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# Recent ISEE Observations of the Magnetopause and Low Latitude Boundary Layer: A Review*

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**Abstract.** ISEE-1 and 2 satellite observations at the dayside magnetopause have enabled important progress to be made on the solar wind/magnetosphere coupling problem. The ISEE results have emphasized the significance of reconnection and have indicated that the process can occur both in a quasi-steady form and in an unsteady (flux transfer event (FTE)) manner. The detection of FTEs on open field lines within the magnetosphere, the discovery of reverse polarity FTEs, and the observation that FTEs can be associated closely with intervals of quasi-steady reconnection flow, all support further the view that FTEs are reconnection phenomena. Indeed, a sharp distinction need not exist between FTEs and the type of reconnection event described as quasi-steady.

**Key words:** Magnetopause – Low latitude boundary layer – Reconnection – Flux transfer events

## Introduction

The magnetopause or the outer boundary of the Earth's magnetic field, is the location of some of the most fundamental, yet arguably the most controversial processes in magnetospheric physics: that is those which effect the transfer of solar wind mass and momentum to the terrestrial magnetosphere. There is little doubt now that the solar wind does supply a significant fraction of the mass, and a dominant amount of the momentum and energy involved in magnetospheric motion. In particular it drives the magnetospheric convection system, which is central to our understanding of the macroscopic distribution of plasmas and electromagnetic fields (both DC and AC) within the magnetosphere (see Cowley, 1982; Southwood, in press).

The controversy, which has persisted despite the twenty years of in situ satellite measurements, concerns the exact form that the coupling takes. Discussion has centred principally around two mechanisms: the first involving magnetic reconnection between solar and terrestrial magnetic fields as described first by Dungey (1961), and the second involving a "viscous-like" interaction, with diffusion of solar plasma across the magnetopause (Axford and Hines, 1961). The continuing debate, and especially the lack of direct empirical evidence in favour of reconnection, led Lemaire and Roth (1978) to suggest a hybrid coupling model involving "impulsive penetration" of solar wind plasma irregularities into the magnetosphere.

Shortly after the latter suggestion was made, the ISEE-1 and 2 satellites began providing the first high time and 3D resolution plasma data from the dayside magnetopause, where the primary coupling interactions are believed to take place. These measurements have thrown considerable light on the solar wind/magnetosphere coupling problem, and a discussion of the most recent ISEE results on this topic will form the basis of this review. For a thorough assessment of magnetopause and low latitude boundary layer research prior to mid-1982, the reader is referred to the review by Cowley (1982).

The new ISEE results have involved largely reconnection and, to reflect this emphasis, the paper divides as follows. Two sections describe the in situ evidence from ISEE that dayside reconnection occurs both in a quasi-steady form (next section) and as a transient, patchy (flux transfer event) process (subsequent section), with brief theoretical descriptions of the expected signatures in the field and plasma data included in each case. The next section considers the ISEE observations pertaining to the low latitude boundary layer and offers a fresh interpretation for the pulsed boundary layer features reported by Sckopke et al. (1981). In the penultimate section the relative importance of the different coupling processes at the magnetopause are assessed in terms of the cross-magnetosphere potential to which each gives rise. Conclusions and important remaining questions comprise the last section.

## Quasi-Steady Reconnection

Although the temporal and spatial characteristics of reconnection have yet to be established, early results suggest that at times it occurs in the large scale quasi-steady manner envisaged by Dungey (1961) and described subsequently by Petschek (1964) and Levy et al. (1964). Twelve examples of quasi-steady reconnection have been published to date (Paschmann et al., 1979; Sonnerup et al., 1981; Gosling et al., 1982), with further cases identified but not yet reported (G. Paschmann, pers. comm., 1982).

Before reviewing this evidence, let us first briefly consider the signatures in the electromagnetic field and plasma which one would expect to see when steady subsolar reconnection is occurring. Figure 1 shows a cross-section through

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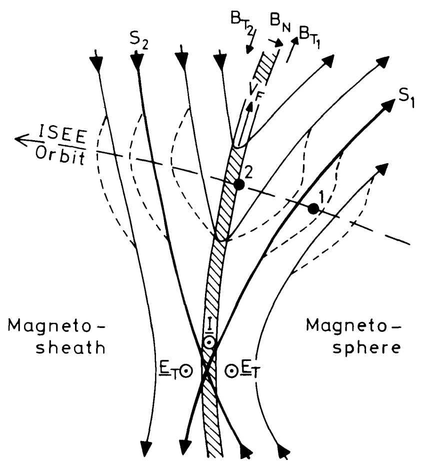


**Fig. 1.** Meridian cross-section of the dayside magnetopause illustrating the signatures of steady subsolar reconnection for antiparallel external and internal magnetic fields. The field lines are shown as solid lines, with the dashed lines denoting the field distortions which may occur following a short pulse of stronger reconnection which erodes extra flux

the dayside magnetopause current layer (shown hatched), covering a region from slightly south, to well north of, a reconnection *X*-line. The significance of the dashed field lines in the vicinity of the ISEE satellites (marked *1* and *2*) will be explained later. Those magnetosheath and magnetosphere field lines connected to the *X*-line are called separatrices and are marked by an *S*.

The electromagnetic effects associated with reconnection are a magnetic field component $B_N$ normal to the boundary, and an electric field $E_T$ tangential to the current sheet. These two effects change the momentum of inflowing magnetosheath plasma through an acceleration process which can be pictured as similar in action to a slingshot. Maxwell field tension forces the sharply bent open flux tubes to shorten by contracting polewards at the speed $V_F = E_T/B_N$, thereby causing plasma acceleration through the release of magnetic field energy (Cowley, 1979; 1980). The plasma acceleration can be understood in an equivalent manner without recourse to the moving field line picture, as due to the $\mathbf{I} \times \mathbf{B}_N$ body force. Electromagnetic energy is liberated to the plasma in the current layer (at the rate $\mathbf{I}.\mathbf{E}_T$) because the magnetopause current $\mathbf{I}$ has a component parallel to $\mathbf{E}_T$. In addition to plasma acceleration the other characteristic plasma feature of subsolar reconnection is a mixing of magnetosheath and magnetospheric plasmas along the open flux tubes.

