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FLUX TRANSFER EVENTS AT THE DAYSIDE MAGNETOPAUSE: TRANSIENT RECONNECTION OR MAGNETOSHEATH DYNAMIC PRESSURE PULSES?

M. Lockwood[1]

Rutherford Appleton Laboratory, Chilton, United Kingdom

Abstract. The suggestion is discussed that characteristic particle and field signatures at the dayside magnetopause, termed "flux transfer events" (FTEs), are, in at least some cases, due to transient solar wind and/or magnetosheath dynamic pressure increases, rather than time-dependent magnetic reconnection. It is found that most individual cases of FTEs observed by a single spacecraft can, at least qualitatively, be explained by the pressure pulse model, provided a few rather unsatisfactory features of the predictions are explained in terms of measurement uncertainties. The most notable exceptions to this are some "two-regime" observations made by two satellites simultaneously, one on either side of the magnetopause. However, this configuration has not been frequently achieved for sufficient time, such observations are rare, and the relevant tests are still not conclusive. The strongest evidence that FTEs are produced by magnetic reconnection is the dependence of their occurrence on the north-south component of the interplanetary magnetic field (IMF) or of the magnetosheath field. The pressure pulse model provides an explanation for this dependence (albeit qualitative) in the case of magnetosheath FTEs, but this does not apply to magnetosphere FTEs. The only surveys of magnetosphere FTEs have not employed the simultaneous IMF, but have shown that their occurrence is strongly dependent on the north-south component of the magnetosheath field, as observed earlier/later on the same magnetopause crossing (for inbound/outbound passes, respectively). This paper employs statistics on the variability of the IMF orientation to investigate the effects of IMF changes between the times of the magnetosheath and FTE observations. It is shown that the previously published results are consistent with magnetospheric FTEs being entirely absent when the magnetosheath field is northward: all crossings with magnetosphere FTEs and a northward field can be attributed to the field changing sense while the satellite was within the magnetosphere (but close enough to the magnetopause to detect an FTE). Allowance for the IMF variability also makes the occurrence frequency of magnetosphere FTEs during southward magnetosheath fields very similar to that observed for magnetosheath FTEs. Conversely, the probability of attaining the observed occurrence frequencies for the pressure pulse model is 10^{-14}. In addition, it is argued that some magnetosheath FTEs should, for the pressure pulse model, have been observed for northward IMF: the probability that the number is as low as actually observed is estimated to be 10^{-10}. It is concluded that although the pressure model can be invoked to qualitatively explain a large number of individual FTE observations, the observed occurrence statistics are in gross disagreement with this model.

1. Introduction

Evidence for transient magnetic reconnection at the dayside magnetopause was put forward in 1978 by two sets of authors independently. Russell and Elphic [1978] noted characteristic signatures in the magnetic field close to the magnetopause, as observed by the ISEE 1 and 2 spacecraft, which they termed "flux transfer events" (FTEs). Independently, Haerendel et al. [1978] discussed what they termed "flux erosion events," observed by the HEOS 2 spacecraft. Subsequently, a large number of studies have interpreted these signatures in terms of the remnant newly opened flux tubes produced by time-dependent, and spatially localized, magnetic reconnection, as proposed by Russell and Elphic [e.g. Paschmann et al. 1982; Cowley, 1982; Berchem and Russell, 1984; Rijnbeek et al., 1984; Saunders et al., 1984; Southwood et al., 1986; Farrugia et al., 1987a; Lockwood et al., 1988].

Recently, however, there has been a revival of interest in the effects of solar wind and/or magnetosheath dynamic pressure pulses on the magnetosphere. Much of this has been due to the similarity of transient flow and current signatures, observed in the dayside auroral ionosphere in association with dynamic pressure pulses, to those originally predicted for FTEs. This has prompted Sibeck [1990] to question whether magnetopause FTE signatures are indeed caused by transient reconnection and to propose that such effects can often, or perhaps always, be attributed to magnetopause motions in response to transient changes in the dynamic pressure of the solar wind, at least in the magnetosheath. The similarities between dynamic pressure pulse and transient reconnection signatures at the dayside magnetopause were also pointed out by Elphic [1988].

