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FLUX TRANSFER EVENTS: SCALE SIZE AND INTERIOR STRUCTURE

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Abstract. We report the first direct investigation of the spatial properties of flux transfer events (FTEs) at the Earth's dayside magnetopause. Simultaneous magnetometer and plasma data from the ISEE 1 and 2 satellites are combined to show that magnetosheath FTEs can have a scale size of order an Earth radius in the magnetopause normal direction. We confirm that the magnetic field within the events appears to be twisted, this twisting corresponding to a core field-aligned current of magnitude a few x 10^5 A. We also show evidence for plasma vorticity in FTEs. The transverse flow and field perturbations accompanying the three events studied obey approximately the Walén relation for a propagating Alfvén wave.

Introduction

Haerendel et al. (1978), using HEOS 2 magnetometer and plasma data from the dayside magnetospheric boundary layer, suggested that magnetic field reconnection at the Earth's magnetopause might occur in a transient and localised manner. However, it was not until the high resolution ISEE measurements became available that convincing evidence for such a process was recognised in the form of signals in the magnetosheath called flux transfer events (FTEs) (Russell and Elphic, 1978). To date, interpretation and data analysis have supported Russell and Elphic's (1978) suggestion that FTEs result from reconnection occurring on short space and time scales (e.g. see the recent reviews by Cowley (1982) and Saunders (1983)).

Despite the interest which flux transfer events have attracted, the dual-satellite capabilities of ISEE have not yet been exploited to determine directly either their scale size or their internal structure. In previous dual-satellite FTE work (Russell and Elphic, 1978, 1979; Elphic and Russell, 1979), based on magnetometer recordings from the first months of the ISEE mission in 1977, similar signals were seen at both satellites in the periods of data analysed, indicating that the FTE scale size exceeded the prevailing satellite separations of $\gtrsim$ 1000 km. To investigate the spatial structure of an FTE open tube, it is necessary to examine ISEE 1 and 2 data for events recorded between September 1978 and January 1979, and during October and November 1979, when satellite separations at the dayside magnetopause were at their maximum for the mission. Separations during these intervals were directed mainly normal to the boundary and varied from $\sim$ 1000 km to $\sim$ 20000 km, though due to the telemetry problem of tracking both satellites at large separation there were few instances of simultaneous data for separations above $\sim$ 7000 km.

In this report we combine magnetometer and plasma data from both satellites in order to study a series of magnetosheath FTEs recorded when the satellites were separated normal to the boundary by about 5500 km. The magnetic field measurements were obtained by the UCLA fluxgate magnetometers (Russell, 1978) while the plasma data come from the LANL/MPE fast plasma experiments (Bame et al., 1978).

Observations

Figure 1 displays ISEE 1 and 2 magnetometer and plasma data for a 42-minute interval on October 23, 1978, when the satellites were outbound in the dawn magnetosheath at a GSM local time and latitude of 1000 hours and 40°N. ISEE 2 (lighter trace) was leading ISEE 1 (darker trace) along the orbit by 5700 km. The plasma parameters plotted are moments of two-dimensional distributions (e.g. see Paschmann et al., 1978) obtained at 6s resolution (ISEE 1) and 12s resolution (ISEE 2). Three-dimensional plasma data are not presented as their time resolution (48s) was insufficient to resolve properly the FTEs. The three densities (cm^{-3}) shown are N_p the total plasma density, $\overline{N}_p$ the density of energetic (9 - 40 keV) ions, and $\overline{N}_E$ the density of energetic (2 - 20 keV) electrons. While N_p is dominated by cool magnetosheath plasma, the two latter densities are dominated by hot particles of magnetospheric origin. The magnitude V (km s^{-1}) and components (V_X, V_Y) of the equatorial plasma bulk flow are also given, the latter in satellite (approximately GSE) coordinates where X points sunward and Y duskward.

The magnetic field data are 12s-averages overlapped by two-thirds, and are presented as orthogonal components in boundary normal (LMN) coordinates based on the Fairfield (1971) model magnetopause normal. Also plotted is the field magnitude B, and a quantity α_{LM}, which is the field angle in the LM plane (tangential to the magnetopause) defined such that α_{LM} = 0° is directed towards $\hat{\underline{L}}$ (northward) and α_{LM} = 90° points towards $\hat{\underline{M}}$ (westward).