With these basic theoretical ideas in mind, let us now consider the ISEE data showing the first in situ evidence that reconnection occurs in a quasi-steady form. "Quasi-steady" in this context means that reconnection persists for longer than the five minutes required to set up a flow of open flux tubes over the entire dayside boundary. The most studied example occurred on 8 September 1978, during an outbound passage at a GSM local time and northern latitude of ~1140 h and ~26°.

Plasma and magnetic field data are displayed for both ISEE-1 and 2 separately in Fig. 2 (also see Paschmann

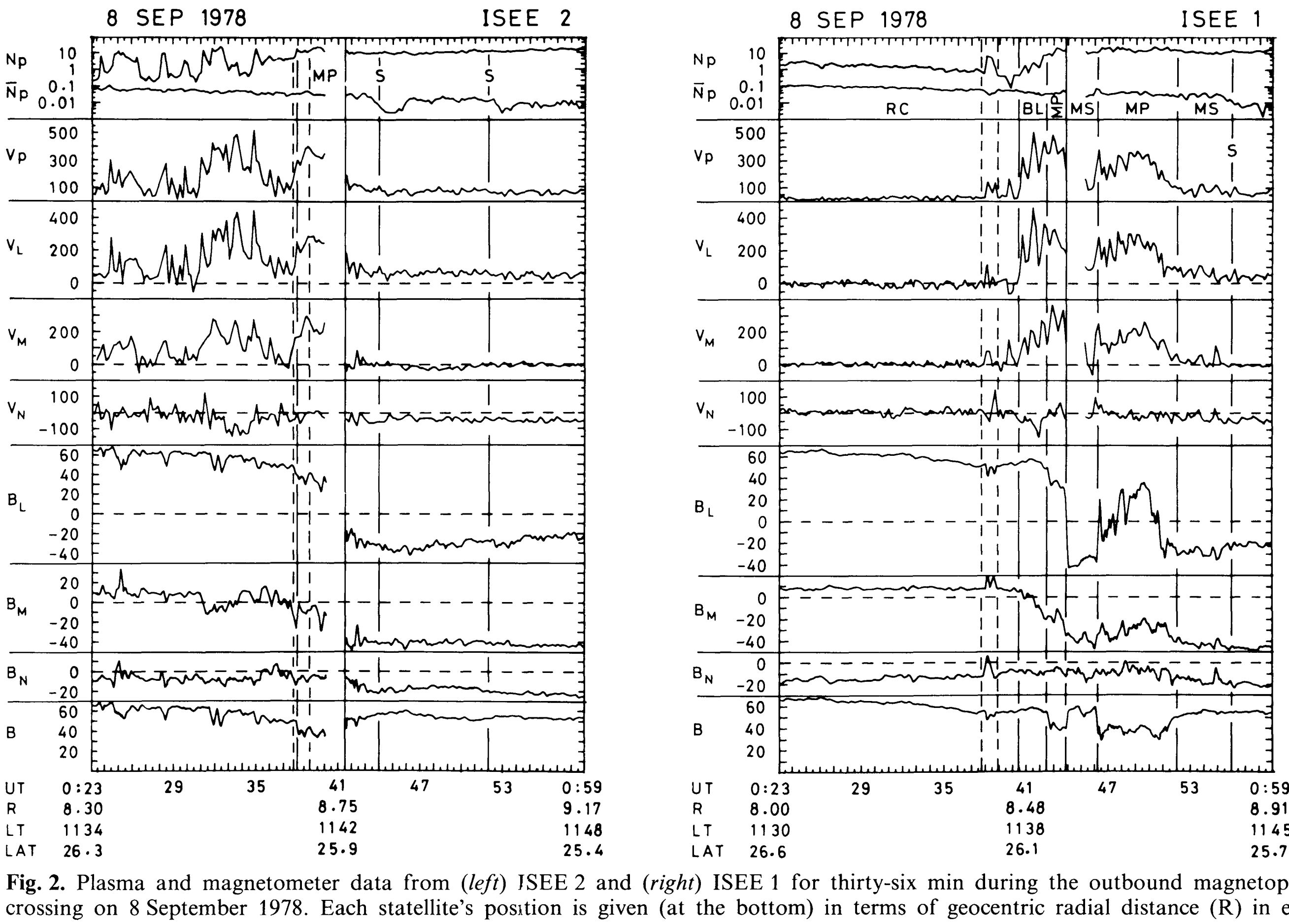


**Fig. 2.** Plasma and magnetometer data from (*left*) ISEE 2 and (*right*) ISEE 1 for thirty-six min during the outbound magnetopause crossing on 8 September 1978. Each statellite's position is given (at the bottom) in terms of geocentric radial distance (R) in earth radii, and GSM local time (LT) and latitude (LAT)

