Kennel and Coroniti, 1979). Also,

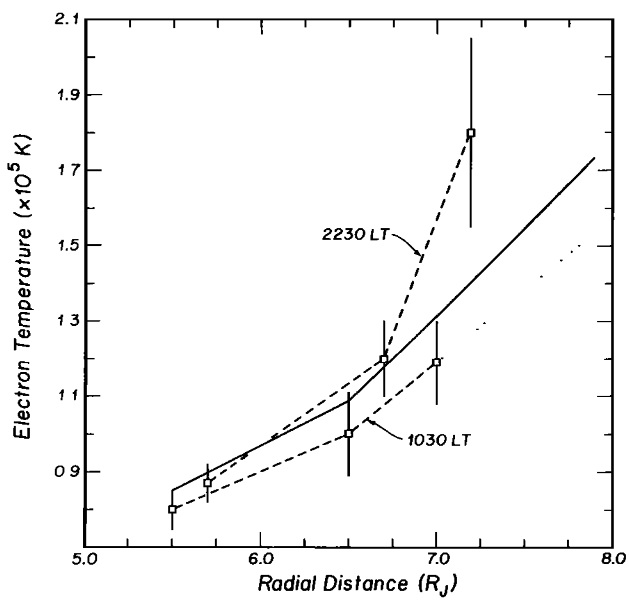

Figure 2. Electron temperatures at 1030 and 2230 L.T. (Shemansky and Sandel, 1982) are shown as dashed lines and the theoretical result for T_e (2230) is the solid line.

its orientation is predominantly dusk-to-dawn and incompatible with a brightening of the torus at the dusk meridian.

Another possibility is that ionospheric dynamo winds create a global circulatory convection pattern that maps out into the magnetosphere. The diurnal (1,−2) wind eigenmode analyzed by Coroniti (1974) could be stimulated by the solar wind over the polar cap or driven by solar irradiance over the dayside hemisphere. However strong this effect is, the wind blows toward higher latitudes at local noon and this would result also in a sunward convection flow in the magnetosphere of the opposite sign to that needed to explain the LTA of the EUV emissions.

The required antisunward convection flow leads us to consider that the electric field may be a consequence of preferential escape down the tail of Jovian plasma (Hill et al., 1974). The actual magnetic field (B_{tail}) and flow speed (v_{tail}) where E_c originates is uncertain but we can estimate

$$E_c = 4 \text{ mV/m}(v_{tail}/400 \text{ km s}^{-1})\,(B_{tail}/10 \text{ nT}) \quad (18)$$

allowing for other values of the product vB. Thus, the direction and magnitude of the field at the source are compatible with what is required. However, no quantitative theoretical models of the magnetohydrodynamics of plasma escape down the tail exist at present and we cannot ascertain if an electric field of the magnitude given by (18) should be present at 6 R_J also.

Are there any observations that suggest the presence of $\vec{E}_c$ and antisunward perturbations to the corotational flow besides the EUV asymmetry? The plasma probe on the Voyager 2 spacecraft noted the presence of significant inward radial flow velocities on the dayside pass as well as tailward flows on the nightside pass. However, this result is not conclusive pending further analysis of the data from the A,B,C detectors (McNutt et al., 1981).

Recently, Trauger et al. (1980) and Brown (1982) have analyzed Doppler shifts of SII forbidden line emissions at λ6716 and λ6731 from the Io torus. The data, corrected for the relative motion of Earth and Jupiter, were used to infer whether the torus plasma corotates rigidly with the system III (1965) spin period. The method requires accurate pointing to source regions equidistant from Jupiter to east and west. In addition, the analysis assumes that the plasma motion is azimuthally symmetric about Jupiter. This implies that an effective rest frame wavelength, λ_o, of the emission can be obtained as the mean of oppositely Doppler-shifted lines on the two sides of the torus. Both Trauger et al. and Brown report values of λ_o red-shifted by about 0.05 Å relative to the values obtained by Bowen (1960) from observations of gaseous nebulae.

A residual redshift of 0.05 Å corresponds to a plasma speed of 2 km/s antisunward. Since the rigid corotation speed is $\simeq$ 75 km/s at 6 R_J this represents a 3% velocity perturbation if the wavelengths of Bowen are accepted as true rest frame values. On the other hand, if the plasma motion is azimuthally symmetric to the level of better than 3%, the reference wavelengths as obtained represent more accurate determinations of the rest frame values than those of Bowen.

