Statistics of depleted flux tubes in the jovian magnetosphere

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Abstract

On many of its passes through the Io torus the Galileo spacecraft has detected the presence of what appear to be thin magnetic flux tubes with fields somewhat higher than their surroundings. On these flux tubes the magnetic pressure is sufficiently above the pressure of neighboring tubes that it is possible the plasma contributions to the pressure within these tubes are depleted. Due to their short duration, they are only detectable in high time-resolution magnetometer data. Herein we survey all high time-resolution data that are available over the full Galileo mission and present a final statistical study. These tubes occupy 0.32% of the torus outside the orbit of Io. None are found inside. Their strength indicates that the ratio of the thermal pressure to magnetic pressure in the outer torus is about 2%. Comparison of the observed electron density in the neighborhood of these tubes indicates that the ion temperature is in the range 30–100 eV, consistent with other estimates. The amount of magnetic flux transported by these thin tubes could supply the amount of magnetic flux mass-loaded and transported to the magnetotail if the inward velocity is about 300 times that of the outward transport. Finally, the thin flux tubes are found in clusters, as they would occur if they resulted from the breakup of larger flux tubes.

1. Introduction

The exploration of the jovian system by the Galileo spacecraft has been one of both excitement and challenge. Many new and unexpected phenomena have been discovered and a much longer time has been spent in orbit than ever envisioned by mission planners. At the same time Galileo has been communications challenged. Its high-gain antenna failed to deploy. While some instruments, at least in portions of the orbit, could take useful data at a very low rate, commensurate with the bandwidth of the communication system (about 20 bits per second), many instruments could only acquire their prime data by operating at a high data rate, storing the measurements to tape and transmitting the contents of the tape recorder slowly.

The Galileo magnetometer can provide data at the very lowest rates, with measurements averaged over periods as long as hours, up to much higher rates of several samples per second (upper limit dependent on mission phase). The low-sample-rate data have allowed coverage of the dynamics of the entire magnetosphere, while the high-rate data have enabled microscale processes such as ion-cyclotron waves to be probed. One of the phenomena, observable only in high-rate data in the Io torus, is the occurrence of what appear to be thin flux tubes of slightly elevated magnetic field strength (Kivelson et al., 1997). The magnetic field strength profile often has a flat top with sharp edges. The difference in magnetic field strength is equivalent to a transverse pressure difference equivalent to the plasma pressure expected in this portion of the jovian magnetosphere, leading to the conclusion that these flux tubes are depleted in their thermal plasma. We know of no mechanism in the jovian magnetosphere that could generate propagating waves of this nature. Thus, it is most reasonable to assume that these features are convecting, time-stationary flux tubes.

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The initial paper discussing these events (Kivelson et al., 1997) did not distinguish the isolated elevated flux tubes from those occurring at the outer edge of the warm plasma torus at about 7.6R$_I$. The outer edge of the torus appears to be marked by an enhancement of plasma beta and a reduced field strength (see Kivelson et al. (1997, Fig. 3) and Russell (2001, Fig. 21). The flux tubes here transition with increasing radial distance from being mainly enhanced with a few dropouts to being mainly depressed with a few enhancements. This is the classic signature of crossing a boundary and that boundary appeared, as the paper correctly noted, to be undergoing the interchange instability. There is also strong plasma heating in this region (Frank and Patterson, 1999). The other phenomenon, which we have referred to as depleted flux tubes, occurs in a quieter environment and does not appear to be connected with a boundary. In contrast to the boundary flux tubes that are almost too numerous to identify separately, the depleted flux tubes are relatively rare. It is this relatively rare phenomenon usually found deep in the Io torus that we study herein.

Intermittent interchange of flux tubes had been expected in the Io torus as the means by which the mass added to the magnetosphere at Io in the form of heavy ions could be transported outward and a "steady-state" mass profile of the magnetosphere maintained (Pontius et al., 1986; Southwood and Kivelson, 1987). Thorne et al. (1997), following this model, used arguments based on the associated signature of these structures in energetic particle data to estimate that they moved inward at about 100 km/s. A different way of estimating their velocity is magnetic flux conservation. If they are carrying magnetic flux inward to replace that being transported outward with the plasma, then their observed occurrence rate allows a velocity estimate to be calculated. Previous reports on these depleted flux tubes (Russell et al., 2000b, 2001a) and the statistics reported below place this occurrence rate near 0.3%.

