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Implications of Depleted Flux Tubes in the Jovian Magnetosphere

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Abstract. A rare but persistent phenomenon in the jovian magnetosphere is the occurrence of apparently depleted flux tubes, whose magnetic pressures are significantly above ambient levels. These flux tubes occur about 0.25% of the observing time in the region of the Io torus in the Galileo high resolution data. The importance of these tubes is that they can return to the inner magnetosphere the magnetic flux that has been convected radially outward with the iogenic plasma to the tail. The paucity of these tubes is consistent with the expected flux return rates if the tubes are moving inward at an average rate of about 5-10 km/s in the torus. Depleted flux tubes have yet to be observed inside of the Io orbit where the plasma beta is lower than in the hot torus. Estimates of the plasma density outside the tube from plasma wave measurements enable the average perpendicular temperature to be obtained from the magnetic field change. Extrapolating this temperature back to Io, we obtain an average ion temperature of approximately 60 eV. These values are generally consistent with earlier Voyager observations but on the low side of their range of uncertainty, and agree quite well with contemporaneous Galileo measurements where these are available.

1. Introduction

The engine that drives the dynamics of the jovian magnetosphere is the mass loading process at Io that adds as much as possibly 1000 kg/s of iogenic plasma to the magnetosphere [*Hill et al.,* 1983]. In steady state this plasma must be lost to either precipitation into the ionosphere or to radial convection followed by reconnection. In principle, reconnection with the solar wind could take place but the high Mach number of the solar wind at Jupiter [*Russell et al.,* 1982] and the resulting lower efficiency for reconnection [*Scurry and Russell,* 1991] mitigate against this. Thus we expect that the necessary reconnection would take place on the nightside. For the latter process to operate ions must be separated from the magnetic field lines on which they were transported outward and the depleted flux tubes returned to the inner magnetosphere. The separation can be accomplished by reconnection in the near tail region [*Russell et al.,* 1998]. Approximately 80,000 Wb s^{-1} are loaded at Io and about the same amount of flux as observed to be emptied per second in the jovian tail [*Russell et al.,* 2000]. The depleted flux tubes produced must then float back to the inner magnetosphere against the outward radial transport of the mass-loaded flux tubes.

In the jovian magnetosphere it is possible to replenish the magnetic flux in the inner magnetosphere with small depleted flux tubes if these tubes move quickly enough. The inward transport process is akin to inverting a full glass of water sealed with a porous cap. Water slowly seeps out to be replaced by bubbles of air that float to the "top" of the inverted glass to replace the water that has been lost from the bottom. The water moves downward slowly while the tiny bubbles move upward rapidly. But are such tubes present? Unfortunately small rapidly moving flux tubes are difficult to detect with Galileo because the data rate of Galileo most often is of the order of one sample of the magnetic field every 20s, when there is data at all. Two periods when high resolution measurements with rates of several samples per second are available are the initial torus passage in December 1995, the so-called J0 pass, and on a series of passes in 1999 and 2000 when high resolution data were obtained in the torus as perijove was lowered toward Io's orbit. Figure 1 shows the location of these observations. We have examined these data for the occurrences and properties of any depleted flux tubes.

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2. Observations

We detect depleted flux tubes by comparing their magnetic energy density with that of their neighbors. A depleted tube will have greater magnetic pressure than neighboring flux tubes with which it is in pressure balance because its neighbors have pressure contributions from both the plasma and the magnetic field. Strictly speaking our evidence is only that the flux tubes are missing some plasma energy density that their neighbors possess. We cannot directly check the density of these tubes with either the plasma analyzer or the plasma wave spectrometer because the cycle times of these instruments are too long.

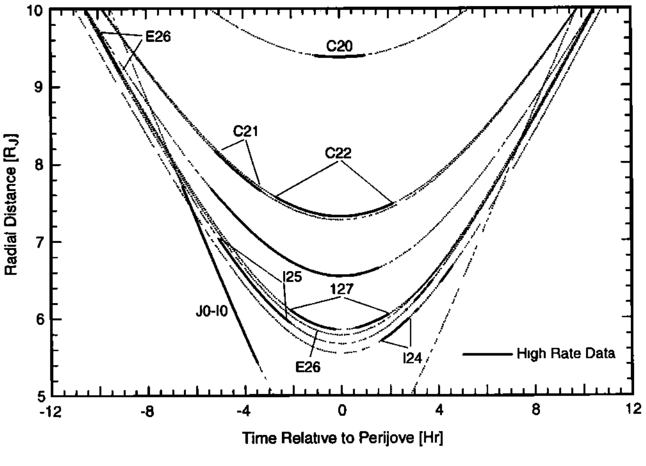

Figure 1. The radial range of high resolution data on passes J0, C20, C21, C22, C23 and I24. Solid lines show the location where the high resolution data were transmitted.