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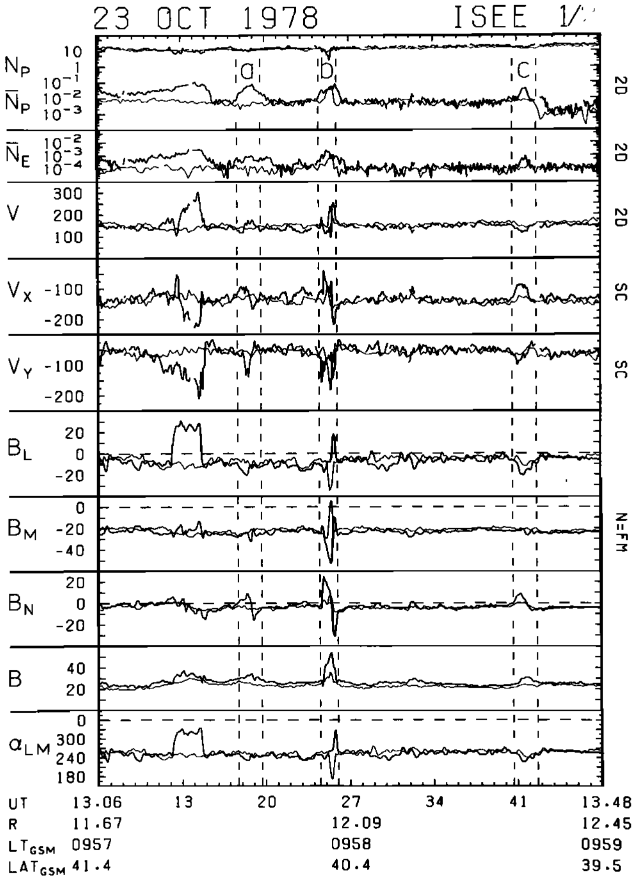

Fig. 1. Plasma and magnetometer measurements for ISEE 1 (heavy line) and ISEE 2 (light line) on October 23, 1978. The plasma data are shown in the top five panels, and consist of various 2D density and flow parameters which are described fully in the text. The magnetic field data are displayed in boundary normal coordinates such that B_N is outward along the boundary normal, B_L is along the projection of the GSM $\underline{Z}$-axis in the magnetopause plane, while B_M completes the orthogonal triad and points westward. The normal direction had GSM-components (0.794, -0.300, 0.529) and was calculated using the Fairfield (1971) model. The bottom panel shows the field angle in the LM plane, defined by $\alpha_{LM} = \tan^{-1}(B_M/B_L)$. ISEE 1's position is given at the base of the Figure in terms of geocentric radial distance (R) in Earth radii, and GSM local time (LT_{GSM}) and latitude (LAT_{GSM}). At 1326 UT the satellites were separated by 5540 km along the model normal.

At 1326 UT the satellite separation in LMN coordinates was (890, 1100, -5540) km measured from ISEE 2 to ISEE 1. Thus ISEE 2 was 5540 km further from the magnetopause than ISEE 1.

Three magnetosheath FTEs, labelled (a), (b) and (c), are marked by pairs of dashed vertical guidelines. These FTEs show the positive-negative pulse in B_N characteristic of a standard (rather than a reverse) polarity event (Rijnbeek et al., 1982). In studying these FTEs let us consider first the magnetic field and density data. Event (b) at 1325 UT is seen clearly by both satellites. This is evident from the B_N signals, the increases in field strength, and the order of magnitude rise in the fluxes of energetic ring current ions and electrons. These latter approach levels recorded during an apparent magnetopause encounter by ISEE 1 between 1312 and 1315 UT. The energetic particle behaviour and the slight decrease in total density are consistent with plasma mixing along open field lines, as noted previously for magnetosheath FTEs (Paschmann et al., 1982). The amplitude of the B_N signal and the field deflection tangential to the magnetopause inside the FTE are different at the two locations. ISEE 1, the satellite closest to the magnetopause, sees the stronger B_N signal. While the magnetic field at ISEE 1 rotates 70^o towards the magnetospheric field direction, at ISEE 2 the field simultaneously rotates 70^o in the opposite direction.

In a later FTE, (c), at 1341 UT, ISEE 1 again observes the larger amplitude B_N signal, though the accompanying tangential field deflection is now directed away from the magnetospheric direction. From the magnetometer data alone one might argue that ISEE 2 just grazed the event, but the absence of a flux increase in the energetic particles indicates that it passed outside the open flux tube. The third clear standard polarity FTE, (a), at 1318 UT illustrates both an instance where just one satellite (ISEE 1) sees an event and a case where essentially no tangential field tilting occurs.