Transient currents in the dayside auroral ionosphere in response to a major solar wind dynamic pressure increase were observed by Farrugia et al. [1989], who also observed the associated inward compression of the magnetopause. In addition, Sibeck et al. [1989a] have shown that both the vortical flow event described by Todd et al. [1986] and one of the vortical current events described by Lanzerotti et al. [1987] followed shortly after changes in the solar wind dynamic pressure. This has led to much debate as to whether these ionospheric events may have been caused by the dynamic pressure changes [Lanzerotti, 1989; Sibeck et al., 1989b; Bering et al., 1990; Lockwood et al., 1990]. These observations had previously been interpreted as possible ionospheric FTE signatures, based on predictions for a circular ionospheric footprint of a newly-reconnected FTE flux tube with uniform and constant ionospheric conductivities [Southwood, 1985, 1987; Lee, 1986; McHenry and Clauer, 1987]. However, recently Lockwood et al. [1990] and Elphic et al. [1990] have presented strong evidence that transient dayside aurorae and associated bursts of flow are FTE signatures. These events are greatly elongated along the polar cap boundary and accompanied by considerable conductivity structure and changes [see Sandholt et al., 1990]. For these, and other, reasons the flow and current signatures differ significantly from the original expectations of FTE effects in the ionosphere. It is therefore somewhat ironic that other processes, probably induced by solar wind dynamic pressure changes, appear to be able to produce signatures which are very similar to those originally predicted for FTEs.

The ionospheric signatures of FTEs and dynamic pressure pulses have been discussed in detail by Lockwood et al. [1990] and it is not the purpose of this paper to discuss them further. Rather we wish to investigate the magnetopause signatures predicted for such effects, compare them with various examples of FTE observations, and consider the implications for the statistical surveys of FTE occurrence by Rijnbeek et al. [1984], Berchem and Russell [1984], Southwood et al. [1986], and Smith and Curran [1990].

2. Predicted Magnetopause Signatures

Structures in the dayside magnetopause produced by a burst of transient reconnection or by a pulse of enhanced solar wind dynamic pressure will cause variations to be observed by a spacecraft close to this boundary (see review by Elphic [1988]). This section presents

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[1] Also at Blackett Laboratory, Imperial College, London.

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predictions of the signatures which would be expected by spacecraft at various distances from this boundary. Because FTEs are primarily detected by a characteristic bipolar disturbance in the boundary normal magnetic field, B_N, we consider only this component initially. (Note that B_N is defined as positive for the outward normal to the magnetopause, i.e., away from the Earth.) We also consider the particle populations which would be observed by the spacecraft.

The transient reconnection model (model "A") employed is that originally suggested by Saunders [1983] and recently expanded by Southwood et al. [1988] and Scholer [1988a, b, 1989]. This model is similar to that originally invoked by Russell and Elphic [1978, 1979] to interpret FTEs, other than the facts that the reconnection burst is not necessarily limited to a short (~1-2 Earth radii, R_E) reconnection X line and that some reconnection can continue after the burst. It is used here because it can explain electron streams observed on the edges of the newly reconnected flux tube and the observed flux of heat away from the X line in terms of the ongoing reconnection. In addition, the putative ionospheric FTE signatures reported by Lockwood et al. [1990] and Elphic et al. [1990] (the latter seen in association with conjugate spacecraft measurements of magnetopause FTEs) indicate longer (~10 R_E) reconnection X lines. However, it should be noted that, with the notable exception of the electron streams and heat flux, the magnetopause signatures predicted here would be virtually the same for the Russell and Elphic model.

