OBSERVATIONS OF THE EARTH'S CROSS-TAIL CURRENT SHEET AND THEIR IMPLICATIONS

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Abstract

Observations of the neutral sheet in the Earth's magnetotail are presented to show different magnetic signatures of the neutral sheet which have been used to infer (1) wave profiles on the neutral sheet surface, (2) magnetic islands embedded in the neutral sheet, and (3) localized turbulent magnetic field regions. The occurrence of these features even at magnetospheric quiet conditions suggests that the above features are intrinsic to the current sheet and may possibly play a role in its stability. There are indications that these features are common to other current sheets in space.

Introduction

One of the most extensively surveyed current sheets in space is in the Earth's magnetotail where the cross-tail current flows in the plasma sheet between the northern and southern tail lobes. The cross-tail current is believed to be driven by the solar wind dynamo action at the magnetopause and a portion of the current is transmitted to the ionosphere via magnetic-field-aligned currents. The cross-tail current extends from a downstream distance of about 10 R_E (R_E = earth radius) to possibly more than 1000 R_E. The typical energies of thermal ions and electrons in this current (plasma) sheet are 5 keV and 1 keV, respectively. The number densities range from <0.1 to ~ 1 cm^{-3}, with plasma beta (ratio of particle pressure over magnetic pressure) varying from ~ 0.1 to >1. The current densities are about 3×10^5 A/R_E near the earth and decrease exponentially with an e-folding distance of about 60 R_E. A significant portion of the current is conducted in the neutral sheet region at the center of the current sheet.

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Observed Neutral Sheet Signatures

The neutral sheet is recognized as the region in which the magnetic field orientation reverses from pointing sunward to tailward or vice versa. The field reversal is often accompanied by a decrease in field magnitude and an increase in the field elevation angle (northward field). There are various departures from this type of classical signature of the neutral sheet. Observed deviations are the following: (1) the field elevation angle may decrease in a rather stepwise fashion at the neutral sheet crossing; (2) the dawn-dusk field component at successive neutral sheet crossings may be alternately duskward and dawnward; (3) the field component normal to the neutral sheet may become southward occasionally at multiple neutral sheet crossings; (4) the field magnitude may be minimum at the start of the neutral sheet transition rather than in the middle; and (5) all field components may show large, rapid fluctuations and the dawn-dusk component may become the largest field component occasionally.

Inferred Features of the Current Sheet

The observed magnetic field signatures of the neutral sheet have been used to infer the structure of the current sheet. For example, the observed feature (1) in the previous section has been used to infer a wave profile of the neutral sheet surface mainly along the tail axis (Speiser, 1973). Indeed, such observed field variations are reproduced very well by the one-dimension equilibrium current sheet solution (Harris, 1962) modified to allow for such a wave profile. In the solar magnetospheric coordinate system, the magnetic vector potential appropriate for this case may be written as (Lui, 1983)

$$A_y = -B_o L \ln\left[\cosh\left(\frac{Z - A \sin kX}{L}\right)\right] + B_n X \qquad (1)$$

where B_o is the field magnitude outside the current sheet, L is the current sheet thickness, B_n is the field component normal to the sheet, A is the amplitude of the wave and k is the wave-number. The waves have periods of a few to about 10 minutes (Pc5 micropulsations). Similar wave modulations are detected at the plasma sheet boundary (Spjeldvik and Fritz, 1981) and may be related to hydromagnetic oscillations of the magnetotail (McKenzie, 1970). The signature in feature (2) is indicative also of a wave surface of the neutral sheet in the dawn-dusk direction (Lui et al., 1978). Feature (3) suggests the presence of magnetic islands embedded in the neutral sheet (Schindler and Ness, 1972). The magnetic vector potential which can be used to describe this field geometry is (Kan, 1979)

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$$A_y = -B_oL \ln \left[\frac{\alpha^2 + 1}{2\alpha^2} \cosh \left(\alpha \frac{Z}{L}\right) + \frac{\alpha^2 - 1}{2\alpha^2} \cos \left(\alpha \frac{X}{L}\right)\right] \quad (2)$$

where the parameter α is related to the locations along the X-axis of the X-type neutral lines (at $X = 2n\pi L/\alpha$, n = integer) and O-type neutral lines (at $X = 2(n+1)\pi L/\alpha$) in the island structure. Features (4) and (5) are suggestive of turbulent field structures (Hruska and Hruskova, 1970; Lui, 1983). These features, which are summarized in Figure 1, are apparently not unique to the earth's cross-tail current since similar features are also found in the current sheets in the solar wind (Smith et al., 1977) and in the Jovian magnetotail (Behannon, 1983).

