Plasma injection near Io

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Abstract. Plasma and field observations obtained by the Galileo spacecraft during its first close encounter with Io indicate a much stronger electrodynamic interaction than anticipated. The strength of this interaction can be explained if one assumes that a significant fraction of the Io torus plasma is ionized in the immediate vicinity of the satellite. We adopt a simple model to calculate the strength and pattern of the flow perturbation resulting from a localized equatorial ionization source with dimensions much less than the radial thickness of the torus itself. Comparison with Galileo observations suggests that, when due allowance is made for the oversimplifications in the model, the observations are consistent with the hypothesis that the torus mass loading rate is highly localized near Io, and that Galileo encountered this region of concentrated mass loading at its closest approach altitude of about 0.5 Io radius. This hypothesis may also help explain two otherwise puzzling properties of the torus that were known before the Galileo encounter, the low ion temperature (relative to corotation energy) and the existence of a bright, radially confined "ribbon" feature.

1. Introduction

It is widely conceded that the volcanic satellite Io is the ultimate source of the heavy-ion plasma that populates the Jovian magnetosphere. However, there remains considerable uncertainty, and thus controversy, on the questions of where and how the volcanic ejecta become ionized and hence incorporated into the plasma torus. One feature shared by all models is the "bootstrap" nature of the process: the existing plasma torus interacts somewhere with the un-ionized volcanic ejecta to produce, through electron-impact ionization, new plasma at an average rate sufficient to balance the average loss rate of torus plasma through radial transport to the outer magnetosphere. The models differ primarily in the assumed location of the plasma-neutral interaction region. The "neutral cloud theory" [Shemansky, 1988; Schneider et al., 1989; Barbosa, 1994] assumes that ion sputtering of Io's surface or its atmosphere liberates neutral atoms or molecules, which occupy extended clouds along Io's orbit until ionized by hot electrons of the co-located plasma torus. At the opposite extreme, the volcanic ejecta may be ionized while still airborne in the visible volcanic plumes [Johnson et al., 1980; Sieveka and Johnson, 1984], within a few hundred kilometers of the surface. The most detailed quantitative models of the plasma-gas interaction [Smyth and Combi, 1988a,b, Smyth and Marconi, 1993] suggest that most ionization may occur within an intermediate altitude range of a few Io radii ($R_{Io} = 1820$ km), a conclusion that is supported by our interpretation of the Galileo observations.

There is no direct observational signature of local plasma production within the Io plasma torus. The inferred residence time of torus ions is much larger than the Jovian rotation period [e.g., Smyth and Marconi, 1993], so the plasma content is not expected to vary dramatically with longitude even if the plasma source is localized. Thus, although the visible torus exhibits systematic brightness variations with local time and System III longitude [e.g., Schneider and Trauger, 1995, and references therein], none of these has been attributed to a particular source structure. (Voyager UVS measurements of emission from doubly ionized sulfur [Sandel and Broadfoot, 1982] show an intensity enhancement leading Io by about 40° in its orbit, but spectral information indicates that this enhancement results from an electron temperature variation, not a localized plasma source.)

In the absence of a direct signature, there are at least three indirect observational signatures of local plasma production, all of which were seen by the Galileo spacecraft as it passed within 0.5 $R_{Io}$ downstream of Io: a localized magnetic-field perturbation [Kivelson et al., 1996a], a localized plasma-flow perturbation [Frank et al., 1996], and a localized generation of ion cyclotron waves and mhd mirror-mode waves [Kivelson et al., 1996b]. Another indirect signature of the mass-loading process is the corotation lag of torus plasma, which is observable from Earth in the Doppler shift of torus emission lines [R. A. Brown, 1983; M. E. Brown, 1994]. These Earth-based observations have been successfully interpreted in terms of a model [Pontius and Hill, 1982] that calculates the corotation lag on the assumption that the mass loading rate is azimuthally symmetric within an equatorial annulus near Io's orbit. The fact that the corotation lag varies gradually over a 1 $R_{J}$ ($R_{J}$ is Jupiter's radius = 71,400 km) range of radial distance [M. E. Brown, 1994, 1995] could be interpreted as indicating that mass loading is likewise distributed smoothly over this radial range. However, the atmospheric flywheel effect [Huang and Hill, 1989; Pontius, 1995] tends to produce a long-lived corotation lag over a large region of the torus even if the instantaneous plasma source is restricted to a much smaller subvolume therein.
In this paper we interpret the Galileo Io-encounter observations in terms of a simple analytical model of the flow perturbation produced by a plasma source that is highly localized near Io. We adopt the "unipolar inductor" paradigm [Piddington and Drake, 1968; Goldreich and Lynden-Bell, 1969], in which a steady electric current circuit is established between Io and Jupiter. We explicitly neglect the effects of Alfvén-wave propagation along the field lines. Wave propagation is important in a time-dependent situation and also affects the steady state solution [e.g., Goertz, 1980; Neubauer, 1980] if the wave propagation time between Io and Jupiter is comparable to or greater than the convection time of a flux tube through the Io current-source region [Hill et al., 1983; Neubauer, this issue]. The Alfvén-wave propagation time is

