

CIRCULATION AND DYNAMICS IN THE JOVIAN MAGNETOSPHERE

C. T. Russell^{1,2}, M. G. Kivelson^{1,2}, K. K. Khurana², and D. E. Huddleston²

¹*Department of Earth and Space Sciences, University of California Los Angeles,
CA 90095-1567, USA*

²*Institute of Geophysics and Planetary Physics, University of California Los Angeles,
CA 90095-1567, USA*

ABSTRACT

Io continually adds mass to the Io torus and this density builds up until centrifugal force is sufficient to overcome the line tying of the jovian ionosphere. The magnetic flux is carried outward with this slow radial convection. Under the assumption that 1 ton per second is added to the torus at Io and that the Voyager observed densities and average ion mass are pertinent for the Pioneer and Galileo epochs, a consistent flow pattern arises. The outward flow near Io is a few meters per second. Near Europa the velocity, based on the observations of a Europa plume, rises to about 400 m/s. Beyond 24 R_J in the magnetodisk it is possible to again estimate the velocity. It is about 20 km/s at 25 R_J and about 50 km/sec at 40 R_J consistent with the Voyager LECF measurements. This outflow of magnetic flux is replenished by reconnection of magnetic flux in the near tail and the subsequent inward convection of empty flux tubes into the inner magnetosphere. These flux tubes are seen in the middle magnetosphere and the Io torus. Their scarcity as judged by the fact that they constitute only about 0.4% of the observing time indicates that they are moving inward at a much higher rate than the mass-loaded magnetospheric plasma moves outward. In the neighborhood of the magnetodisk the outflow appears not to be steady as the magnetic flux crossing the current sheet varies greatly from orbit to orbit. This unsteadiness may lead the occasional auroral storms seen in the ionosphere at the feet of these field lines.

INTRODUCTION

The interaction of the jovian magnetosphere with the moon Io results in up to 1000 kg of heavy ions, believed initially to be SO_2^+ before dissociation, to be added to the Io torus (Hill et al., 1983). The mass density of the Io torus increases as a result of the addition of mass until its centrifugal force is sufficient to cause the plasma to slowly drift outward producing, at some radius, a magnetodisk configuration as seen by Pioneer 10 and 11, Voyager 1 and 2 Ulysses and now Galileo. In this paper we review the evidence for the outflow and inflow in the jovian magnetosphere and estimate its magnitude. We also show that the outward transport is not steady. These dynamic events, seen at the inner edge of the magnetodisk, may produce the auroral storms seen in the dawn hemisphere at the feet of these field lines.

EVIDENCE FOR OUTFLOW

Figure 1 shows contours of the density of the Io torus obtained by Voyager (Bagenal et al., 1997). If we integrate these contour maps over $1 R_J$ in radial extent we obtain masses of 8 Mtons, 2.5 Mtons and 1 Mton for the radial ranges from 6 to $7 R_J$, 7 to $8 R_J$ and 8 to $9 R_J$ respectively. If Io supplies mass at a rate of 1 ton/s and if the radial profile is in equilibrium then, there must be an outflow of 9 m/s from 6 to $7 R_J$, rising to 30 m/s from 7 to $8 R_J$ and to 68 m/s from 8 to $9 R_J$ unless there is another major loss mechanism other than radial transport.

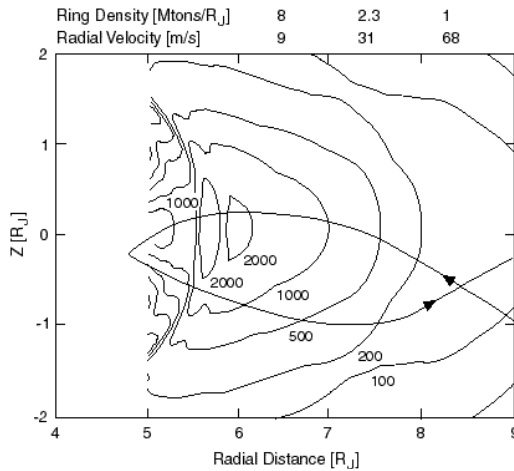


Fig. 1. The Io torus density as observed by Voyager. (from Bagenal et al., 1997). Numbers indicate the vertically integrated mass of the torus in radial bins of $1 R_J$.