The dynamic pressure pulse model (model "B") is that proposed by Sibeck [1990]. This model invokes suggestions of a plasma depletion layer (PDL) outside the magnetopause. This layer could contain a mixture of magnetosphere-like and magnetosheath-like plasmas, but is outside the magnetopause as defined by the change in inclination of the magnetic field. A similar layer of mixed plasma inside the magnetopause is called the low-latitude boundary layer (LLBL), the existence of which is well established. In general a discontinuity could be present at the interface of the PDL and LLBL (i.e., at the magnetopause); however, in order to simulate the FTE observations of Farrugia et al. [1988], Sibeck does not in his paper invoke any change in plasma characteristics at the magnetopause; i.e. the LLBL and PDL together form a gradual transition between magnetosphere and magnetosheath plasma characteristics. This assumption is also adopted here. Recently, several authors have questioned how common the PDL is and whether or not it contains magnetosphere-like plasma or just magnetosheath plasma of lower density than the remainder of the sheath [for example, Hall et al., 1991]. This really is a question of where the magnetopause (defined as where the inclination of the magnetic field changes) usually lies relative to the plasma transition region. In his model, Sibeck places it at the center of this region (i.e., there is both a LLBL and a PDL), whereas Hall et al. place it at the outer edge of the transition region (i.e., there is a LLBL but no PDL). This latter, experimental, observation is interesting because it relates to the magnetopause crossing on the same pass of the Active Magnetospheric Particle Tracer (AMPTE) UKS satellite as the FTE described in detail by Rijnbeek et al. [1987] and Farrugia et al. [1988]: this FTE is the one modeled by Sibeck [1990] by assuming that a PDL was present. However, in this paper we will not discuss further the occurrence probability or characteristics of the PDL, rather we will include it in our discussion in the same way as did Sibeck [1990]. Another important assumption in the pressure pulse model is that the LLBL is considerably thicker during periods of northward interplanetary magnetic field (IMF) than it is when the IMF is southward. Mitchell et al. [1987] found that the ISEE satellites spend more time in the LLBL in the magnetosphere flanks during northward IMF: from this the LLBL has been inferred to be thicker when the IMF points northward. There is no generally accepted explanation as to why this may be the case (one suggestion by Nishida [1989] involves formation of the LLBL by sporadic patchy reconnection throughout the dayside magnetopause), nor has it been satisfactorily demonstrated by a statistical survey. However, this paper does not seek to question this assumption and starts from the premise that the LLBL is thicker for northward IMF and that this does have the effects postulated by Sibeck.

Figure 1 shows the magnetopause structure predicted for models A and B, in the rest frame of the event as it moves away from the equatorial plane. We consider events moving north in the northern hemisphere, which, as we shall see, yield "standard polarity" signatures (i.e., positive B_N deflection followed by a negative one). Events moving south in the southern hemisphere in all cases give the reversed sequence (i.e., a "reversed polarity" event).