\[ \tau_A = \frac{ds}{v_A} \approx 1000 \text{s} \]  

while the flux-tube convection time is

\[ \tau_c = 3R_I \omega_c \approx 100 \text{s} \]  

where \( v_c \) is the plasma convection speed in Io's vicinity, relative to Io, and \( v_o = 57 \text{ km/s} \) is the nominal value of \( v_c \) that would apply if the plasma in Io's vicinity were corotating with Jupiter. (The radius of the current-source region is taken to be 1.5 \( R_I \) and 1.880 \( H \) in accordance with the Galileo observations.) Prior to the Galileo encounter it was customary to assume that \( v_c - v_o \) and hence \( \tau_A \gg \tau_c \), an assumption that clearly favors the Alfvén-wing paradigm [e.g., Goertz, 1980; Neubauer, 1980] in which local wave propagation effects are featured and the connection with Jupiter is ignored. The Galileo observations of Frank et al. [1996], however, show an extended region in which \( v_c/v_o < 1/60 \), hence \( \tau_A \lesssim \tau_c \). This situation suggests, if indeed it does not require, a resurrection of the unipolar-inductor paradigm, where the wave propagation effects are suppressed in favor of explicit consideration of the Io-Jupiter connection.

The logic of the model presented here is identical to that of Pontius and Hill [1982]. The acceleration of newly produced ions to the local corotation speed requires, and produces, a radial "pick up current" that is proportional to the mass loading rate and to the magnitude of the corotation electric field as measured in the (Kepler-orbiting) rest frame of the progenitor atoms or molecules. The pick-up current is closed by magnetic-field-aligned (Birkeland) currents connecting to Pedersen currents in the Jovian ionosphere, establishing a closed current loop that transfers angular momentum from the Jovian atmosphere to the newly produced torus plasma. Current continuity requires a corotation lag that is proportional to the ratio of mass-loading rate to Jovian ionospheric conductance. The present model differs from that of Pontius and Hill [1982] only in the assumed geometry of the plasma source region, which was taken to be azimuthally symmetric in the previous model and is taken to be localized near Io in the present model.

2. Model

The pick up current density [Goertz, 1980; Hill et al., 1983] is

\[ i_r = \frac{\dot{\rho} \left( \Omega - \Omega_K \right)}{\omega_B} \]  

where \( \dot{\rho} \) is the rate of change of the plasma mass density \( \rho \) due to local ionization, \( r \) is distance from Jupiter's rotation axis, \( \Omega \) is the local plasma rotation frequency, \( \Omega_K \) is the (Kepler) rotation frequency of the particles before ionization, and \( B \) is the strength of the magnetic field, assumed to be in the \( -\hat{z} \) direction. A large pick up current probably also implies a substantial Pedersen current in the pick-up region. Without a detailed model of Io's atmosphere and ionosphere, we cannot include the Pedersen current explicitly in our analysis. We can, however, include it implicitly because its functional form is identical to (3) with \( \dot{\rho} \) replaced by \( \sigma_B B^2 \), where \( \sigma_B \) is the local Pedersen conductivity. When a detailed model for Io's atmosphere and ion pick up therein becomes available, the quantity \( \dot{\rho} \) can simply be replaced by \( (\rho + \sigma_B B^2) \) in the following analysis. In the meantime, we simply note that the effective mass-loading rate may exceed the true mass-loading rate because of the neglected effect of the Pedersen current.