Thus, these tubes must be flowing inward on average about 300 times faster than the bulk of the Io torus is moving outward. This outward motion in the hot Io torus outside the orbit of Io is expected to be tens of meters per second (Russell, 2001), based on the observed density profile (Bagenal, 1994) and the canonical 1000 kg s$^{-1}$ added at Io (Hill et al., 1983). According to this calculation the average inward velocity of these structures is only a few km s$^{-1}$, less than that estimated by Thorne et al. (1997). Nevertheless, since these structures should be corotating with Jupiter at a speed of nearly 100 km s$^{-1}$ their durations will be governed by this 100 km s$^{-1}$ speed. We may then convert their temporal profiles into sizes from about 100 to 1000 km in diameter.

Since these flux tubes have the potential for closing the cycle of magnetic flux transport in the jovic magnetosphere, they can play an important role in the dynamics of the jovian (Russell et al., 2000a) after magnetosphere. Thus, it is important to understand them as thoroughly as possible. At this writing Galileo has transmitted to Earth the last of the high-resolution magnetometer data, including data from passes I32 and A34 that provided significant amounts of data inside the orbit of Io. It is the purpose of this paper to examine the statistics of the occurrence of these flux tubes over the entire mission and update our preliminary reports published earlier (Russell et al., 2000b, 2001a).

2. A model for depleted flux tubes

The signature that we use to identify depleted flux tubes is a significant rise in the total field strength over the background noise lasting at least one-half second. This latter constraint is imposed by the sample rate of the magnetometer that was 4.5 Hz early in the mission when using the tape recorder and 3 Hz later in the mission at maximum. Most of the magnetosphere is covered with sample rates ranging from about 0.05 Hz to 0.001 Hz. These low-rate data are useful for many purposes, but since the phenomena we identify as depleted flux tubes only seldom endure as long as 40 s in the high-rate data, the low-rate data do not provide a reliable means of sampling them. Thus we use exclusively the high-rate data with a sample rate from 3 to 4.5 Hz. Fig. 1 shows four sample events, all obtained in the Io torus. The topmost example was obtained close to the orbit of Io where the torus transitions from being hot (on the outside) to cold (inside Io). Since our

![Fig. 1. Examples of depleted flux tubes on 2/22/00 (top 2 traces) and 12/7/95 identified in earlier papers (Russell et al., 2000b, 2001a).](image-url)
interpretation for the contrast between the magnetic pressure inside and outside these tubes is a difference in the plasma pressure inside and out, we would expect the contrast inside and out of the tubes to disappear in the cold torus. Below we show the statistics that support this interpretation.

Since we know of no wave phenomena that can explain the phenomenon, we assume these structures are in pressure balance. If so, they must be depleted flux tubes and must be structure convected with the corotational flow. These magnetic flux tubes last generally 1–10 s as illustrated in Fig. 1 but a few are somewhat longer than this. Thus, in general they are generally 1–10 s as illustrated in Fig. 1 but a few are corotational flow. These magnetic flux tubes last about 100–1000 km across compared to their length of somewhat longer than this. They are truly thin tubes. For a thin tube to maintain its “excess” in magnetic energy density, this excess must be similar to the energy density of the plasma in the ambient Io torus. We assume that these structures are nearly devoid of thermal plasma. We expect them to be populated with energetic particles that could drift into their interiors. However, the amount of filling will be energy dependent.

In order to motivate the statistics we present below and the properties we examine, it is important to sketch the physical picture we have in mind. Fig. 2 illustrates the expected pressure balance in the case where the “depleted” flux tube is completely empty of plasma. The magnitude of the field inside the tube, $B_a$, exceeds the magnetic field in the surrounding plasma, $B_\infty$. If the transverse pressure of the thermal plasma is much less than that of the surrounding magnetic field, then the ratio of the thermal to magnetic pressure, beta, is 2

$$\Delta B/B. \text{ If we independently know the plasma density, we can estimate the temperature of the thermal plasma from the pressure deficit, assuming that energetic particles, because of drift, will be the same inside and outside of the flux tube. Since the Io torus is produced by ion pickup (see, for example, Hill et al., 1983; Vasyliunas, 1983), the plasma pressure should be dominated by heavy ions because all species receive the same velocity boost. Thus, in the Io torus we expect electrons to be cold and protons to be much cooler than the heavy ions of oxygen and sulfur.}

The lower panel of Fig. 2 shows a depleted flux tube at two times during its assumed inward motion. In the Io torus region where depleted flux tubes are seen, the magnetic field strength varies with planetocentric radius, $R$, much as a dipole field varies. Thus as a tube convects inward we expect it to vary in cross section as $R^2$. The radius of the tube will then vary as $R^{1.5}$ if the tube is circular. A circular cross section could be maintained by a small amount of twist in the flux tube. The corotation velocity varies as $R$ so that the duration of a crossing should vary as $R^{0.5}$. Given the variability of the duration of individual crossings, this expected slow change with radial distance will be hard to determine.