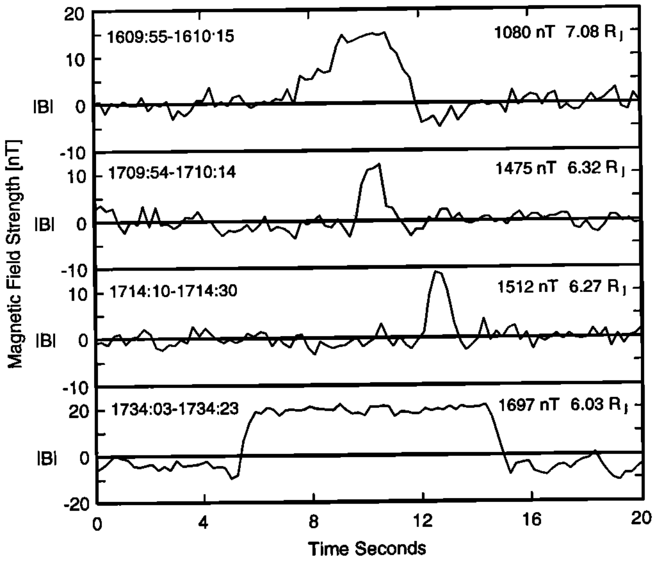

Figure 2. Representative "depleted flux tubes" from the J0 pass. The magnitude of the field is shown with the background field removed. Distance from Jupiter and background magnetic field are given in each panel.

The first evidence for depleted tubes was found on the J0 pass as shown in Figure 2. The bottom event in this figure was discussed in some detail by *Kivelson et al.* [1997] who examined the various evidence for its rapid inward motion without relating this motion explicitly to the substorm-driven magnetic flux cycle. Aspects of this event have also been discussed by *Thorne et al.* [1997] and *Bolton et al.* [1997]. The other events shown are samples of the remaining depleted tubes on this pass. In all, depleted tubes were observed on 0.4% of the J0 pass. In order for these infrequently observed flux tubes to resupply the inner Io torus with magnetic flux, they must be moving inward at a velocity of about 250 to 500 times the outward velocity. We estimate that the outward velocity in this region of the magnetosphere is about 20 m s^{-1} [*Russell et al.,* 2000] so that the average inward velocity of these tubes must be about 5 to 10 km s^{-1}. This average velocity is well below that estimated for the singularly large tube discussed by *Kivelson et al.* [1997] and *Thorne et al.* [1997]. The dimensions implied by these observations should correspond to their transport, not at this radial velocity but at the corotational velocity of about 80 km s^{-1}. Thus the 10 s event contains about 8.5 x 10^5 Wb of magnetic flux and a one-second tube about 1% of this flux.

We have also surveyed the high resolution data available from the C20, C21, C22, C23, I24, I25, E26 and I27 passes for the occurrence of "depleted flux tubes". Data were obtained on these orbits over the radial distances shown in Figure 1. Figure 3 shows the events observed on three of the eight passes. No events were observed on C21, I24, I25 or E26 but there was also little high resolution data acquired on these orbits. Two events were obtained on C20 near 9.4 R_J, outside of the Io torus. The two events seen on C20 are similar in duration to those seen within the torus on J0 but smaller in amplitude. The events on C22 appear to last longer than those seen on other passes, and might be candidates for observing the density within the structure except that the plasma wave signals are weak immediately surrounding this interval. On pass I27 depleted tubes were encountered for 41 s out of the 11580 s pass or 0.35% of the pass. The total observing time on these eight new passes outside of 5.9 R_J was 8.29 x 10^4 s of which 201 were obtained within depleted flux tubes, i.e. about 0.24% of the observing time. This is comparable to but slightly less than the rate seen on J0. Combining these data with those on the J0 pass, 25 depleted flux tubes have been seen beyond 5.9 R_J with a duration of 2305 in 92439 s of high resolution observations for an occurrence rate of 0.25% for these depleted flux tubes.