We assume a spin-aligned dipole magnetic field and integrate (3) across the equatorial current sheet under the "thinsheet" approximation [Vasyliunas, 1983] to obtain the surface current density

\[ J_r = \frac{\eta}{2} \left( \Omega - \Omega_K \right) \]  

where \( \eta = \frac{dpdz/B}{2} \) is the mass content per unit magnetic flux. The pick up current diverges at the outer and inner edges of the mass loading region, producing Birkeland (magnetic-field aligned) current sheets to and from Jupiter's ionosphere, respectively. The closure of this Birkeland current system in the ionosphere determines the electric field in the reference frame of the neutral atmosphere, with the assumption of uniform ionospheric Pedersen conductance, and a frame transformation then gives the electric field, and hence the flow field, in Io's frame of reference.

We assume, again for analytical tractability, that \( \eta \) is uniform within an equatorial circular disk of radius \( a \) centered at Io, and zero elsewhere. In this case the ionospheric current-closure problem has an analytical solution (see the appendix) that can be mapped to the equatorial plane and transformed to Io's reference frame to yield the flow pattern shown in Figure 1. Within the mass-loading disk, the electric field \( E_r \) is purely radial and is uniformly reduced from its upstream value \( E_o \) by the factor

\[ \frac{E_r}{E_o} = \left( 1 + \frac{\eta}{\Sigma} \right)^{-1} \]  

where \( \Sigma \) is the height-integrated Pedersen conductivity of the Jovian ionosphere at each (northern and southern) footprint. The velocity \( v = E/B \) is purely azimuthal and is similarly reduced. The external flow is diverted around the mass-loading region (and Io) in a manner that is reminiscent of potential flow (\( \nabla^2 \phi = 0 \)) but closes more tightly around the obstacle because of the dipole field mapping properties (a circle in the equatorial plane maps to a 2:1 ellipse in the ionosphere; see the appendix). Figure 1 shows the solution for \( a = 1.5 R_I \) and \( E/E_o = 0.4 \) (\( \eta = 928 \)).

It is interesting to compare this result with our earlier result [Pontius and Hill, 1982] for the case of azimuthally symmetric mass loading. The earlier result can be cast into the same form as (5) above with the factor 6 replaced by the factor 4. This difference arises because the localization of the mass-loading region allows one-third of the ionospheric Pedersen current to close outside the flux tube, which produces an effective iono-
Figure 1. Plasma flow vectors (heavy line segments) reported by Frank et al. [1996] from the December 1995 Galileo-Io encounter, superposed on the flow field computed from the model described in the text. The open circle represents Io, and the shaded ring indicates the radius (1.5 $R_J$) of the assumed disc-shaped mass-loading region. The model streamlines are plotted for the case of 60% shielding of the incident flow from the mass-loading disk. The length of the flow vectors denotes the magnitude of the observed velocity, which has a background value (far left and right sides) of about 44 km/s.

3. Comparison With Galileo Observations

Galileo observations [Frank et al., 1996] indicate that the plasma flow relative to Io is virtually stagnated near the point of closest approach (~1.5 $R_J$ downstream of Io's center). In equation (5) above, this would require

$$\dot{M} \gg 6\pi a^2 B^2 \Sigma \sim \left(300 \text{ kg/s}\right)\left(\frac{\Sigma}{1 \text{ mho}}\right)^2$$