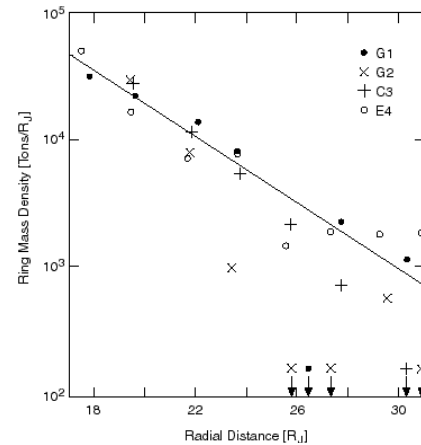


Fig. 2 The radial profile of mass of the magnetodisk estimated by Russell et al. (1998) for the first four Galileo orbits.

We do not have equivalent maps of the magnetospheric density in the middle magnetosphere but we do have an estimate of the velocity nevertheless. This was deduced by the repeated observation of the Europa plume by the Pioneer 10 spacecraft [Intriligator and Miller, 1982]. Assuming that the plume was present continually, Intriligator and Miller deduced an outward velocity of 0.4 km/s. The plume has also been detected by the Galileo spacecraft as a disturbance in the magnetic field (Russell et al. 1999a). The plume appears not to be continuously present. Kivelson et al. (1998) propose that the plume is produced only when the moon passes through the equatorial plane. If so, then there may not be plume plasma produced every time Io is radially aligned with the observing spacecraft. If the interplume spacing is greater than a jovian rotation then outward plume velocity would be less than 0.4 km/s.

In the magnetodisk it is possible to estimate the mass from the magnetic field observations with some assumptions. The difference in the radial field across the disk gives a measure of the current. The normal component of the field across the disk times the current gives the $\mathbf{J} \times \mathbf{B}$ magnetic stress on the plasma. This must balance the outward centrifugal force and the outward pressure force of the thermal plasma. It is possible to estimate this outward pressure force from the diamagnetic decrease in the magnetic field strength surrounding the current sheet, from the thickness of the current sheet and the radial variation of the diamagnetic effect. This has been used by Russell et al. (1999b) to provide the estimates of mass shown in Figure 2. The values vary somewhat from orbit to orbit but typically are about 2500 kg/ R_J at $25 R_J$. For a 1 ton/sec mass addition rate, this mass density gives an outward velocity of 29 km/sec. We should mention here the possible effect of some of the assumptions. We have assumed an isotropic plasma pressure so that by knowledge of the vertical pressure and its radial variation we derived the radial gradient in the plasma sheet. It is most likely that the distribution are pancake shaped and the plasma pressure gradients larger than we calculated. Also in calculating the centrifugal force we have assumed that the plasma corotates. If we use a lesser value then the centrifugal force is reduced by the square of

this factor and the mass density increased. If the density of the current sheet is greater, its outward flow velocity will be less.

An estimate of the radial velocity has been calculated by [Kane *et al.*, 1995] using the LECP data about 40 R_J . This value of 50 km/s is consistent with the measurements presented above as shown in Figure 3. This figure shows that the average velocity of the outward flow rapidly but continuously increases with radius.

ORBIT TO ORBIT VARIATIONS

While Figure 3 shows some consistency in the radial profile of the velocity of plasma, Figure 2 reveals some variations in the density and hence the implied velocity. Another way to study this variability is to examine the magnetic stress on the plasma. This depends only on the field crossing the current sheet and the radial component of the field above and below the current sheet and that depends on fewer assumptions than the mass estimate of Figure 2. This is shown for the first four Galileo orbits in Figure 4. We see that on the first orbit G1 the magnetic stress changed abruptly at the inner edge of the current sheet about 24 R_J while at the other extreme on C3 there was almost no change in the magnetic stress at this point. We would expect if the magnetic stress was weaker and the ring density the same that the flux tubes would slip outward more quickly against the line tying of the ionosphere. If there is greater slippage, then there should be a greater potential drop along the magnetic field lines otherwise anchored in the ionosphere. These potential drops will lead to the acceleration of electrons into the ionosphere and the production of aurora. It is on the dawn side and in the region around $L=25$ to 30 that the aurora are seen and that is where these observations were obtained.