et al., 1979 and Sonnerup et al., 1981). The plasma parameters are 3D recordings with 12 s resolution, and the magnetometer data are 12 s averages plotted every 4 s. The top panel shows $Np$, the total plasma number density ($cm^{-3}$), and $\tilde{N}p$, the density of energetic (8–40 keV) ions. Below are plotted $Vp$, the plasma bulk flow speed ($km\ s^{-1}$), $B$, the magnetic field strength (nT), and the Cartesian components of the flow and field expressed in boundary normal coordinates (Russell and Elphic, 1978). In this coordinate system $\hat{\mathbf{N}}$ is the estimated outward normal to the magnetopause, $\hat{\mathbf{L}}$ points north such that the GSM $\hat{\mathbf{z}}$ axis lies in the $\mathbf{L}-\mathbf{N}$ plane, while $\hat{\mathbf{M}}$ completes the orthogonal triad and points westward. The normal used in Fig. 2 has GSM components (0.768, −0.312, 0.560) and is the minimum variance normal employed by Sonnerup et al. (1981). It differs in direction by 24° relative to the Fairfield (1971) model magnetopause normal (0.953, −0.050, 0.297) for the satellite location. The data are subdivided by vertical lines according to the main plasma regions and boundaries identified by Sonnerup et al. (1981): the ring current (RC), boundary layer (BL), magnetopause current layer (MP), and the magnetosheath (MS). The lines marked $S$ denote the location of the outer reconnection separatrix inferred from the presence of energetic ring current ions in the magnetosheath. The significance of the interval bracketed by dashed lines at ~00:38.30 UT will be discussed later. The satellite separation in LMN coordinates during the interval was ~(300, 1,300, −1,500) km measured from ISEE 2 (the lead satellite) to ISEE 1.

The striking feature of the data is the high speed flow seen by both satellites in the boundary layer and in the region marked as magnetopause. These speeds are 5–10 times greater than those recorded later in the magnetosheath, and as the positive values of $V_L$ and $V_M$ show, the plasma acceleration is directed northward and dawnward (also see Eastman and Frank, 1982). The vector change in plasma momentum across the magnetopause matches expectations for the effect of "slingshot" acceleration from the release of magnetic field stress on open flux tubes (Paschmann et al., 1979). This acceleration is interpreted as quasi-steady because high speed flows are seen intermittently (due to boundary motion) at one or other satellite for at least half an hour. The presence in the vicinity of the magnetospause of an inward-pointing normal magnetic field component of 5–10 nT is clear also. A negative $B_N$ is consistent with a satellite location north of the reconnection $X$-line, as also is the streaming anti-parallel to $B$ of the energetic magnetospheric ions seen in the magnetosheath (Sonnerup et al., 1981; Scholer et al., 1981; 1982; Daly and Fritz, 1982). The detection of energetic ring current ions well outside the magnetopause with no discontinuity in density at the boundary (Fig. 2), and the fact that the plasma density in the boundary layer is intermediate between magnetosheath and ring current values, both imply a mixing of plasmas along open flux tubes.

In short, there exists virtually a complete set of reconnection signatures. The only missing item is a direct measurement of the tangential electric field, which is due to the relevant instrument being in an unfavourable mode during the interval. One observation has proved puzzling though, and that is the behaviour of the energetic electrons (tens of keV and greater) reported by Eastman and Frank (1982) and Scholer et al. (1982). These show a trapped distribution on field lines which the high speed flows and streaming energetic ions imply are open. Since trapped electron distributions are characteristic of closed field lines, Eastman and Frank (1982) and Eastman et al. (submitted) disagree that reconnection is occurring, favouring instead an interpretation based on the impulsive penetration model of Lemaire and Roth (1978). However, Daly and Fritz (1982) present evidence that electrons may be trapped on open field lines, due to magnetic mirroring about the field strength minimum which occurs in the magnetopause current sheet (Fig. 2). Although reconnection theory predicts such a field depression, it would be interesting to investigate the behaviour of the energetic electrons in other reconnection events to establish whether similar behaviour occurred.

The tangential electric field is another feature which needs investigation in the other reconnection events. Tangential electric fields have been reported for a few ISEE magnetopause encounters (Mozer et al., 1978; 1979; Fahleson et al., 1979) but none of these cases correspond to intervals of quasi-steady reconnection. For the boundary crossing on 20 November 1977, which has received the most study in regard to DC electric field behaviour, Mozer et al. (1978; 1979) report an average $E_T$ of 1.7 $mV\ m^{-1}$ and a local power dissipation to the plasma of ~70 $\mu W\ m^{-2}$. However, no significant plasma flow acceleration is observed in this case (Sonnerup et al., 1981), a discrepancy the reason for which is not understood.

As mentioned earlier, in addition to the 8 September 1978 case, eleven other ISEE dayside magnetopause crossings have been published to date with properties suggestive of quasi-steady reconnection. As well as these examples, many further instances of reconnection have been identified in ISEE data where the process, rather than appearing quasi-steady, seems to occur in a transient, patchy manner, referred to as "flux transfer events" or FTEs (Russell and Elphic, 1978). FTEs form the next topic of discussion but it is appropriate to mention them first briefly here, as the data in Fig. 2 contain an observation which may have a significant bearing on their nature. FTEs can occur in close association with intervals of quasi-steady reconnection flow (Paschmann et al., 1982 (their Fig. 3); Rijnbeek et al., 1982) so there could be a physical connection between the two processes. The data enclosed by the dashed vertical lines at ~00:38.30 UT in Fig. 2 are an instance of such association. These observations suggest a basis for the physical connection for as ISEE 1 is encountering an FTE, ISEE 2 located 1,500 km nearer the magnetopause, apparently sees quasi-steady reconnection flow. Further discussion of this point is reserved for later.

## Flux Transfer Event Reconnection

The first suggestion that reconnection may occur as a localised, transient process, was made by Haerendel et al. (1978) following analysis of HEOS 2 magnetometer data from the dayside low latitude boundary layer. ISEE dayside observations have confirmed this suggestion, though the data published to date indicate that patchy or unsteady reconnection occurs in the equatorial vicinity, rather than near the cusps as originally envisaged.