(8)
to ensure $E_i/E_o \ll 1$, where we have taken $a = 1.5 \ R_J$ and $B = 1400 \text{ nT}$ [Kivelson et al., 1996]. It is widely anticipated that $\Sigma \gtrsim 0.1 \text{ mho}$ and that the total mass addition rate for the whole torus is $\dot{M}_T \sim 1000 \text{ kg/s}$ [e.g., Hill et al., 1983, and references therein]. Thus condition (8) is equivalent to the requirement that the rate of mass loading in Io's immediate vicinity is at least comparable to that of the whole torus, a conclusion that has been reached on quite independent grounds by Smyth and Marconi [1993]. Stated differently, the same mass loading rate (~1000 kg/s) that, if distributed throughout the torus volume, would suffice to explain the 3-4% corotation lag therein, would also, if confined near Io, suffice to explain the almost complete flow stagnation observed there. This requirement will be somewhat modified if the ionosphere is collisionally bound, as suggested by Frank et al. [1996], which would imply a large Pedersen conductivity. However, the required large neutral densities would also imply enhanced mass loading by...
electron impact ionization. We therefore do not expect the inclusion of Pedersen currents to substantially alter our conclusion that a considerable fraction of the torus mass loading must occur in the immediate vicinity of Io.

We do not expect, nor do we obtain, a detailed fit between the model flow field and the Galileo plasma flow measurements (Figure 1). The true geometry of the mass-loading region is undoubtedly more complicated than the simple disk that we have assumed, with uniform mass-loading rate inside the disk and zero outside. And the true mapping between Io and Jupiter is undoubtedly complicated by the perturbation magnetic field that is implied by, but neglected in, our analysis above. Moreover, the interaction region undoubtedly exhibits a pronounced upstream-downstream asymmetry [e.g., Cloutier et al., 1978; Southwood and Dunlop, 1984; Neubauer, this issue], which is likewise neglected in our simple electrodynamic model. Nevertheless, there are three fundamental features of the flow observations that are accounted for qualitatively by the model, the near-stagnation of the flow behind Io, the accelerated flow on the edges of the wake, and the inward deflection of the flow toward the center of the wake.

The surface Birkeland current density implied by our model (see the appendix) is distributed sinusoidally around a circular cylinder of radius \(a\), neglecting the dipole curvature of the background magnetic field. More precisely, there are two such cylindrical current sheets of opposing polarity that meet at the edges of the equatorial mass-loading disc and close across it. The associated magnetic-field perturbation is not easily calculated in the equatorial region, but away from the equator (by several times \(a\)) the perturbation is equivalent to that of a two-dimensional (2-D) magnetic dipole in the plane perpendicular to \(B\), with magnetic moment
\[
M = \frac{\pi}{2} I a
\]
where \(I\) is the total Birkeland current in each (upward and downward) sheet. If condition (8) is satisfied, then the total current is close to the maximum value that can be supplied by Jupiter's ionosphere, namely,
\[
I_{\text{max}} = 2a I_{\text{max}} = 12a Z \left( \frac{\Omega_2 - \Omega_b}{\Omega_b} \right)
\]
This maximum current corresponds to the limiting case in which the effective conductance of Io (including pick up and Pedersen conductance) greatly exceeds both the Jovian ionospheric conductance and the torus Alfvén-wave admittance \(1/\mu_s V_A\), where \(V_A\) is the torus Alfvén speed [e.g., Hill et al., 1983; Neubauer, this issue]. If we again take \(a = 1.5 R_{\text{Io}}\), the maximum current is
\[
I_{\text{max}} = 2.6 \text{MA} \left( \frac{\Sigma}{1 \text{ mho}} \right)
\]
and the effective 2-D dipole moment is
\[
M = 10^{13} \text{ A} \cdot \text{m} \left( \frac{\Sigma}{1 \text{ mho}} \right)
\]
which, for \(\Sigma \sim 1 \text{ mho}\), is very close to the value \(0.8 \times 10^{13} \text{ A} \cdot \text{m}\) inferred by Acuña et al. [1981] from their analysis of the magnetic perturbation observed by Voyager 1 as it passed near the current-carrying flux tube (but far from Io). Acuña et al. assumed for their analysis a 2-D dipole representation that was derived from the Alfvén-wing model of Neubauer [1980] but is