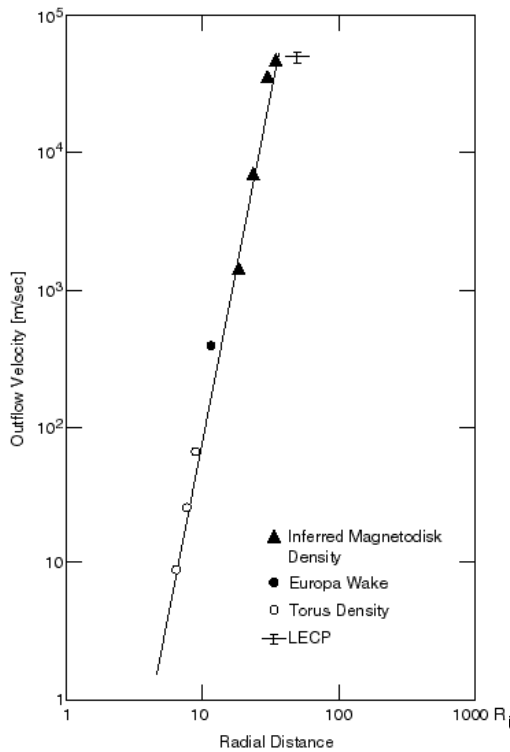


Fig. 3. The outflow velocity deduced from four independent techniques each appropriate to a different radial range. The estimates from the Io torus density and the mass of the magnetodisk were made using a mass addition rate of 1000 kg/s.

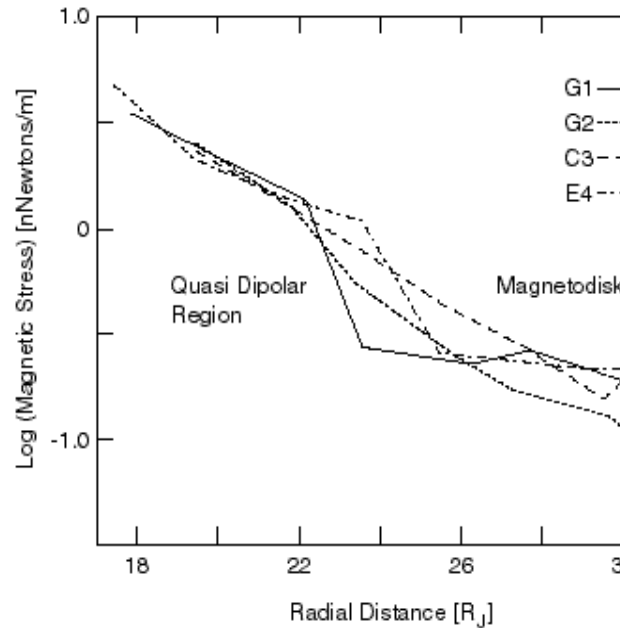


Fig. 4. The magnetic stress in the magnetodisk seen on the first four orbits of Galileo

EMPTY FLUX TUBES IN THE MIDDLE AND INNER MAGNETOSPHERE

The ratio between the mass addition rate at Io and the observed Io torus density, the observed outward velocity of the Europa plume and the inferred density and velocity of the magnetodisk all point to an average inexorable outward flow of plasma moving slowly at first but accelerating rapidly until a velocity of near 50 km/sec is reached around $40 R_J$. This plasma flow carries with it magnetic flux. While the plasma must eventually escape from the magnetosphere at the rate at which Io adds it to the torus, the magnetic flux cannot escape and must be restored to the inner magnetosphere. Reconnection in substorms can separate the ions from the magnetic field and create empty flux tubes. Such reconnection has been observed [Russell *et al.*, 1998, 1999c]. The mere observation of the production of empty flux tubes does not answer the question of how the flux can fight its way upstream against the outward flow of the heavy ions. However, a possible mechanism is inward transport by rapidly moving small flux tubes. Such small flux tubes have observed in the middle magnetosphere and the Io torus (Russell *et al.*, 1999a; Kivelson *et al.*, 1997).