3. Implications

We can use the field increase to estimate the beta of the plasma surrounding the depleted flux tubes ($\beta=2\Delta B/B_0$) assuming that the tube is completely devoid of plasma. Table 1 shows this calculation for representative depleted flux ropes on the J0, C20, C23 and I27 passes. The betas range from about 1 to 3%. Combining this with the plasma number density estimated from the plasma waves we obtain a perpendicular temperature of the plasma ranging from about 30 to 200 eV. Figure 4 shows these temperatures plotted versus radial distance together with two temperature bounds from the Voyager 1 measurements [*McNutt et al.,* 1981; *Bagenal et al.,* 1985] and Galileo plasma analyzer observations of the O^+ temperature on the J0 pass [*Crary et al.,* 1998]. The first two speculate that the correct temperatures lie near the center of the two Voyager 1 limits. Eight of our 16 values lie within this band, four lie above it and four lie significantly below it. The four above the line all occurred on I27. Three of the four below the line all occurred on the J0 pass. We note that many of the values of O^+ temperature deduced by *Crary et al.* [1998] were also well below the Voyager values.

The last column of Table 1 shows the magnetic latitude. Observations at higher latitudes correspond to higher temperatures than at low latitudes but some of the variation may

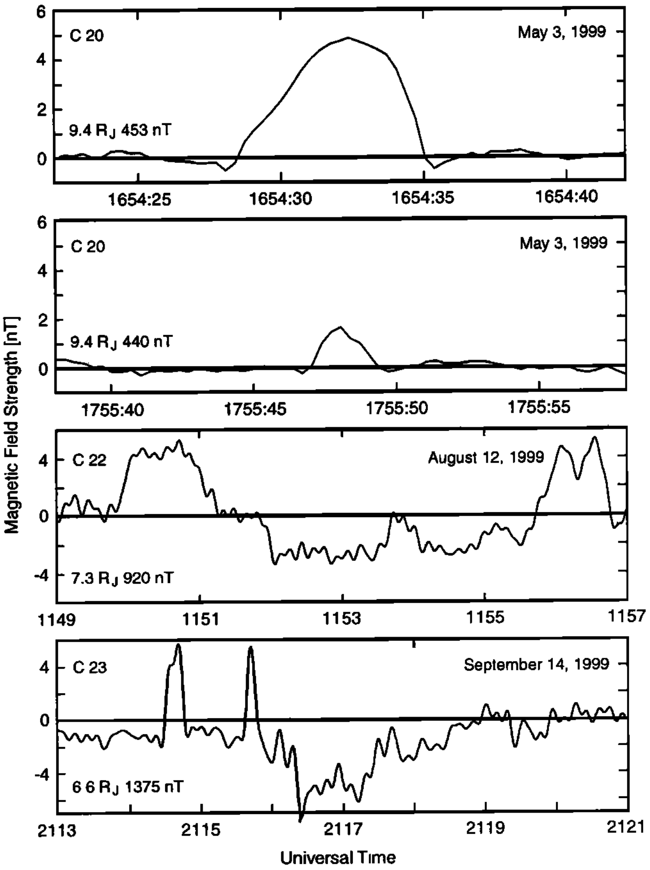

Figure 3. Representative "depleted flux tubes" from the C20, C22 and C23 passes. Distance from Jupiter and background magnetic field are given in each panel.

Table 1. Depleted Flux Tube Properties

Time Date	 UT	B [nT]	ΔB [nT]	ΔE [10^{10}eVm^{-3}]	β	Density [10^8m^{-3}]	$T_\perp$ [eV]	R [R_J]	Mag. Lat.
12/7/95	1734	1695	24.3	20.5	0.029	38	54	6.0	3.2°
	1712	1490	11.0	8.2	0.016	32	27	6.3	4.4°
	1646	1300	9.4	6.1	0.015	23	27	6.6	5.9°
	1631	1200	10.8	6.4	0.018	18	36	6.8	6.2°
	1610	1080	14.4	7.7	0.027	11	68	7.1	6.9°
5/03/99	1756	440	1.8	3.9	0.008	1.1	36	9.4	-1.2°
	1654	453	4.5	1.0	0.020	0.5	203	9.4	-5.9°
8/12/99	1150	920	4.5	2.1	0.010	2.0	110	7.3	-5.1°
9/14/99	2114	1375	13.0	8.9	0.019	11	81	6.6	7.9°
2/22/00	1119	1925	9.5	9.1	0.010	13	68	5.9	-9.8°
	1307	2042	7.0	7.1	0.007	12	61	5.9	-7.0°
	1412	1830	23.0	20.9	0.025	15	137	6.1	-3.9°