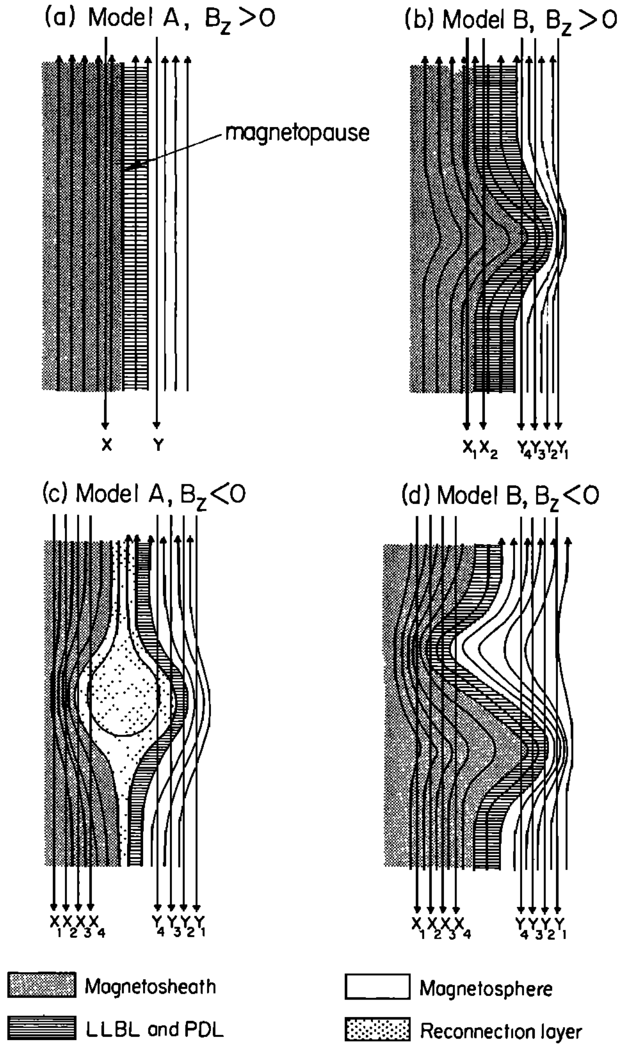

Fig. 1. Magnetopause boundary deformations for two models of FTEs. (a and c) The time-dependent reconnection model of Southwood et al. [1988] and Scholer [1988a] (model A). (b and d) The dynamic pressure pulse model (model B) proposed by Sibeck (1990). (a and b) are for northward IMF, (c and d) are for southward IMF. In each case, the solid line within the PDL/LLBL is the magnetopause, as defined by the inclination of the magnetic field, except in Figure 1c where it is the last closed field line. The various plasma regions are shaded according to the key given. Structures in the boundary are shown in their own rest frame in which satellites initially within the magnetosheath (X_n) or magnetosphere (Y_n) move in the direction shown. Events are considered moving northward in the northern hemisphere.

2.1. Northward IMF Signatures

Figure 1a shows the situation predicted for the reconnection model (A) when the IMF, and hence the magnetosheath field, is northward. The LLBL is inside the magnetopause. A PDL may or may not be present, but because it is not important to the model it is omitted here. A satellite X is on the magnetosheath side of the boundary, and another Y is on the magnetosphere side. This case is trivial because there is no perturbation to the magnetopause or the LLBL, and hence no variation is seen by any spacecraft in either particles or fields.

Figure 1b shows a boundary indentation during a transient magnetopause event induced by a pulse of enhanced magnetosheath dynamic pressure (model B). (This will generally be produced by a pulse of enhanced dynamic pressure of the upstream solar wind, but it has been suggested that it could be produced by the bow shock when the IMF points approximately radially [Fairfield et al., 1990].) At this point it should be noted that it has never been demonstrated that a patch of solar wind plasma of enhanced dynamic pressure will, in fact, survive passage through the bow shock and appear as a similar patch at the magnetopause. Indeed, from the gas-dynamic model, it may be expected that the enhanced pressure would be applied to the entire dayside magnetopause and not produce a localized indentation [see Elphic, 1988]. Nonetheless, seemingly localized compressional magnetopause events have been observed, apparently in conjunction with increases in solar wind dynamic pressure [Sibeck et al., 1989a; Fairfield et al., 1990], and this paper does not address this concern. Rather, it accepts the postulate of the dynamic pressure model that the patch is incident upon (and indents) the magnetopause. In Figure 1b, the IMF has a northward component. The event moves along the magnetopause, away from the point of impact with the magnetosheath flow, as described by Sibeck [1990]. Figure 1 shows events in their own rest frame, for which the satellites (X_n and Y_n) move in the direction shown. In Figure 1b, the magnetosheath field lines are drawn as indented within the event, and the magnetosphere field lines are draped over it. Sibeck [1990] has pointed out that the boundary-normal flow (and hence the B_N perturbation) will be smaller for a trough (as the event in Figure 1b appears from the magnetosheath) than for a crest (as the same event appears from the magnetosphere).

Figure 2 gives the boundary normal magnetic field component, B_N, expected as the event passes over the satellites, which are at various distances from the unperturbed magnetopause, as shown in Figure 1b. The shading denotes the type of plasma population which would be observed, using the same shading scheme as Figure 1. In all cases, a bipolar B_N signature is observed, the primary characteristic of FTE observations.

Figure 2a is for satellite X_1, which always remains within the magnetosheath, whereas Figure 2b is for X_2, which is initially in the PDL but moves briefly into the magnetosheath at the event center. As discussed above, these perturbations observed outside the magnetosphere will be weaker than the corresponding signatures within the magnetosphere; section 4.3 discusses the probability that they would be observed. Figures 2c - 2f show the various magnetosphere signatures which would be observed. Satellite Y_1 remains within the magnetosphere proper; Y_2 enters the LLBL; Y_3 enters the LLBL and the PDL; while Y_4 passes through both the LLBL and the PDL and briefly enters the magnetosheath during the event. The signature for Y_4 is that invoked by Sibeck [1990] as an explanation of the FTE structure observed by Farrugia et al. [1988], with one generalization. In his Figure 5, Sibeck does not predict any change in B_N as the satellite passes through the magnetopause. This requires B_L in the magnetosheath to have the same magnitude as in the magnetosphere. Although this coincidence could occur, in general we would expect B_L to vary across the magnetopause, and hence we would see a discontinuity in B_N. In Figures 2e and 2d, the magnetosheath B_L is taken to be a bit smaller than in the magnetosphere. However, the discontinuity would not normally cause the bipolar B_N signature to fail to be classified as an FTE, except possibly if B_L in the magnetosheath was only very weakly northward.