Figure 5 shows time series of the vector component and the field strength for a putative pair of empty flux tubes in the middle magnetosphere. The data rate here is once per 12 seconds and the tubes are observed for 100 seconds each. Figure 6 shows the magnetic field strength for four apparently empty flux tubes in the Io torus. The magnetometer sample rate in the Io torus is four vectors per second. Most of the events last one or two seconds except for the event beginning at 1734:09 that lasts 9.5 seconds. Seven events were seen in the Io torus lasting a total of 22 seconds in the hour and a half of available high resolution data. Hence empty flux tubes were observed only 0.4% of the time. If the Galileo trajectory is representative of the entire Io torus than for the empty flux tubes to compensate for the outward drift of

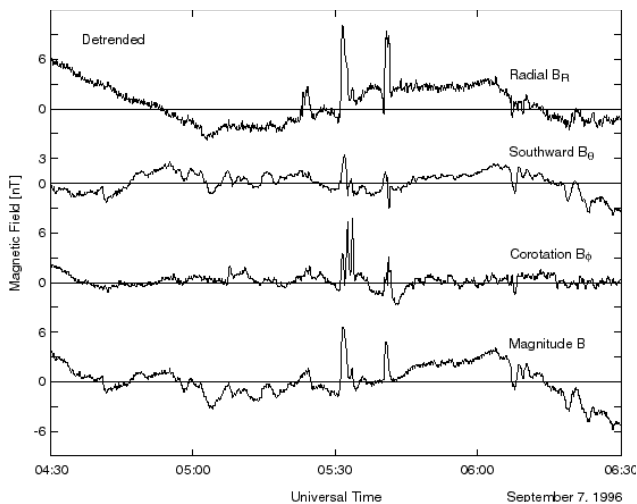


Fig. 5. Time series of the RTS data from Galileo on the second orbit of Jupiter in the radial, southward and corotational directions together with the total field at a radial range of $11.5 R_J$. The jumps in the field strength just after 0530 UT have been interpreted as empty flux tubes.

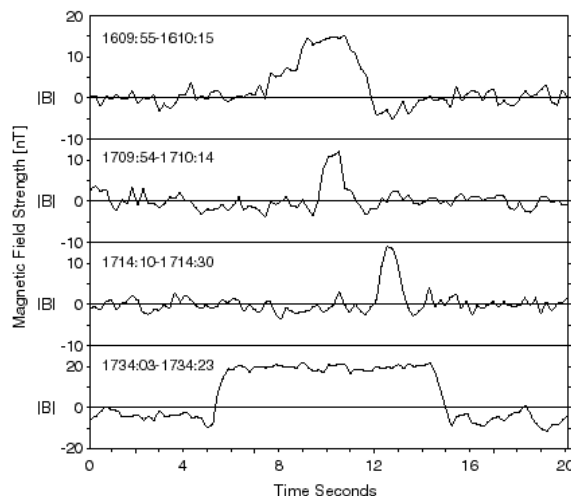


Fig. 6. The total magnetic field strength for four intervals during the Galileo torus pass with background field subtracted. The data were recorded at 4 sample per second. The jumps in field strength have been interpreted as the passage of empty magnetic flux tubes.

plasma laden tubes, then these empty tubes must be moving at an inward velocity, 250 times the outward velocity of the plasma laden tubes. In the Io torus this velocity is about 10 m/s, so the average inward velocity must be about 2.5 km/s. This is less than the inward radial velocity of the Galileo spacecraft of 5 km/s and much less than the corotational velocity of the plasma relative to Galileo of 57 km/s. Thus we use the corotational velocity to convert from the temporal duration to a diameter. We obtain an average

flux of 3×10^4 Webers in each tube not counting the large tube at 1734:09 that has 4×10^5 Webers. This larger tube could also be moving somewhat faster because of its larger size. [Kivelson *et al.*, 1997] have independently estimated an inward speed of 200 km/sec for this event. Using the corotational velocity at the distance of Galileo to calculate the flux in the middle magnetosphere event shown in Figure 4 we obtain a flux of 3×10^7 Webers. Note that in both Figures 4 and 6 the background field has been subtracted.

SUMMARY AND CONCLUSIONS

The Io torus adds ion to the jovian magnetosphere at a rate that has been estimated to be as much as a ton per second. This material moves outward slowly at first at rates of about 9 m/s at $6.5 R_J$ increasing with radial distance so that at $12 R_J$ the velocity is about 400 m/s, at $25 R_J$ about 29 km/sec and at $40 R_J$ 50 km/s. At these rates the ions added to the Io torus require about a year to reach Europa but can transit the magnetodisk from its inner edge to $50 R_J$ in only a period of a week or less. Four independent means of estimating the outward velocity go into this radial profile. Only two of these depend on the accuracy of our estimated iogenic source rate.