We note that a redshift of 0.05 Å is close to the wavelength uncertainty quoted by Bowen of ± 0.04 Å and the Jupiter observations may well be yielding more accurate intrinsic wavelengths for these emissions as suggested by Trauger et al. and Brown. However, the important point is that through an independent line of reasoning we have concluded that a 2 km/s antisunward velocity field superimposed on an azimuthal corotation velocity is quantitatively sufficient to produce the EUV brightening at dusk. Such a flow would violate the assumption of azimuthal symmetry and thus be inconsistent with the analysis of SII emissions. We suggest that additional analysis in this area may be called for. If wavelengths of other forbidden lines are systematically longer than those catalogued by Bowen, this might suggest that the redshift of 0.05 Å is intrinsic to the region near 6 R_J at Jupiter. Comparison with solar emission/absorption lines would also serve as a check on this possibility.

Another test for the convection electric field is to see if the plasma orbits are offset relative to Jupiter toward dawn. At 6 R_J the offset $\Delta R = \epsilon R_0 \simeq 0.18\ R_J$ may be resolvable. This would require that an emitting region on the west be isolated and followed around to the east for comparison of radial displacement. Imaging of the SII torus may also yield an answer to the question of orbit offset (see, e.g., Pilcher, 1980).

Implications for the Outer Magnetosphere

If a dawn-to-dusk electric field is present at 6 R_J, the immediate implication is that plasma flow in the outer magnetosphere down the tail produces a residual effect manifest to the Io torus. In this sense the solar wind shapes the magnetospheric cavity and magnetotail providing a symmetry axis in space for an east-west oriented electric field. Outflow of Iogenic and Jovian plasma down the tail provides the absolute sense (dawn-to-dusk) and magnitude (~ 4 mV/m) of the electric field. The existence of the field as close in as 6 R_J would suggest that the global convection electric field is imposed by boundary conditions that demand plasma escape preferentially in the antisolar direction within the magnetopause boundary.

The actual escape direction is probably rotated several hours past midnight. Allowing for both a finite radiative phase shift and a peak EUV intensity at 1900 L.T., we have computed that $\vec{E}_c$ is oriented toward 1940 L.T. and thus ϕ_{escape} = 0140 L.T. This counterclockwise skewing suggests that the magnetopause configuration also has a dawn-dusk asymmetry with a "bulge" (broader extent) on the dawn side. This effect can be associated with the component of bulk plasma momentum in the $(-\hat{y})$ direction exerting a greater dynamic pressure on the dawn magnetopause as plasma escapes tailward. The stagnation point of the Alfven surface lies on the dawn side and we expect significant dawn-dusk asymmetry also throughout the middle and outer magnetosphere.

It is difficult to ascertain what the global convection pattern should look like. Simple analogy with Earth might suggest that a large-scale two cell convection pattern exists with antisunward flow interior and sunward flow on the outer edges. However, this is not necessarily the case at Jupiter. We have considered a uniform convection electric field $\vec{E}_c$ for simplicity. In the general framework of electric multipoles given by Barbosa (1979a,b) the electric field at 6 R_J can be interpreted as the most slowly varying electric field component for an interior problem with boundary conditions imposed at or near the Alfven surface. At Earth, the dipole moment is the dominant term and the two cell pattern is very evident in ground magnetometer records. At Jupiter, higher order electric field moments (comparable to the dipole term) are required to describe the complex flow patterns envisioned by Kennel and Coroniti (1979). We would only require that the dipole term survive at 6 R_J for a uniform field while the higher order electric field components, important near the source surface, go to zero with decreasing distance from the boundary toward Jupiter.

Finally, we emphasize the distinction between our model and the "corotating convection pattern" proposed by Hill et al. (1981). These authors have considered a fast systematic outflow of plasma throughout the inner magnetosphere which is attributed to a magnetic anomaly fixed in system III coordinates. The departure from azimuthal symmetry is a specific function of λ_{III} magnetic longitude. In our model the plasma moves in closed orbits located within the Alfven surface and some additional mechanism (e.g., Siscoe and Summers, 1981) is required for radial transport outwards. Departure from azimuthal symmetry is a specific function of local time.

In conclusion, a "Jupiter-like" convection pattern may exist whose signature is a distortion of plasma orbits near the radius of Io and elsewhere due to a small (3%) convection electric field oriented from dawn-to-dusk. The inner magnetosphere is dominated by the corotation field and the outer magnetosphere is dominated by a convection field on the antisolar side associated with outflow of Iogenic and Jovian plasma. We have concluded that these two distinct spatial regions may not be totally isolated from each other but are electrically coupled. Residual features of one regime are retained in the other in a complete description of Jovian flow dynamics. The presence of the convection electric field may be observable by earth-based monitoring of the Io plasma torus. If such an effect is confirmed, future theoretical models of the outer magnetosphere and plasma outflow should make allowance for the electrodynamic coupling to the inner magnetosphere.

Note added: After submission of this work we learned that Ip and Goertz have submitted a paper to Nature with similar conclusions.

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