The data in Fig. 1 show that magnetosheath flux transfer events can have a scale size L_N normal to the magnetopause of at least 5500 km. Statistical results of a larger survey to be reported elsewhere in fact point to an L_N value $\sim$ 1 Earth radius, R_E, for the prominent magnetosheath events (B_N magnitude $\geq$ 10 nT peak-to-peak and time scale $\geq$ 1 minute).

The oppositely directed field tilts inside event (b) are another significant feature of the data in Fig. 1. Previous workers (Paschmann et al., 1982; Cowley, 1982) have noted that the continuity of the B_N signal across an FTE implies a twisting or spiral geometry to its internal magnetic structure. The additional observation here of oppositely directed tangential field perturbations clearly substantiates that interpretation. We have seen differently or oppositely directed field tilting associated with FTEs on several occasions when the satellites have been well separated (separation > 10^3 km), with event (b) the most striking example yet found.

To help clarify why the interior field appears twisted let us consider the plasma flow behaviour during the FTEs in Fig. 1. Changes in flow speed and direction accompany the three events. FTE (b), in particular, shows differently directed flows at the two satellites pointing to plasma vortex motion which could be related to the field twisting (see also Paschmann et al., 1982). In fact closer inspection suggests a basic relationship between the flow and field perturbations. The X and Y satellite coordinate directions correspond respectively within 37^o of the N and -M directions in boundary normal coordinates. Perturbations in V_X and B_N appear in phase during the three FTEs, as also do the perturbations in V_Y and $-B_M$ for event (b) once the effect of field compression is eliminated. We have checked these relationships by replotting the field data in GSE coordinates and normalising to remove the change in field strength. In all cases the X and Y GSE component field and flow perturbations satisfy approximately the Walén relation for an Alfvén wave propagating antiparallel to the ambient field; namely $\underline{b}_\perp = B_o \underline{v}_\perp/A$, where $\underline{b}_\perp$ and $\underline{v}_\perp$ are the transverse field and flow perturbations, A is the Alfvén speed and B_o the background field strength. As an Alfvén wave carries both a field-aligned current density $(\underline{\nabla}_\perp \times \underline{b}_\perp /\mu_o)$ and a parallel vorticity $(\underline{\nabla}_\perp \times \underline{v}_\perp)$, it clearly has properties appropriate to explain the field twisting and vortex motion which appear associated with the FTEs in Fig. 1. In these standard polarity events the wave would have been generated equatorward and sunward of the satellites.

Discussion

It is clear now that FTEs are of sufficient size to contribute significantly to the transport of magnetic flux which drives magnetospheric convection. The flux transfer effected by an individual FTE may be estimated by combining the FTE scale sizes normal and tangential to the magnetopause. The latter dimension is about 2 R_E and follows from the typical FTE time duration of 1-2 minutes and the FTE bulk speed along the magnetopause of 100-200 km s^{-1}. Taking the FTE normal dimension as 1 R_E, and the field strength as 50 nT, gives a flux value associated with an FTE of $\sim 4 \times 10^6$ Wb. Since FTEs recur at a particular location about every 8 minutes (Rijnbeek et al., 1983), it follows that the voltage associated with the process is at least $\sim$ 10 kV. This is a lower limit for the total cross-magnetosphere voltage attributable to FTEs (see e.g. Rijnbeek et al., 1983).

Figure 2 illustrates schematically the field twisting indicated by the FTE observations in Fig. 1. The upper diagram shows how one might visualise a magnetosheath FTE viewed from outside the magnetosphere. The reconnected tube is shown speckled for clarity with its magnetospheric 'end' terminated close to where the tube crosses the magnetopause. Field tension causes the reconnected tube to contract northward and westward in the direction of the open arrow. A satellite encountering the tube near the location AA'A" sees a standard polarity (+/-) B_N signal due to the field twisting about the flux tube axis. The spiral field is indicated by the wavy field line and corresponds to a core field-aligned current flowing towards the ionosphere. A satellite would see differently directed field tilting in the LM plane depending on whether it bisects the FTE Earthward or beyond the open tube center as the FTE sweeps past. For the field twist geometry shown in Fig. 2, towards (away) field tilting with respect to the magnetospheric field direction would prevail closest to (furthest from) the magnetopause.