\[
\Delta B = \frac{\mu_s}{4 \pi} \sim 300 \text{ nT} \left( \frac{\Sigma}{1 \text{ mho}} \right)
\]
which, for \(\Sigma \sim 1 \text{ mho}\), is close to the maximum perturbation \((\Delta B/R_\text{Io} - M_s)\) allowed in the Alfvén-wing model [Neubauer, 1980] for fully shielded flow, where \(M_s \sim 0.15\) is the Alfvén mach number of the corotational flow relative to Io, and \(R_\text{Io} \sim 1800 \text{ nT}\) is the background field strength. However, the limiting current is determined in the present model by Jupiter's Pedersen conductance \(\Sigma\), and in the Alfvén-wing model by the torus Alfvén-wave admittance \(1/\mu_s V_A\), so the apparent agreement results from the coincidental fact that \(\mu_s \Sigma \sim 1\) (if \(\Sigma \sim 1 \text{ mho}\)).

A northward field perturbation of similar magnitude is anticipated (but not as easily calculated) in the vicinity of Galileo's closest approach, just downstream of the region of intense radial pick-up currents that provide closure of the Birkeland current sheets. The observed large-scale field perturbation was closer to 600 nT near closest approach [Kivelson et al., 1996a, b]. There are at least two plausible explanations for the apparent factor-of-2 discrepancy between Voyager and Galileo results: (1) the total current flowing in the Io-Jupiter circuit may have been larger during the Galileo encounter than during the Voyager encounter (larger variations than this are routinely inferred from decametric radio emissions), and/or (2) the perturbation observed by Galileo may include additional contributions from local currents (e.g., magnetization currents) that do not diverge and hence do not connect to Jupiter via Birkeland currents. Acting alone, the first explanation would imply a value \(\Sigma \sim 2 \text{ mhos}\) for the Jovian ionospheric conductance in (13) above. The second explanation has also been suggested by Frank et al. [1996]. The even larger but more localized perturbations, approaching 1000 nT, that were observed by Galileo in the wake region can be attributed either to nonlinear wave structures associated with the pick-up process [Kivelson et al., 1996b], or to a filamentary structure of the pick-up process that produces larger but more localized field perturbations for a given total current.

The Galileo plasma-wave observations [Kivelson et al., 1996] suggest a region of intense ionization and pick-up within \(1 R_{\text{Io}}\) of closest approach, imbedded within a broader but less intense region of ion pick-up extending at least \(5 R_{\text{Io}}\) on either side. Similarly, the plasma flow [Frank et al., 1996] is strongly perturbed near Io and less strongly, but still significantly, perturbed in a broader region extending at least \(5 R_{\text{Io}}\) on either side. This two-tiered structure has a natural explanation within our localized mass-loading scenario. Within the region of nearly stagnant flow (within about \(1.5 R_{\text{Io}}\)), electron-impact ionization is intense not only because the energetic-electron flux is enhanced there [Williams et al., 1996] but also because a given torus flux tube takes an inordinately long time to transit this region. On the other hand, the rate of charge exchange is proportional to the relative speed between ionized and neutral species, which is ordinarily dominated by the relative drift speed in the torus. Thus, charge-exchange collisions are virtually absent in the stagnation region. (Although symmetric charge-exchange
reactions do not alter the plasma mass density, they do contribute to the pick up current density and hence to the plasma wave and flow signatures associated with ion pick up [Pontius and Hill, 1982, and references therein]. Their neglect in the above analysis is only justified a posteriori by virtue of their supression in the region of almost-stagnated flow. They would otherwise be competitive with electron-impact ionizing collisions in the torus environment [e.g., Smyth and Marconi, 1993].] By contrast, on the flanks of the stagnation region, the torus flow past Io is even faster than the ambient upstream flow (Figure 1), while the energetic electron flux is severely diminished [Williams et al., 1996], so that charge exchange may become the dominant contributor to the pick up current. Thus we propose that electron-impact ionization, aided by the observed energetic-electron beams, is responsible for the observed near stagnation of the flow near 1.5 $R_{\text{Io}}$, while charge exchange is largely responsible for the less dramatic but still significant corotation lag (~15%) observed in a broader region extending to at least 5 $R_{\text{Io}}$. In this interpretation, we provisionally accept the background flow speed of 44 km/s reported by Frank et al. in the region within 5 $R_{\text{Io}}$, although Frank et al. have noted that uncertainties in their data analysis make it impossible at present to rule out a value much closer to full corotation (57 km/s relative to Io). Even if further analysis or observations show the actual background speed (and hence the upstream speed) to be close to the full corotational value, one still has the plasma wave observations of Kivelson et al. [1997] showing a clear signature of distributed mass loading within 5 $R_{\text{Io}}$.