Dependence on Substorm Activity

Although the different types of neutral sheet signatures which deviate from the classical neutral sheet signature tend to occur more frequently with increasing substorm activity, it is important to note that all these features have been observed even during magnetospheric quiet conditions when no substorm activity is indicated by the AE

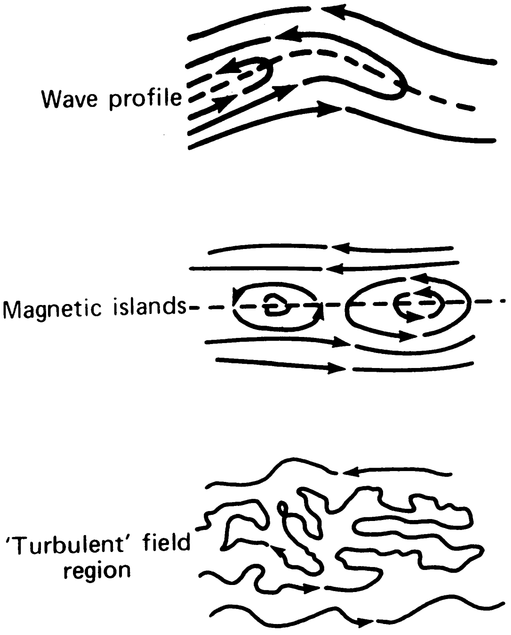

FIGURE 1. A sketch of three basic features in the earth's cross-tail current sheet.

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index and global auroral images (see e.g. Lui and Meng, 1979). This result suggests that the structures sketched in Figure 1 are intrinsic features of the current sheet rather than uniquely tied with substorm occurrence, which is consistent with recent theoretical work (Kan, 1979; Zwingmann and Schindler, 1980) that equilibrium tail configuration can be obtained with magnetic island structures embedded within.

Conclusion

Observations indicate that the cross-tail current sheet contains several intrinsic features such as wave profiles, magnetic islands and localized turbulent regions. The fact that similar features are found in the current sheets in the solar wind and in the Jovian magnetotail suggests these features to be common for current sheets in space. The role these features play in the stability of a current sheet is yet to be determined.

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DISCUSSION

Birn: I have two comments: a. The smooth current sheet equilibrium solutions are just a subset of possible solutions. Most of the solutions indeed show wavyness and even island structure. b. Most of the current sheet crossing are due to the motion of the plasma sheet across the satellite and are therefore connected with some kind of dynamic state of the plasma sheet which would explain, at least in part, why the current sheet is seldom found to be "quiescent".

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Lui: a) I do not disagree with your statement. One of the points in my presentation is that the initial state of the current sheet is far from smooth and investigation of the current sheet stability for initial states with these structures seems appropriate. b) Plasma sheet motion does not imply the current sheet to be in some kind of dynamic state, e.g. motion induced by the diurnal wobbling of the magnetic dipole axis. Furthermore, the word "quiescent" is in reference to substorm activity and is used to describe the initial state of the current sheet before the dynamic evolution later as a substorm develops.

Vasyliunas: You cannot really distinguish between waves in the current sheet surface and tilts of the whole surface (which are in effect waves of infinite wavelength).

Lui: The interpretation of tilt instead of wave is a possibility, but is a very unlikely one for the following reason. The tilt required to account for some of the observations is more than 30°. If the tail axis is tilted by such an extent, it would mean that the tail deviates substantially from the solar wind flow direction. Since the tail extends at least 100 R_e and possibly > 1000 R_e, this tilt may make the tail present as much an obstacle to the solar wind as the dayside magnetosphere. Furthermore, plasma sheet boundary waves of similar wavelength have been observed by the ISEE satellites.