The discovery of signatures in the ISEE data indicative of isolated reconnected magnetic flux tubes was first reported by Russell and Elphic (1978; 1979) and Elphic and Russell (1979). These "flux transfer events" (FTEs) were

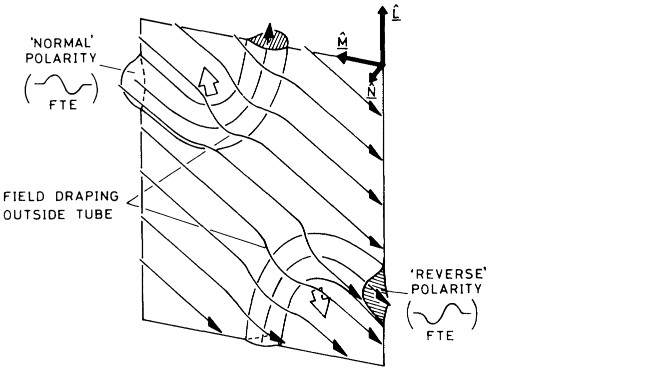


**Fig. 3.** Schematic view (from the magnetosheath) of two open FTE flux tubes shortly after a localised reconnection event at the dayside magnetopause. The southerly contracting open tube gives rise to the recently discovered "reverse" polarity FTE. The LMN coordinate directions are included for reference in the top right hand part of the sketch. (Figure is after Rijnbeek et al., 1982)

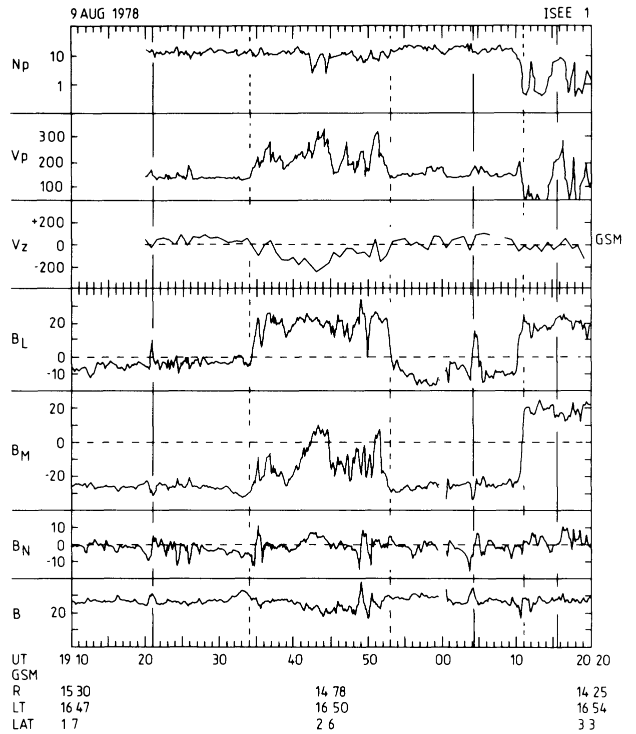


**Fig. 4.** ISEE 1 plasma and magnetic field measurements of the magnetopause region for the inbound crossing on 9 August 1978. The plotted parameters and their units are identical to those described for Fig. 2, except $V_z$, which is the GSM $z$ (northward) component of the plasma velocity (km s$^{-1}$). "Reverse" polarity FTEs are denoted by the vertical guidelines at ~19:21 and ~20:04 UT, while the dashed line at ~20:11 identifies the magnetopause. (Figure is after Rijnbeek et al., 1982)

initially identified from their characteristic signal in the magnetic field when expressed in boundary normal (LMN) coordinates; namely, a bipolar (positive followed by negative) perturbation in $B_N$, together with a northward tilting of the magnetosheath field. Previous interpretational work (Russell and Elphic, 1978; Paschmann et al., 1982; Cowley, 1982) has shown that these properties are characteristic of reconnection occurring on a short-scale.

The origin of the FTE $B_N$ signal can be understood with the aid of Fig. 3 (after Rijnbeek et al., 1982) which shows a sketch of the dayside subsolar magnetopause shortly after a localised reconnection event has occurred near the equator in the centre of the diagram. A southerly (−**L**) and easterly (−**M**) directed group of magnetosheath field lines has reconnected with the northerly directed magnetospheric field, so that the magnetic tension force causes the two parts of the reconnected open tube to contract along the magnetopause in the directions indicated by the open arrows. This contraction gives rise to perturbations in the overlying magnetosheath plasma and field. A satellite observing the northwards moving open tube will see a positive perturbation in the magnetic field component normal to the magnetopause as the tube approaches, and a negative perturbation as it recedes. The southward moving open tube, however, will give rise to a reverse $B_N$ signature, that is, negative followed by positive, and a reverse polarity FTE will be seen. Within the open tubes deflections in the plasma flow and field direction should occur (Cowley, 1982; Rijnbeek et al., 1982). In particular, the magnetosheath ends of the tubes will be pulled towards the Earth's field direction, while the magnetospheric ends will be pulled similarly towards the direction of the magnetosheath field. The plasma flow inside the northerly moving open tube should be deflected northward and westward relative to the ambient magnetosheath flow, while the plasma flow within the southerly contracting open tube should be perturbed southwards and eastwards.

Nearly all the flux transfer events reported in the literature to date were observed soon after ISEE satellite launch in the late autumn of 1977, when ISEE was sampling northern GSM latitudes of typically 20°–40°. These FTEs all possess the positive followed by negative $B_N$ polarity expected for open tubes moving north following reconnection near the equator. The first report of a negative or reverse polarity FTE has been given recently by Rijnbeek et al. (1982). The data presented by these authors are shown in Fig. 4 and come from the inbound ISEE boundary pass on 9 August 1978 which occurred only 2° above the GSM equator. Plasma measurements (taken from Sonnerup et al., 1981) are shown above magnetometer recordings plotted in boundary normal coordinates. This boundary crossing has added interest because Sonnerup et al. (1981) identify the interval between 19:34 and 19:53 UT as one where quasi-steady reconnection was occurring. In particular it is the only example published so far where the satellite was situated south of the reconnection region. This is indicated in Fig. 4 by the southward deflection in direction of the accelerated plasma flows.