The lower part of Fig. 2 illustrates more clearly the spatial variation envisaged for the FTE interior field. Cross sections through the plane AA'A" of the open flux tube (see upper sketch) are shown for the three events in Fig. 1. The sketches are drawn looking anti-parallel to the FTE axial field (dotted circle) and illustrate the NM* plane where M* points northward in a direction nearly perpendicular to the ambient magnetosheath magnetic field. The open tubes are shown hatched with the magnetopause marked by a thicker line. FTE motion is indicated by the open arrows labelled v_{FTE} and the resulting trajectories of the ISEE satellites through each event are shown by the lines marked 1 (ISEE 1) and 2 (ISEE 2). These latter are shown as straight lines for simplicity, thus ignoring any radial magnetopause motion during the encounter. The sketches are drawn to the same scale with the satellites separated by 5500 km in the $\underline{N}$ direction. The direction of field twisting is indicated by the anti-clockwise arrowed dashed lines, which in these events also corresponded to the direction of plasma circulation.

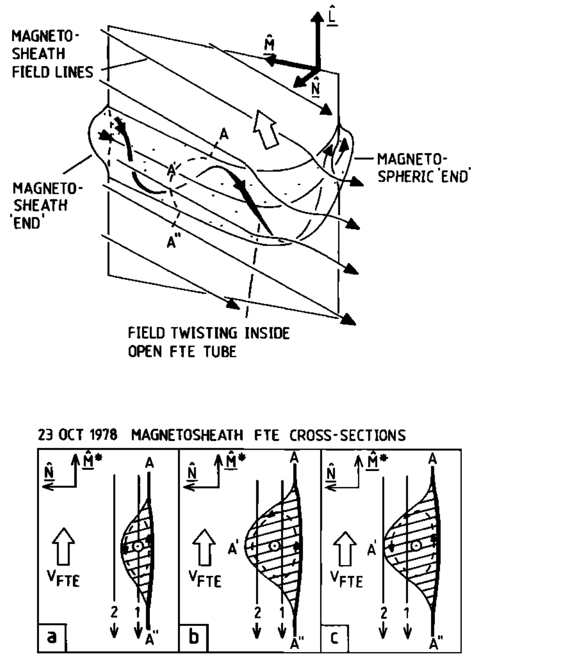

Fig. 2. Sketches illustrating the field twisting in magnetosheath flux transfer events. The upper schematic shows the twisting in three-dimensions viewed from outside the magnetosphere. The lower diagram shows views looking along the axes of the three FTE events (a, b and c) marked in Fig. 1, as the net motion v_{FTE} of the open tubes carries them across the two ISEE satellites.

In event (a) ISEE 1 passes through the heart of the structure and sees a clear standard polarity B_N signal and essentially no tangential field tilting. In event (b) which has a larger scale size than (a), ISEE 1 passes slightly Earthward of the tube center and observes a substantial B_N signal together with slight towards (northward) field tilting which increases sharply later in the event possibly due to outward magnetopause motion. Meanwhile ISEE 2, 5500 km further from the magnetopause, sees a smaller amplitude B_N signal and large away (southward) tilting of the field. In event (c) the ISEE 1 encounter occurs beyond the tube center such that a clear B_N signal and away field tilting are observed.

The magnitude of the core field-aligned current along the FTE tube axis can be estimated using Ampere's Law. For a 1 R_E diameter flux tube associated with a B_N signal amplitude of 15 nT, the parallel current is $\sim 2 \times 10^5$ A. The question as to where this current projects within the magnetosphere will form an interesting topic for future research. One would certainly expect observable effects, for conservation of flux implies an FTE spatial scale of $\sim$ 200 km at ionospheric altitudes, which is comparable to the width of the Region 1 Birkeland current system there. Also, projecting to the ionosphere the 2 x 10^5 A field-aligned current accompanying an FTE gives an ionospheric Birkeland current density $J_{\parallel} \sim 4\ \mu Am^{-2}$, which exceeds the average Region 1 $J_{\parallel}$ value near noon (e.g. Potemra et al., 1979) by about a factor of three.

The relationship between the flow and field perturbations associated with FTEs should be studied in greater depth. We have pointed out that the events in Fig. 1 satisfy approximately the Walén relation for an Alfvén wave propagating anti-parallel to $\underline{B}_o$. This suggests that the FTE magnetic flux tube is twisted and that the twist propagates along the reconnected tube. The signature in the normal component is not simply due to the draping of exterior field lines around that tube.

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