The persistent infrared hot spot at the Jovian footprint of the Io flux tube [Connerney et al., 1993] is consistent (as noted by Connerney et al.) with the unipolar-inductor scenario adopted here. It is known from Voyager 1 measurements [Acuña et al., 1981] and confirmed by Galileo measurements [Kivelson et al., 1996a, b] that the Io-Jupiter circuit carries a total current ~2 MA. The motion-induced voltage that drives this current is ~0.5 MV (the corotational electric field relative to Io, times 1.5 Io diameters in accordance with the Galileo observations). Thus a total power -(2 MA)x(0.5 MV) = 1 TW to Io, times 1.5 Io diameters in accordance with the Galileo observations. This power provides an upper limit for the plasma flow power input to Io.

4. Conclusion

We have presented a simple model of the plasma flow perturbation that is driven by a localized equatorial region of enhanced ionization and mass loading, idealized as a circular disk in the equatorial plane centered at Io. The model accounts qualitatively for the observed features of the plasma flow in Io’s vicinity, including the strong deceleration of the flow just downstream of Io, the accelerated flow around the sides, and the inward deflection of the flow toward the center of the downstream wake (Figure 1). A quantitative match to the observed flow is not to be expected from such a simple model. For example, the model result shown for illustration in Figure 1 corresponds to a 60% reduction of the upstream electric field within the mass-loading disk; this choice gives a reasonable qualitative fit to the observed deflection of the flow in the wake and flank regions, but does not replicate the almost complete stagnation of the flow at closest approach. To explain the severe reduction of the flow observed there we would have to instead assume an electric-field reduction of ~98%. A more detailed model, in which the mass loading rate is allowed to vary smoothly with altitude, would presumably be able to match both features simultaneously. A quantitative description of the observed flow and field perturbations will probably require consideration of several features neglected here, including (local) Pedersen, diamagnetic, and acceleration currents as well as the self-consistent magnetic field perturbations.

However, even the present oversimplified model allows us to conclude that the observed large-scale flow and magnetic-field perturbations can be produced by local pick up currents, provided that the localized mass-addition rate is a significant fraction of the rate (~1000 kg/s) that is usually invoked to supply the whole Io plasma torus. This conclusion is consistent with Bagenal’s [1997] assessment of the local ionization rate based on Galileo in situ plasma observations. Pedersen currents in a gravitationally bound Io atmosphere are formally equivalent to pick up currents in our analysis [see also Neubauer, this issue]; their inclusion would reduce the mass-loading requirement by an unknown factor, but probably not by an order of magnitude.

On the basis of our interpretation of the Galileo results, we can identify three distinct regions of the Io plasma torus with respect to the local rate of mass loading and the resultant degree of corotation lag: (1) a localized region within ~0.5 $R_{\text{Io}}$ of Io’s surface where a large mass-loading rate, due to impact ionization of Io’s neutral atmosphere, produces a near stagnation of the flow in Io’s reference frame; (2) a surrounding region within ~10 $R_{\text{Io}}$ of Io where an intermediate pick up rate (with, however, little net mass addition), due to charge exchange in Io’s extended exosphere, produces a corotation lag ~15%; and (3) the remainder of the plasma torus, where a corotation lag ~3% is maintained by the atmospheric flywheel effect and perhaps also by a low background rate of impact ionization and charge exchange in a relatively tenuous neutral cloud. Insofar as the corotation lag is concerned, the first region, and probably also the second, are established by the Galileo observations [Frank et al., 1996], and the third is established by Earth-based Doppler observations [R. A. Brown, 1983; M. E. Brown, 1994, 1995]. Published Earth-based observations could not have resolved the first two regions; this would be a worthwhile objective for future such observations if it proves to be feasible. The inferred distribution of mass-loading rates seems consistent with expectations based on existing chemical/dynamical models [Smyth and Marconi, 1993], coupled with the Galileo results indicating an unexpectedly large ionization rate in Io’s atmosphere.