In the magnetosheath both before and after the interval of quasi steady reconnection, unsteady reconnection was occurring in the form of flux transfer events at ~19:21 and ~20.04 UT. These FTEs display all the characteristics described by Russell and Elphic (1978; 1979) and Paschmann et al. (1982), except that here the $B_N$ polarity is negative to positive, and the magnetosheath plasma flow is deflected southward (albeit at one data point). From the discussion earlier, the latter properties are those expected for open FTE flux tubes located south of the reconnection region and connected to the Earth's southern hemisphere. The energetic ion streaming which accompanies both events also is consistent with connection to the southern hemisphere (P.W. Daly, pers. comm., 1982). Thus the FTE and quasi-steady reconnection properties both indicate that reconnection was occurring north of the satellite. Although Rijnbeek et al. (1982) only discussed the one event, reverse polarity flux transfer events are observed during several other boundary crossings near or south of the GSM equator (Berchem and Russell, 1982; R.P. Rijnbeek, pers. comm., 1982).

## Low Latitude Boundary Layer Observations

The origin of the low latitude boundary layer (LLBL), the region containing tailward flowing plasma earthward of and adjacent to the magnetopause with characteristics intermediate between the magnetosheath and magnetosphere, is clearly basic to our understanding as to how solar wind momentum is transferred to the magnetosphere. Satellite observations prior to ISEE generally indicated that diffusion of each plasma population across the magnetopause was the primary LLBL formation mechanism (Hones et al., 1972; Akasofu et al., 1973; Eastman et al., 1976; Haerendel et al., 1978; Eastman and Hones, 1979). High resolution plasma measurements recorded by ISEE in the LLBL have also been interpreted as indicating an origin involving diffusion (Hones et al., 1982; Eastman et al., submitted). Sckopke et al. (1981) also claim consistency with diffusion providing the diffusion coefficient is sufficiently large. However, it is not proven that diffusion is always the source of the layer. When reconnection is occurring a plasma population is set up interior to the magnetopause with properties similar to that of a diffusively driven boundary layer. The major distinction when reconnection is dominant is that the boundary layer flow may exceed the exterior flow speed because the plasma is subjected to the $\mathbf{I} \times \mathbf{B}_N$ force as it penetrates the magnetopause.

The fact that several ISEE boundary layer crossings agree in detail with the occurrence of quasi-steady reconnection, indicates that in these cases diffusion was not the main boundary layer source. The existence of magnetosheath FTEs also implies a boundary layer origin not involving diffusion. Indeed, a scan of the Los Alamos/Garching ISEE fast plasma data shows that bursts of plasma acceleration, accompanied by "sharp-edged" pulses of magnetosheath plasma, are a common boundary layer feature, and often possess a 1–2 min timescale similar to that reported for magnetosheath flux transfer events.

Since FTEs were discovered in the magnetosheath, early work concentrated on their magnetosheath characteristics. However, if the interpretation suggested by Russell and Elphic (1978) involving localised magnetic reconnection across the magnetopause is correct, each magnetosheath FTE should have a counterpart feature inside the magnetosphere (see Fig. 3). The latter should appear as a pulse of accelerated magnetosheath plasma and possess magnetic field perturbations similar to those which accompany magnetosheath FTEs, except that in this case the field should be pulled towards the sheath field direction if the sheath flow is sub-Alfvénic (Cowley, 1982). In the absence of magnetic mirroring on open field lines the energetic particles should exhibit streaming along $\mathbf{B}$, as in magnetosheath FTEs.

The first reports of magnetospheric FTEs with the above properties have recently been made by Daly and Keppler (1982) and Paschmann et al. (1982). A possible

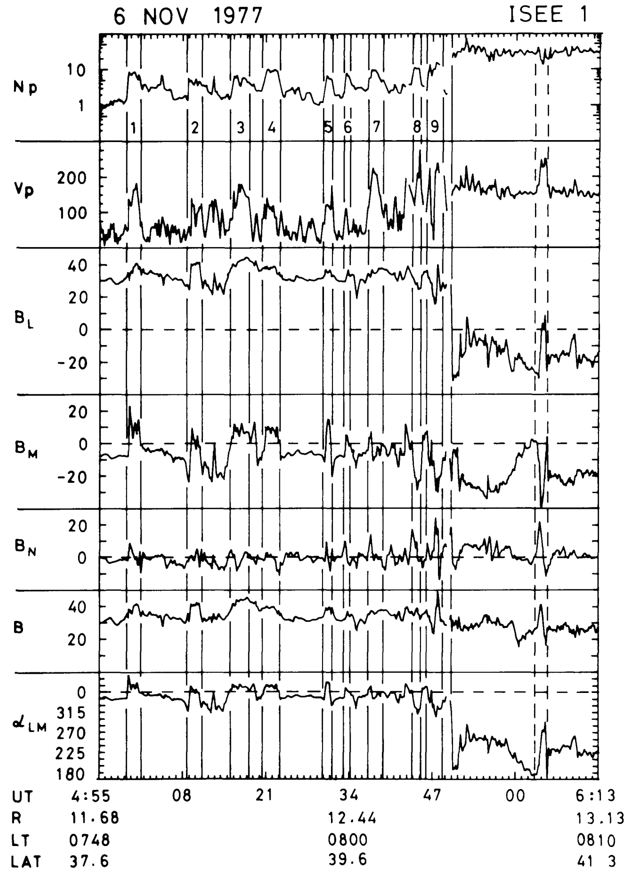


**Fig. 5.** ISEE 1 plasma and magnetometer recordings for the 6 November 1977 outbound crossing of the low latitude boundary layer and magnetopause. With the exception of $\alpha_{LM}$, the field angle in the LM plane, the plotted parameters are the same as described previously. The main intervals (or "pulses") of flowing boundary layer plasma are marked by vertical lines and numbered near the top of the diagram. A magnetosheath FTE is bracketed by the dashed guidelines at ~06:04 UT

example of another counterpart feature was noted by Rijnbeek et al. (1982) and is marked in Fig. 4 by the right-hand vertical guideline. This feature is associated with a pulse of accelerated plasma, a reverse polarity (negative/positive) perturbation in $B_N$ and a slight tilting of the boundary layer field towards the magnetosheath field direction. Clearer examples of internal FTEs exist in the ISEE LLBL crossing which has received most study to date, the 6 November 1977 outbound pass. This dawn flank northern latitude boundary layer passage has been studied by Sckopke et al. (1981) and Paschmann et al. (1982). The interpretation given below is based on ideas developed by the author together with S.W.H. Cowley and D.J. Southwood.