also be temporal. Figure 4 shows the value expected for the perpendicular temperature if the plasma conserved its first adiabatic invariant as it convected outward. Some of our cooler values lie closer to this line. However, since the radial transport time through the torus is several months [*Russell et al.*, 2000] collisional cooling with electrons may also be important.

At Io the temperature varies from 50 to 140 eV. There is so much scatter in the data that it is impossible to tell whether there is a radial variation in temperature here. A temperature near 50 eV is consistent with the theoretical estimates of *Barbosa et al.* [1983]. We note that if a flux tube is only partially depleted and we assume it is fully depleted our estimated plasma temperature will be too low. Since most long duration depleted tubes have sharp features and not rounded tops, we do not expect they contain significant plasma but the shorter tubes do show evidence of rounded tops.

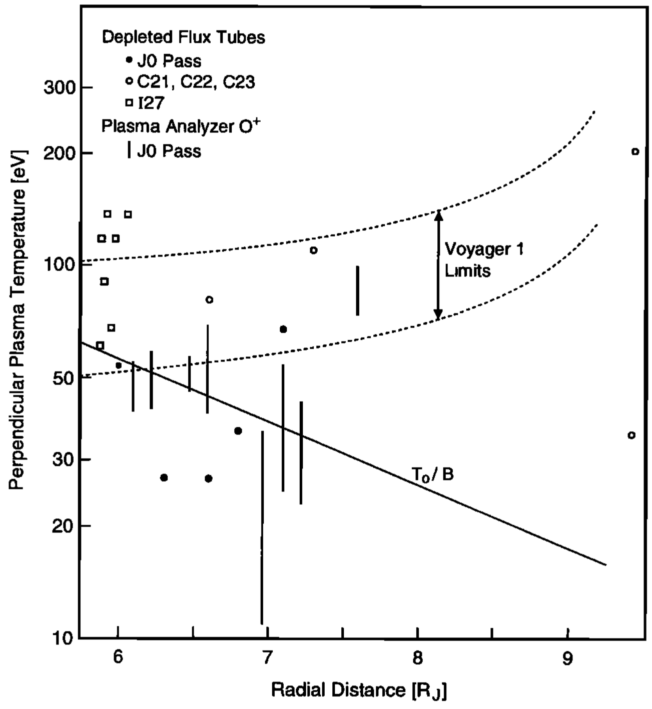

Figure 4. Perpendicular plasma temperature versus radial distance. Upper pair of lines indicate range of total ion temperatures reported by Voyager plasma team. Lower straight line gives expected temperature for adiabatic transport of a ring distribution of pickup plasma. Vertical lines give range of temperatures consistent with O^+ distributions [Crary et al., 1998].

We have chosen to show *Crary et al.'s* [1998] temperature only for O^+. The temperatures of the other (minority) species are colder. Thus the inferred and directly observed temperatures are in even closer agreement than it appears in Figure 4.

4. Discussions and Conclusions

The latest Galileo passes through the Io torus on the C20, C22, C23 and I27 orbits show the same features as on the J0 pass in 1995. These apparent narrow, depleted tubes of magnetic flux which, if they are moving as rapidly as we presume, can replace the mass-loaded flux tubes at Io. This requires a magnetic flux transport rate of about 80,000 Webers per second which is approximately the rate at which flux tubes are both loaded at Io and emptied in the distant magnetosphere.