The magnetic flux tubes that return from the reconnected magnetic flux in the tail appear to travel inward much more rapidly than the outward moving flux. This results in a much smaller area of inward moving flux tubes than outward moving tubes. Moreover, these inward moving tubes are small and therefore difficult to detect except in the highest resolution magnetometer data. While it is conceivable that all the returned flux is transported by slender empty flux tubes, we cannot be sure that this is so. However, we can understand why empty flux tubes could travel inward faster than heavily laden flux tubes can travel outward. Empty flux tubes can more easily support the parallel electric fields needed to decouple the flux tube from the ionosphere than the "full" flux tubes. On the other hand we do not as yet understand what determines the size of these individual flux tubes. The observations appear to show that a reconnection events of the size of 10^9 Webers are seen at 50 - $100 R_J$. At $12 R_J$ the inward moving tubes appear to have about 3×10^7 Webers each and in the Io torus about 10^5 Webers. The outward transport of ions seems not to be steady in the region of the magnetodisk. The magnetic flux crossing the current sheet and hence the magnetic stress on the magnetodisk changes significantly, especially near $24 R_J$, from orbit to orbit. This is the region in which jovian auroral storms are seen in the ionosphere. We speculate that the reconfiguration of the current sheet stresses occurs when the plasma convection velocity in the current sheet increases rapidly with radial distances in the neighborhood of $24 R_J$ for some period of time. This might be occasioned by an external change in the outer magnetodisk configuration or by some process in the inner magnetosphere itself.

ACKNOWLEDGMENTS

This work was supported by the National Aeronautics and Space Administration with a research grant through the Jet Propulsion Laboratory.

REFERENCES

- Bagenal, F., F. J. Crary, A. I. F. Stewart, N. M. Schneider, D. A. Gurnett *et al.*, and W. R. Paterson, Galileo measurements of plasma density in the Io torus, *Geophys. Res. Lett.*, 24, 2119-2122 (1997).
Hill, T. W., A. J. Dessler, and C. K. Goertz, Magnetospheric models, in *Physics of the Jovian Magnetosphere*, (edited by A.J. Dessler), Cambridge Univ. Press, New York, 353-394 (1983).
Intriligator, D. S., and W. D. Miller, First evidence for a Europa plasma torus, *J. Geophys. Res.*, 87, 8081-8090 (1982).

- Kane, M., B. H. Mauk, E. P. Keath, and S. M. Krimigis, Hot ions in Jupiter's magnetodisc: a model for Voyager 2 Low-Energy Charged Particle measurements, *J. Geophys. Res.*, *100* (A10), 19473-19486 (1995).
- Kivelson, M. G., K. K. Khurana, C. T. Russell, and R. J. Walker, Intermittent short-duration magnetic field anomalies in the Io torus: Evidence for plasma interchange, *Geophys. Res. Lett.*, *24*, 2127-2130 (1997).
- Kivelson, M. G. et al., Europa and Callisto: Induced or intrinsic fields in a periodically varying plasma environment, *J. Geophys. Res.*, *104*, 4609-4625 (1999).
- Russell, C. T., K. K. Khurana, D. E. Huddleston, and M. G. Kivelson, Localized reconnection in the near Jovian magnetotail, *Science*, *280*, 1061-1064 (1998).
- Russell, C. T., D. E. Huddleston, K. K. Khurana, and M. G. Kivelson, The fluctuating magnetic field in the middle jovian magnetosphere: Initial Galileo observations, *Planet Space Sci.*, *47*, 133-142 (1999a).
- Russell, C. T., D. E. Huddleston, K. K. Khurana, and M. G. Kivelson, Observations at the inner edge of the jovian current sheet: Evidence for a dynamic magnetosphere *Planet Space Sci.*, *47*, in press, (1999b).
- Russell, C. T., K. K. Khurana, M. G. Kivelson, and D. E. Huddleston, Substorms at Jupiter: Galileo observations of transient reconnection in the near tail, *Adv. Space Res.*, in press, (1999c).