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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 $7.6R_J$. 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 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 $1000\,\mathrm{kg\,s^{-1}}$ added at Io (Hill et al., 1983). According to this calculation the average inward velocity of these structures is only a few $\mathrm{km\,s^{-1}}$, less than that estimated by Thorne et al. (1997). Nevertheless, since these structures should be corotating with Jupiter at a speed of nearly $100\,\mathrm{km\,s^{-1}}$ their durations will be governed by this $100\,\mathrm{km\,s^{-1}}$ 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 jovian 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

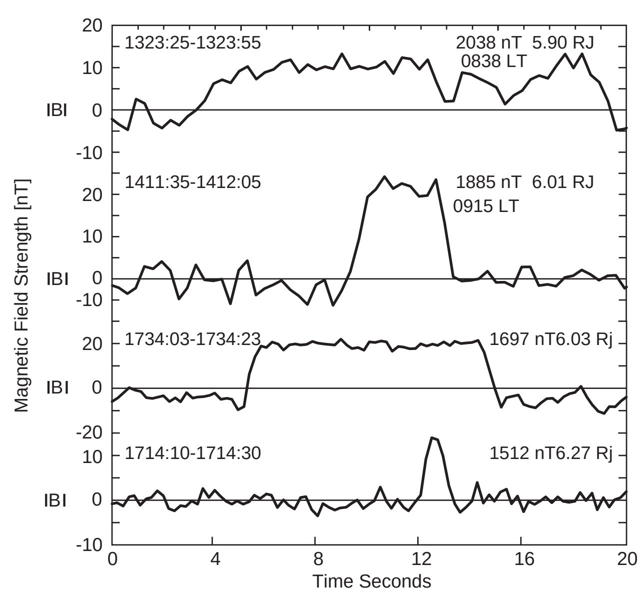

Fig. 1. Examples of depleted flux tubes on 2/22/00 (top 2 traces) and 12/7/95 identified in earlier papers (Russell et al., 2000b, 2001a).