Plasma Wave Signatures of Density-Depleted Flux Tubes in Saturn's Inner Magnetosphere

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1. Overview

Upper hybrid resonances observed with Cassini’s Radio and Plasma Wave Science (RPWS) instrument have been used to detect density depletion in Saturn’s magnetosphere in 2004 (Person et al., 2005). These bands occasionally show a sharp, abrupt decrease in frequency indicative of localized depletions in the electron density. The intensity of the upper hybrid band drop appears well below the amplitude levels of the background emissions outside the depletion event. These amplitude variations have been correlated with plasma density depletions (Andre et al., 2005). Examples of upper hybrid amplitude drop-outs within this range of plasma density depletions from the RPWS sounder and the Electron Spectrometer of the Cassini Plasma Spectrometer (CAPS) are shown in Figure 1. The distribution of 424 amplitude drop-outs for eighteen equatorial crossings (11 Rj) is shown as a function of radial distance and longitude, x, y, and z, along the longitude coordinate have been derived from the model of Kurth et al. (2006). The distribution of the events with radial distance shows that the amplitude drop-outs occur with decreasing electron density (Rj) with the most significant occurrence between 7 Rj and 9 Rj. The amplitude drop-outs tend to cluster between 8 Rj and 9 Rj, for 45° < J < 220° but the greatest concentration of drop-out events shifts to higher radial distances, occurring between 7 Rj and 9 Rj, for > J < 45° and < J < 220°.

2. Plasma Waves Signatures of Density-Depleted Flux Tubes

Between January 19, 2005 and July 3, 2006, Cassini passed through the innermost region of Saturn’s equatorial plane. The RPWS instrument operated near continuous measurements of the upper hybrid resonance emissions within 11 Rj for most of these passes. This electric field spectrometer shows a nearly continuous upper hybrid resonance emission band for the equatorial pass on November 27, 2005. The upper hybrid resonance frequency, f_{rh}, the smooth emission band has been determined by Andre et al. (2006). The amplitude drop-out in the upper hybrid resonance emission band in the RPWS instrument is shown in Figure 1. In this figure, the RPWS observed amplitude drop-outs in flux tubes with hot, dense plasma moving outward along the flux tube, the plasma frequencies of the electron and ion, and a measured density drop-out in the upper hybrid resonance frequency (bottom panel) indicate that a 70% drop in the electron density for the fourth event and very modest density depletions of 40% or less for the other three events. This example is especially interesting because evidence of density-depleted flux tubes is inferred inside 9 Rj.

The detection of faint, upper hybrid emission bands inside the flux tubes in Figure 1 shows that the events occur during the times of upper hybrid resonance decay or if the event is a number of plasma waves with high density and wave enhancements. One example of an electrostatic plasma wave instability is the higher order cyclotron harmonics. These waves are generated by the large scale anisotropy in the electron distribution at the boundaries of the flux tube. On March 8, 2006 (Figure 2) there is a cluster of flux closely spaced flux tube bands, detected by the RPWS instrument (panel 1). The boundaries of the flux tube events are detected by dashed vertical lines and the events are labelled across the top of the three panels and across the bottom of the lower two panels. Again the CAPS LSS data confirms the classical plasma signs of the interacting flux tube: the variable ion-electron composition, the electron population and the appearance of a high-energy population inside the flux tube (panel 2), with a corresponding fall in the ion energy (panel 3). A drop in the electron density of nearly an order of magnitude for each event (panel 4) is also consistent with the presence of a higher order cyclotron harmonic (panel 3). Strongly confined within the boundaries of the flux tube is another evidence of the high density depletions detected by the ion population in the upper arc. Similar electron cyclotron harmonics are also seen inside the density depleted intervals, defined by the vertical arrows in the top panel of Figure 1.

Figure 2

Another plasma wave event often observed in the interacting flux tubes is the radio emissions at the electron plasma frequency, f_p. Electromagnetic radiation at electron plasma frequency occurs at the plasma density gradient at the edges of the flux tube, resulting in the f_p radio emission at 6 kHz for the Cassini pass depicted in Figure 1 on November 27, 2005 in 4 figure. The f_p radio emission is also seen in the boundaries of the flux tube in 4. A weaker radio emission at twice the electron plasma frequency, 2f_p, is seen both inside and outside the flux tube in Figure 2 at 110 kHz with enhanced emissions inside the flux tube. Similar but much smaller emissions can be seen inside the flux tube in Figure 2.

Intense electromagnetic chorus events are also observed just below 2 kHz at the electron cyclotron frequency. These intense electromagnetic emissions, propagating in the whistler mode, are enhanced inside the flux tube by the temperature anisotropy of the plasma.

The flux tube event in Figure 4 is another of the intense convecting flux tube events found deep in Saturn's magnetosphere. The event observed on May 10, 2006, is typically strong, smooth, and continuous outside the flux tube on both sides. The bottom panel is an electron density profile derived from the upper hybrid resonance frequency (Person et al., 2005) at the boundaries of the flux tube. There is a small, but definite density increase at the boundary of a flux tube, with a modest decrease in density at the trailing wake of the convecting flux tube. Both of these density perturbations can be attributed to the motion of the reconnected flux tube, which is convecting inward toward the planet (to the left) and pushing into the cold and dense surrounding plasma of the inner magnetosphere.

4. The Diminishing Width of Conveacting Flux Tubes

Most of the events detected in the f_p data, like the one seen in Figure 1, are convecting having widths of less than 1000 km. Only a few of the larger events have widths that exceed 300 km. In Figure 4, the widths of the amplitude drop-out events are plotted as a function of the radial distance from Saturn. The majority of the 424 drop-out events identified in the f_p data, with widths less than 1200 km are found uniformly distributed over the range (CAPS LSS). However, there are a few events with widths greater than 2400 km are found beyond 7 Rj and tend to increase in size with increasing radial distance. This would appear to support the conclusion of Bark and others (2001), who postulated that an interacting flux tube would be strongly convected out of the flux tube, which is convecting radially inward toward Saturn.

5. The Longitudinal Dependence of Convection Flux Tubes

We have identified 424 f_p amplitude drop-outs in the RPWS equatorial data that are associated with interacting flux tubes. This plot represents the distribution of these events as a function of radial distance and longitude. The longitude values are derived from the Saturnian longitude model introduced by Kurth et al. (2006), which is based on the modulon in the radio signal of Saturnian kilometric radiation (SKR). The distribution shows the expected fall off in the density-depleted flux tubes inside 9 Rj, consistent with the occurrence of demagnetization of ions associated with the interacting flux tubes (Bark et al., 2001). There is a longitudinal effect in the distribution of the f_p amplitude drop-outs detected at the Saturnian equator is consistent by Hill et al. (2005) in their study of injection events from Cassini’s first non-equatorial orbit. In this study, there is a phased increase in density-depleted flux tubes between 6 Rj and 8 Rj. But for > J < 45° and < J < 220°, the distribution shifts to higher radial distances, clustering between 8 Rj and 9 Rj. The longitudinal effect is consistent with the long dependence of Saturn's kilometric radiation (Kurth et al., 2006) and the longitudinal dependence of the plasma and magnetic field in Saturn’s inner plasma disk (Nygard et al., 2006).

References


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