ISEE 1 plasma and magnetometer data for a 78 min interval spanning the boundary layer and magnetopause regions on 6 November 1977 are shown in Fig. 5. The plasma data are 3D measurements with 12 s resolution, and the field recordings are displayed in boundary normal coordinates using a normal calculated by approximating the magnetopause as a tangential discontinuity. This normal differed in direction by 20° relative to the Fairfield (1971) model normal employed by Sckopke et al. (1981) but the conclusions described below are independent of which normal is used. The bottom panel shows the field angle

$\alpha_{LM}$ in the LM plane (tangential to the magnetopause) defined in the same manner as the angle $\alpha'_B$ displayed by Sckopke et al. (1981) (see their Fig. 3), with $\alpha_{LM}=0°$ directed along **L** (northward) and $\alpha_{LM}=90°$ pointing towards **M** (westward).

At the start of the interval shown in Fig. 5 ISEE was in the tenuous plasma sheet plasma (also see Sckopke et al., 1981). The boundary layer (BL) plasma of magnetosheath origin was encountered first at $\sim$04:59 UT, and is identified by the sharp increase in density and bulk flow speed. The magnetopause, indicated by the sharp reversal in $B_L$ was crossed only once at $\sim$05:50 UT. During the intervening 51 min, nine (numbered from left to right) quasi-periodic "pulses" of boundary layer plasma were observed, each having a distinctive saw-tooth or square-wave density profile. The latter feature, and the density profile for pulse (9), are clearer in the higher time resolution 2D density data published in Sckopke et al. (1981). This publication also shows that the bulk flow in the pulses was generally directed tailwards.

Turning attention to the lower panels in Fig. 5, and in particular to the $\alpha_{LM}$ plot, it is clear that the BL pulses are accompanied by well defined rotations in the magnetic field. The principal field perturbations occur in the **M** or east-west component. During pulses (1) to (6) $B_M$ increases sharply and the field, as indicated in the $\alpha_{LM}$ plot, rotates tailwards by $\sim 30°$. In the Hones et al. (1982) BL field perturbation terminology, this field tilting would be described as "reverse draping". While a consistent $B_M$ deflection is not observed in pulse (7), pulses (8) and (9), closest to the magnetopause, show $B_M$ tilts directed opposite to those seen in the earlier pulses. The field now rotates sunward by $\sim 30°$ relative to the ambient field direction at 04:55 UT. This deflection is towards the magnetosheath field direction, as expected for field pulling if the magnetopause is open and the sheath flow is sub-Alfvénic (see Fig. 3).

Another feature which distinguishes the pulses closest to the magnetopause is their larger plasma flow speeds. The bulk flow is enhanced by 50–100 km s$^{-1}$ relative to the background magnetosheath level and to flow speeds in pulses (1) to (6). A similar speed increase also occurred in the magnetosheath associated with the prominent flux transfer event marked by the vertical dashed lines at $\sim$06:04 UT. Inside the FTE the field clearly tilts towards the ambient magnetospheric direction. One should also note that $B_N$ deflections similar to those which accompany this magnetosheath FTE, occur in the vicinity of pulses (5) to (9). Furthermore, the duration of the BL pulses is very similar to that reported typically for magnetosheath FTEs of 1–2 min. In view of these similarities it is difficult not to believe that, at least, pulses (8) and (9) are on open tubes and are closely related to magnetosheath FTEs (see also Paschmann et al., 1982). This conclusion is supported by the Lindau energetic particle data (kindly supplied by P.W. Daly) which show strong streaming of the energetic ($>$25 keV) ions antiparallel to **B** inside pulses (8) and (9), and in the magnetosheath FTE, thus indicating open tubes connected to the Earth's northern hemisphere. Furthermore, all the boundary layer pulse flux tubes are nearly empty of energetic ($>$20 keV) electrons.

Accepting that pulses (8) and (9) correspond to the magnetospheric ends of open FTE fluxtubes, the question arises as to the origin of the earlier pulses where the field tilts the other way and the flow speeds are lower. In theory

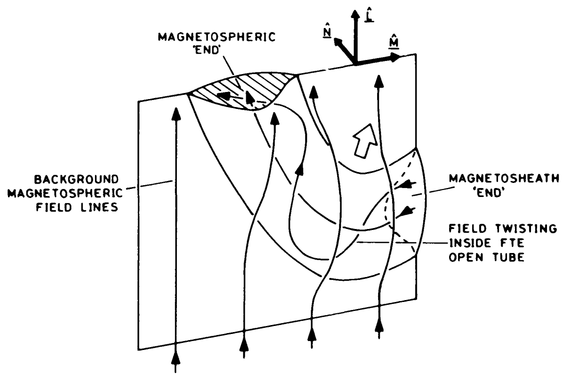


**Fig. 6.** Sketch of a tailward and northward propagating FTE observed from inside the magnetosphere. The field within the open tube is shown twisted as implied by the observed $B_N$ perturbations. It is suggested that these "internal" FTEs may correspond to the BL "pulses" reported, for example, by Sckopke et al. (1981)

these features could arise from diffusive plasma entry at northern high latitudes, as Hones et al. (1982) discuss. However, this would mean different source mechanisms for the early and late BL pulses, when it is very tempting to see the data as a connected sequence of pulse encounters across the BL region.