These tubes are observed throughout the Io torus and there is evidence in low temporal resolution data for their presence in the middle magnetosphere as well [*Russell et al.*, 1999]. If, as we suppose, these flux tubes provide the return magnetic flux from the ion separation process in the jovian tail, then they should not be observed within the orbit of Io. We now have 1.16×10^4 seconds of coverage inside 5.9 R_J, gathered on the J0 and I24 passes. These data show no evidence for any "depleted flux tubes" with field strengths exceeding their neighbors. If depleted flux tubes occurred at the same rate in this region we would have observed them for a period of about 36 seconds. Thus the fact that we had no observations of this phenomenon is statistically significant. We would not expect to see depleted flux tubes in this region if our hypothesis of their origin is correct both because they would not be as buoyant in the lower density cold torus region and because they would not be discernible in the low beta cold torus plasma.

The tubes also tell us about the nature of the torus plasma. If the tubes are completely depleted, then the beta of the surrounding plasma is about 0.02 and the temperature of the plasma is typically 60 eV near Io. The mass addition process at Io produces plasma whose thermal speed is the flow speed in the pickup region. A temperature of 60 eV would result only if most of the plasma is picked up when the flow is less than half the corotational speed at Io. Alternatively a large contribution of pickup protons would be required, but this is not consistent with Voyager measurements [*Bagenal*, 1994] nor with Galileo data [*Frank and Paterson*, 1999]. Thus the 50 eV temperature implies cooling as envisioned by *Barbosa et al.*, [1983]. The inferred temperatures are also quite consistent with the Voyager observations, and the Galileo plasma analyzer temperatures.

The combined observations indicate that the temperature of the torus ions is quite variable from month to month. Since radial transport times are long in the torus, and the plasma circles Jupiter many times as it passes through the torus, we expect these changes to reflect long term changes in the torus rather than local time variations. There is also a hint of an increase of temperature with increasing radius. Finally, the consistency of the inferred ion temperatures with those directly measured provides some assurances that the "depleted flux tubes" are quite empty. This in turn is quite consistent with our model for the massloading, transport and tail reconnection process that has been proposed to power the jovian magnetospheric engine [Russell et al., 2000].

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References

Bagenal, F., Empirical model of the Io plasma torus: Voyager's measurements, *J. Geophys. Res.*, *99*, 11,043-11,062, 1994.

Bagenal, F., R. L. McNutt, Jr., J. W. Belcher, H. S. Bridge and J. D. Sullivan, Revised ion temperatures for Voyager plasma measurements in the Io plasma torus, *J. Geophys. Res.*, *90*, 1985.

Barbosa, D. D., F. V. Coroniti and F. V. Eviatar, Coulomb thermal properties and stability of the Io plasma torus, *Astrophys. Journal*, 274, 429-442, 1983.

Bolton, S. J., R. M. Thorne, D. A. Gurnett, W. S. Kurth and D. J. Williams, Enhanced whistler-mode emissions: signatures of interchange motion in the Io torus, *Geophys. Res. Lett.*, *24*, 1997.

Crary, F. J., F. Bagenal, L. A. Frank and W. R. Paterson, Galileo plasma spectrometer measurements of composition and temperature in the Io plasma torus, *J. Geophys. Res.*, *103*, 29,359-29,370, 1998.

Frank, L. A. and W. R. Paterson, Production of hydrogen ions at Io, *J. Geophys. Res.*, *104*, 10,345-10,354, 1999.

Hill, T. W., A. J. Dessler and C. K. Goertz, Magnetospheric models, in *Physics of the Jovian Magnetosphere*, edited by A. J. Dessler, pp. 353-394, Cambridge Univ. Press, New York, 1983.

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.

McNutt R. L., Jr., J. W. Belcher and H. S. Bridge, Positive ion observations in the middle magnetosphere of Jupiter, *J. Geophys. Res.*, *86*, 1981.

Russell, C. T., M. M. Hoppe and W. A. Livesey, Overshoots in planetary bow shocks, *Nature*, *296*, 45-58, 1982.

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, 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., M. G. Kivelson, K. K. Khurana and D. E. Huddleston, Circulation and dynamics in the jovian magnetosphere, *Adv. Space Res.*, *26*, 1671-1676, 2000.

Scurry, L. and C. T. Russell, Proxy studies of energy transfer in the magnetosphere, *J. Geophys. Res.*, *96*, 9541-9548, 1991.

Thorne, R. M., T. P. Armstrong, S. Stone, D. J. Williams, R. W. McEntire, S. J. Bolton, D. A. Gurnett and M. G. Kivelson, Galileo evidence for rapid interchange transport in the Io torus, *Geophys. Res. Lett.*, *24*, 1997.

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