In this model the force that drives depleted flux tubes inward against the average outward flow of the torus plasma is buoyancy. Just as a bubble rises quickly in a can of leaking fluid, the buoyant flux tube accelerates to the appropriate velocity for its size and the mass difference. A probable ultimate source for these depleted flux tubes is magnetic reconnection in the post midnight sector of the near tail (Russell et al., 1998). While reconnection appears to begin in the plasma sheet, it soon reaches near-vacuum conditions above and below the plasma sheet where it can reconnect rapidly, cutting off magnetized plasma islands that can be released down the tail once reconnection reaches open field lines that have only one foot connected to Jupiter. Then the inner, emptied portion of the flux tube is buoyant and can convect inward. As we discuss below, the rate of transport of magnetic flux from the reconnection region is consistent with the amount of flux tube loading and transport near Io and the rate of reconnection in the near tail. However, the depleted flux tubes are narrow and not the broad structures expected to be created by reconnection. Thus, there would have to be some disintegration of the larger structure into thin fibers as the magnetic flux moves inward if this model were to be correct. We now examine the properties of these flux tubes to see if they are consistent with this model.

3. Occurrence

As noted above, the depleted flux tubes generally become detectable in the Galileo magnetic measure-
ments only when the sample rate is greater than about 1 vector per second. Fig. 3 shows where all despun high-resolution Galileo data were acquired. One previously unexamined segment from 2324 UT on December 7, 1995 to 0126 UT on December 8 was used in these statistics. The data could not be despun but they could be used to identify depleted flux tubes. All local times have now been sampled and significant data are now available inside the orbit of Io. Fig. 4 shows examples of depleted flux tubes observed on orbit I32. Examples on earlier passes can be found in papers by Russell et al. (2000b, 2001a).

Table 1 shows the high-resolution coverage of each of Galileo’s passes through the jovian magnetosphere divided into two radial ranges, outside and inside Io’s orbit. In over 18,000 s no depleted flux tubes were detected inside Io’s orbit. Outside Io’s orbit 29 events were seen in slightly over 112,000 s. A total of 358 s were spent inside depleted flux tubes or 0.32% of the time while Galileo was outside Io’s orbit. Under our hypothesis that these flux tubes replace the outward moving mass-loaded flux tubes, the average inward velocity of the depleted flux tubes must be about 300 times that of the outward moving tubes.

While on some passes no depleted flux tubes were found, on no pass was there only a single flux tube encountered. They were always seen in groups of two or more. Examples of these are the events seen of the first pass by Io and illustrated in Fig. 2 of Russell et al. (2000b) and on passes C22 and C23 shown in Fig. 3 of that same paper. The passes in which no events were found (C21, I24, I25, E26, I31, A34) were shorter than 2 h. On some of the longer passes multiple events were observed separated by over 2 h. Such separations are reminiscent of the repetition times of jovian substorms and it is possible that large regions of recently closed flux tubes break up into smaller tubes in transport. The lack of detected depleted flux tubes inside Io’s orbit may have two causes. The tubes may stop moving inward because their buoyancy disappears or they may no longer be detectable. We discuss this again below once we have examined the properties of individual ropes.

4. Flux tubes and surrounding plasma

The properties of sample-depleted flux tubes are given in Table 2 including the ambient magnetic field strength, the change in field strength, the corresponding change in magnetic energy density, the implied beta or ratio of thermal to magnetic pressure, the density of electrons in neighboring flux tubes detected by the plasma wave detector (Gurnett et al., 1992), the inferred ion temperature, and the planetocentric distance and magnetic latitude. The ion temperatures are obtained by dividing the electron density by the inferred plasma pressure, assuming that the ions are all singly ionized. Since the depleted flux tubes frequently have sharp edges, we assume that they have been able to exclude the thermal plasma quite well. The derived ion temperatures run from 27 to 203 eV.