A possible explanation for the change in character of field tilting as the magnetopause is approached is embodied in Fig. 6, which illustrates how one might visualise a BL FTE observed from inside the magnetosphere. The magnetosphere and magnetosheath "ends" of the open tube are indicated in the sketch; a satellite outside the magnetopause would see the latter as a magnetosheath FTE. Field tension, shown by the open arrow, causes the reconnected BL flux tube to tilt sunwards relative to the background magnetospheric field, thus producing a negative $B_M$ perturbation. As the reconnected tube contracts northward along the magnetopause it distorts the ambient field and thus gives rise to the bipolar positive to negative $B_N$ perturbation discussed above. However, as Paschmann et al. (1982) and Cowley (1982) independently point out, this draping effect can not be the sole cause of the $B_N$ signal, since there would be then zero $B_N$ field inside the open tube, whereas the observed signals resemble sinusoids and certainly do possess an interior $B_N$ component. This implies that the field lines are twisted about the FTE flux tube axis due to a field-aligned current flowing along the open tube. The field twisting is indicated in Fig. 6 by the wavy field line.

A field-aligned current can explain why the field tilting in the earlier boundary layer pulses was opposite to that seen in the pulses closest to the magnetopause. Figure 6 shows that if the twist in the interior field becomes large enough, tailward tilting of the field could occur in the fluxtube section furthest from the magnetopause. Evidence for strong spatial structure inside the 6 November 1977 BL pulses is indicated by the simultaneous observation of oppositely directed field tilts at ISEE 1 and 2 for a brief interval during pulse (9) (data not shown). Apart from this instance, however, the ISEE 1 and 2 plasma and field data are very similar throughout the BL passage, indicating that satellite separations much greater than the $\sim$500 km existing at the time are generally necessary to examine the spatial structure inside BL pulses. A study of dual satellite data for the autumn and early winter of 1978, when ISEE separations near the magnetopause much exceeded 500 km, should be productive. A further point favouring the notion of field twisting in FTEs is that reversals in the direction of field tilt, as in the 6 November 1977 BL pulses, are observed also in magnetosheath FTEs. A clear example is seen in Fig. 15 of Elphic and Russell (1979) (also see Fig. 2 of Paschmann et al., 1982).

Having discussed the physical properties of FTEs in the magnetosheath and boundary layer, let us now consider further the observation noted above, that during the 8 September 1978 boundary crossing ISEE 1 sees an FTE while ISEE 2, located approximately 1,500 km nearer the magnetopause, apparently observes quasi-steady reconnection flow. Referring to Fig. 2 and the interval in question at $\sim$00:38.30 UT, the FTE is identified with the prominent $B_N$ perturbation and is associated with a pulse of accelerated boundary layer plasma a decrease in the energetic ($>8$ keV) ion density and a dropout in the flux of energetic ($>20$ keV) electrons (see Fig. 8 of Scholer et al., 1982 for the latter information). These properties coupled with a deflection in field direction by $\sim 15^\circ$ away from the magnetosheath field direction and an in/out plasma flow component normal to the magnetopause, are similar to those which accompanied pulses (1) to (6) in the November 1977 boundary layer crossing (Sckopke et al., 1981). Although the $B_N$ perturbation is not of the "classic" FTE type, a bipolar $B_N$ signal is observed when the data are plotted using either the Fairfield (1971) model magnetopause normal or a tangential discontinuity normal. It is interesting to note that ISEE 2, as also did ISEE 1 later, observed FTE-like signals before encountering the region of quasi-steady reconnection flow. For example, weak FTE signatures exist in the ISEE 2 $B_N$ record at $\sim$00:25 and $\sim$00:28 UT, each associated with a pulse of magnetosheath plasma.

These facts raise the question as to whether a sharp distinction can really be drawn between FTEs and the type of event discussed by Sonnerup et al. (1981) and referred to as "quasi-steady" reconnection. Cowley (1982) suggests that the two phenomena may simply represent different regions on a continuous spectrum of space and time scales. If variations occur in the rate at which reconnection erodes magnetic flux, one might expect bulges containing extra flux to form. As these bulges contract polewards in the reconnection flow they would give rise to FTE signals in the overlying magnetosphere and magnetosheath field regions but not in the central open field line region between. The dashed lines in Fig. 1 indicate schematically the distortion to the steady state reconnection field pattern envisaged due to the change in flux tube cross-section accompanying a pulse of increased eroded flux. Although Fig. 1 is drawn for antiparallel internal and external magnetic fields, similar field distortions would occur in cases where the fields are not strictly antiparallel. In this context, the ISEE satellite positions in Fig. 1 apply for the interval at 00:38 UT on 8 September 1978. Before and after the field bulge encounter, ISEE 1 is located earthward of the inner separatrix $S_I$, but crosses it as the bulge is passing. The plasma flow at ISEE 1 is dominated largely by an in/out motion associated with the bulge passage, but it is curious why the accelerated flows at ISEE 2 are substantially larger (see Fig. 2). While the interpretation outlined above is tentative, it provides a framework for empirical study.

## Reconnection or Diffusion: Which Process Dominates?

This review has highlighted the recent experimental evidence for magnetic field reconnection at the dayside magnetopause. Although some readers may disagree with this choice of emphasis, the ISEE satellite results have pointed up the significance of reconnection. This in situ evidence should be added to the large mass of indirect evidence accumulated during the past twenty years (Cowley, 1982). By its very nature a diffusive coupling process can not explain the accelerated plasma flows which a short scan of the ISEE Los Alamos/Garching plasma data shows are present commonly in the boundary layer.