In addition to providing a plausible interpretation of the Galileo results, the localized mass-loading scenario can also explain two observed properties of the Io torus that were well known before the Galileo/Io encounter: (1) a perpendicular (to B) ion temperature throughout the torus that is significantly less than the corotation energy [e.g., R. A. Brown, 1982;
Belcher, 1983; Schneider and Trauger, 1995), contrary to expectation based on ion pick up in the full coronal electric field, and (2) the radially confined "ribbon" enhancement of torus brightness near Io's orbital distance, evident both in ground-based visible emissions from singly-
ionized sulfur [Schneider and Trauger, 1995, and references therein] and in Voyager 1 based uv emissions from doubly 
ionized sulfur [Volwerk et al., 1997, and references therein]. Schneider and Trauger [1995] have noted that the low ion 
temperature is expected if most ions are picked up in a region very near Io in which the convection electric field strength is significantly less than its corotational value. We propose that the "ribbon" feature represents a downstream coronal plume of enhanced ion density produced by the localized plasma source at Io.

The idea that the ribbon is a coronal plume generated by a localized plasma source at Io is consistent with recent interpretations of Voyager UVS observations indicating a very narrow ribbon feature with radial thickness \( \leq 0.2 R_J \) [Dessler and Sandel, 1993] containing plasma concentrations \( \sim 10^4 \) cm\(^{-3} \) [Volwerk et al., 1997]; this is comparable to the concentration measured by Galileo near its closest approach to Io [Frank et al., 1996; Gurnett et al., 1996] and an order of magnitude larger than typical torus concentrations just outside the ribbon. Further modeling work is needed to see if this scenario can shed light on the curious observed variations [e.g., Schneider and Trauger, 1995] of ribbon brightness and position with Jovian longitude and local time.

Appendix

We define a two-dimensional equatorial Iocentric Cartesian coordinate system \((x, y)\) with \(\hat{x}\) in the corotation direction and \(\hat{y}\) toward Jupiter. The equatorial surface density of the pick up current (text equation (4)) is assumed to be uniform in the \(-\hat{y}\) direction within a circular disc of radius \(a\) and zero outside. Its divergence is compensated by a cylindrical Birkeland current sheet with surface current density

\[ 2I_L = -J_x(y/a) \]  

(A1)

where \(J_x\) is given by (4) of the text. The factor 2 accounts for equal contributions from Birkeland currents to the northern and southern hemispheres of Jupiter. When this Birkeland current cylinder is mapped to Jupiter's ionosphere along dipole magnetic field lines, the originally circular cross section becomes an ellipse with the \(y\) dimension compressed twice as much as the \(x\) dimension. We employ the method of Pontius and Hill [1989] to obtain the electrostatic potential \(\phi\) in the ionosphere, in the reference frame of the atmosphere (assumed to be corotating). The solution procedure is entirely analogous to that of Pontius and Hill [1989] except that the azimuthally directed centrifugal drift current considered by Pontius and Hill [1989, equation (A1)] is here replaced by the radially directed pick up current (4) of the text). The potential \(\phi\) is then mapped back to the equator and transformed to Io's frame to obtain

\[ \phi_{\text{eq}} = E_y \]  

(A2)

\[ \phi_{\text{eq}} = 2b \sinh \left[ E_o \sinh u + \left( E_x - E_o \right) e^{-u} \right] \]  

(A3)

where \(b = 3^{1/2} a\), \(E_o = (\Omega_J - \Omega_K) r B\) is the electric field in Io's frame but far from the interaction region, and the field \(E_x\) within the disk is given by (5) of the text. The elliptic coordinates \((u, v)\) are defined by

\[ u = \Re \cosh \left[ \frac{x + i y}{2b} \right] \]  

\[ v = \Im \cosh \left[ \frac{x + i y}{2b} \right] \]  

(A4)

such that

\[ x = b \cosh u \cos v \]  

\[ y = 2b \sinh u \sin v \]  

(A5)

Figure 1 shows the potential solution for \(E_x/E_o = 0.4\).

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References