The beta of the surrounding plasma varies from 0.007 to 0.029. The events with the highest beta are close to, but outside of, Io’s orbit. The low beta events tend to occur just inside Io’s orbit. We would not expect to be able to detect depleted flux tubes much inside Io’s orbit because the plasma is colder there and the contrast in plasma pressure inside and outside a flux tube would disappear. We note that though the density of the inner (cold) torus is lower than that of the outer (hot) torus, it
is not negligible. Thus a depleted flux tube could move well inside Io and displace denser cold torus flux tubes outward. This outward displacement of the inner torus would maintain a steady state in the same way the outer torus moves outward to balance its mass flux. Since fast neutrals produce the coldest ions at the inner edge of the cold torus where they move closest to corotational velocity, this outward displacement would result in an apparent cooling at any fixed radial distance. However, since depleted flux tubes have no magnetic signature in the cold torus we cannot measure this effect with our technique.

5. Discussion and conclusions

If an $S^+$ ion were picked up at 100 km/s, the fastest velocities seen at Io, then the perpendicular velocity would be equivalent to the thermal velocity of a 1670 eV ion. Since the maximum temperature we see is about 200 eV, the average mass must be less and/or the source region of the fast neutrals must be low in the Io exosphere where the flow velocity of the Io torus is expected to be much reduced. For example, a mass of 16 amu and a velocity of 50 km/s could produce the maximum observed energy of 200 eV. To get the median
The inferred temperature as a function of radial distance is plotted in Fig. 7 of Russell et al. (2000b) and compared with direct measurements by Galileo and Voyager. The temperatures fall in the range reported by Voyager, but there is much variation and the temperatures are much less than expected for heavy ion pickup. Furthermore, they agree with the Galileo plasma analyzer ion temperatures reported by Crary et al. (1998). One possible answer for the orbit-to-orbit changes is a variable source of light ions (protons) in the pickup. Another possibility is a variable velocity of the plasma in the altitude range where the mass loading first occurs and fast neutrals are produced. This region could be low in the exosphere where charge exchange can occur readily (Russell et al., 2001b).

The torus plasma is produced by Io and stays mainly in the range of magnetic latitudes that Io occupies as Jupiter spins. It cannot move along field lines because it is cold and centrifugal forces dominate (Hill et al., 1983; Vasyliunas, 1983; Meyer-Vernet et al., 1995; Meyer-Vernet, 2001). Meyer-Vernet et al. (1995) showed that density and temperature should be connected by an approximate polytropic law. This law implies that if density decreases with latitude (as we expect intuitively) beta should too. More recently, Moncuquet et al. (2002) have presented a comprehensive model of the latitudinal and radius structure of the Io torus with a plot (their Fig. 3) of the latitudinal variation of the density in the torus. Using the approximate polytropic law of Meyer-Vernet et al. (1995), we can use this latitudinal variation to predict that of beta. Beta should vary roughly as the square root of the density. Fig. 5 shows the $\beta$ values of Table 2 plotted versus latitude together with the function $0.3 \cos(9\lambda)$ where $\lambda$ is the magnetic latitude in degrees. Since Galileo data were obtained close to the rotational equator and the centrifugal equator is two-thirds of the way between the rotational equator and the magnetic equator, a centrifugal latitude scale may be drawn approximately by taking two-thirds of the latitude shown. We do not include points obtained beyond $8.5R_J$ because of the distinct probability that these were obtained beyond the outer edge of the Io torus. According to the calculations of Moncuquet et al. (2002), we would expect a drop in density of about 2–3 at $7^\circ$ off the centrifugal equator. The observations are too scattered for a definitive test but certainly are qualitatively consistent with this model.

In summary, the thin tubes of elevated magnetic flux observed by Galileo in the region of the hot outer Io torus appear to be depleted of thermal plasma. As such they should be buoyant and return flux to the inner magnetosphere, maintaining the magnetic flux that would otherwise be removed by the flux tube “interchange” process that takes plasma-laden flux tubes to the outer magnetosphere where ions can be lost from the magnetosphere via reconnection. While these tubes cannot be observed in the cold inner torus inside the orbit of Io, these tubes should be buoyant there as well so that the inner torus must be slowly convecting outward as well as the outer torus. While the beta in the inner torus is close to zero and undetectable by our technique, outside Io it is close to 0.02. This value varies with latitude approaching zero at $10^\circ$ latitude, north and south. This value is consistent with direct measurement of ion temperatures by Voyager and Galileo. These thin flux tubes are seen in clusters suggesting that they have evolved from the breakup of larger structures. Their occurrence rate of 0.32% indicates they would have to move 300 times faster than the outward moving plasma to resupply the mass-loading region with magnetic flux. This radial velocity need only be of the order of 10 km/s in the torus. This magnetic flux transport rate is also similar to the estimated reconnection rate in the near tail. Thus these structures, while small, may play a critical role in the dynamics of the jovian magnetosphere by completing the transport of magnetic flux to the mass-loading region.

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