It should be emphasized, however, that boundary layers also exist when the magnetosheath magnetic field is directed northward and there is no evidence either for quasi-steady or FTE reconnection. Clear examples of such BLs, which appear thick, unstructured and lacking in plasma acceleration, are seen in Fig. 1 of Russell and Elphic (1978) (also see Fig. 1 of Paschmann et al. 1978) and in Fig. 4 of Eastman et al. (submitted). The occurrence of boundary layers when the IMF is northward indicates that reconnection is not the only solar wind/magnetosphere coupling mechanism. For example, Reiff et al. (1981), in a study comparing the cross polar cap potential drop (typically 50–100 kV), measured by low altitude satellites with solar wind parameters, identify a background value of $\sim$30 kV that is independent of IMF orientation. They suggest that this voltage could be associated with a mechanism other than reconnection, although it may include a residual potential arising from earlier intervals when IMF $B_Z$ was southward, due to the inertia of the coupled atmosphere-ionosphere-magnetosphere convection system. To reduce the effect of such inertial lag, Wygant et al. (submitted) studied polar cap potentials following prolonged periods ($\sim$3 h) of northward IMF. They found that the voltage then declined to about 20 kV, a value which is comparable to the maximum in situ estimate for the convection potential generated by tailward closed flux tube transport in the low latitude boundary layer. For example, let us consider the 6 November 1977 boundary layer passage shown in Fig. 5. If, as Sckopke et al. (1981) favour, these boundary layer observations are on closed field lines, the typical pulse bulk speed ($\sim$150 km s$^{-1}$), field strength ($\sim$40 nT) and estimated layer width ($\sim$6,000 km), and the fact that such flows are present for roughly a third of the time, give a voltage of $\sim$12 kV, or $\sim$24 kV for dawn and dusk BLs combined. However, if as suggested here these BL flows are mainly on open field lines, then $\sim$24 kV is clearly an upper limit for the convection potential generated by non-reconnection processes. Similarly the combined voltage values of $\sim$5–25 kV suggested by the flank BL observations reported by Eastman (1979), Eastman and Hones (1979) and Eastman et al. (submitted), also should be considered upper limits for the voltage arising from closed BL flux tube motion. Thus, as observations at both low and high altitudes indicate that non-reconnection processes provide only a small, though possibly significant, fraction of the total magnetospheric voltage, diffusion at the magnetopause may be, at best, only of moderate importance in driving magnetospheric flows (also see Cowley (1982) for a detailed discussion of this topic).

In contrast, quasi-steady and FTE reconnection can easily give rise to voltages of the correct order for driving magnetospheric convection. The preliminary evidence available so far (Sonnerup et al., 1981) indicates that quasi-steady reconnection can occur over a broad region of the dayside magnetopause, covering roughly four hours of local time either side of noon (a linear dimension of $\sim 25\ R_E$). Using the inferred tangential electric field for the 8 September 1978 reconnection event of $\sim 1\ \mathrm{mV\ m^{-1}}$, gives a total voltage across this region of $\sim 150$–$200$ kV, which is a factor of 2–3 greater than typical cross-magnetosphere values. Although this voltage is an upper limit, since the instantaneous longitudinal extent of the reconnection region may be restricted, the value is compatible with reconnection playing a major role in magnetospheric dynamics.

The transfer of magnetic flux associated with FTEs also contributes a significant voltage. Russell and Elphic (1978) estimate the magnetic flux eroded by a single FTE to lie in the range $2 \times 10^6$ to $3 \times 10^7$ Wb. From the limited data published so far, FTEs recur typically on a 5–20 min timescale, so if $\sim 10^7$ Wb is transferred every $\sim 10$ min, the mean voltage associated with the process is $\sim 20$ kV. If the local time extent of an FTE is restricted, this value will be a lower limit, because not every FTE may be seen at a particular magnetopause location. In summary, the fact that total magnetospheric voltages of $\sim 50$–$100$ kV may be obtained readily from the observed reconnection processes but not from diffusively driven closed flux tube motion in the LLBL, supports the view that reconnection is the dominant process in coupling the solar wind to the magnetosphere and in driving magnetospheric convection.

## Conclusions and Key Remaining Questions

The major factor which limited magnetopause studies prior to ISEE was the time resolution and 2D nature of satellite plasma instrumentation. The high time resolution 3D fast plasma experiments on ISEE have provided the first convincing in situ evidence for quasi-steady (or large-scale) reconnection. More commonly though, reconnection seems to occur as a small-scale or localised process in the form of flux transfer events (FTEs), which can have either a normal or a reverse polarity, depending upon whether the nett motion of the open flux tube is north or south. The discovery of FTEs on open tubes within the magnetosphere, and the fact that most of the quasi-steady reconnection events published to date have clear FTEs in close association, (in one instance ISEE 1 observes an FTE simultaneous to ISEE 2 apparently seeing quasi-steady reconnection), is additional evidence that FTEs are reconnection phenomena. These recent findings strengthen the view that reconnection is the dominant mechanism for coupling solar wind mass and momentum to the magnetosphere.

An important remaining question concerns the IMF conditions under which reconnection takes place, and in particular, the factor determining whether it occurs as a quasi-steady or FTE process, if indeed a sharp distinction exists at all between these two phenomena. The only controlling parameter apparent so far is the dependence on IMF $B_Z$: all the reconnection events and FTEs published to date occur when IMF $B_Z$ is near to zero or negative. A topic also requiring further investigation is the location of the reconnection region: is it situated near the equator as Dungey (1961) predicted and as all the in situ evidence available so far largely supports, or does it also occur in the cusps as Haerendel et al. (1978) suggested? One also wishes to determine the source of the field-aligned currents which accompany FTEs, and to investigate where these currents close in the magnetosphere. Are they, for example, compatible in direction and magnitude with the low altitude Region 1 field-aligned currents as Cowley (1982) suggests? These are some of the present questions in a fascinating and rapidly progressing subject.

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