2.2. Southward IMF Signatures

The reconnection model invoked here (A) is shown in Figure 1c. We have not included a PDL, but we will comment on the effect on magnetosheath FTE signatures were it to be present. The Southwood et al. [1988]/Scholer [1988a] FTE model predicts a bubble in the magnetopause reconnection layer produced by a burst of enhanced reconnection rate. This bubble is threaded by loops of newly opened field lines, produced by the burst of enhanced reconnection rate. The reconnection layer plasma is a mixture of warmed magnetosheath and magnetosphere plasma. Scholer [1989] has shown by numerical simulations of this model that the plasma characteristics within the bubble need not be homogeneous, which would add structure within the event as seen by satellites X_3, X_4, Y_3, and Y_4. Note that in Figure 1c, the solid line between the LLBL and the reconnection layer is the last closed field line: in the other parts of this Figure, the solid line in the LLBL/PDL is the magnetopause, as defined by the magnetic field inclination.

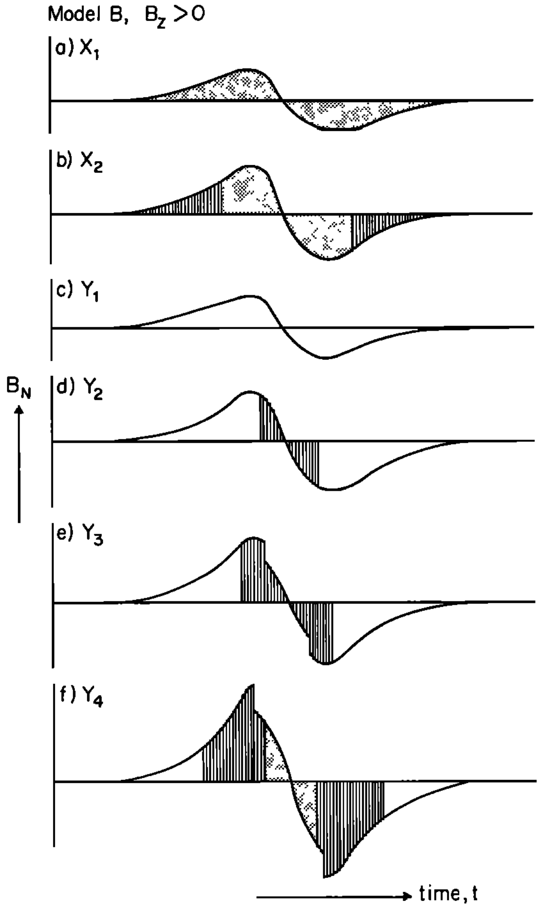

Fig. 2. Boundary normal magnetic field variations, B_N, for the dynamic pressure pulse model (B) and northward IMF (i.e., for the magnetopause structure shown in Figure 1b). The shading defines the plasma population using the same coding as Figure 1. The various parts refer to the satellites shown in Figure 1.

The signatures expected for the eight spacecraft shown are plotted in Figure 3. In every case, there is the bipolar B_N signature characteristic of FTEs. The satellites X_1 and X_2 see a bipolar signature (Figure 3a), but because they both remain within the magnetosheath (i.e., they only observe the draped field), the only difference between the two will be that X_2 will see a larger signature than X_1. If, however, a layer of energetic magnetospheric particles were present outside the magnetopause, X_2 could see some magnetosphere-like plasma at the event center. Satellites X_3 and X_4 cut into the reconnection layer at the event center (Figure 3b), and any PDL would be observed at the edges of the reconnection layer. Because the edges of the reconnection layer map to the reconnection X line, streaming (~100 eV) electrons may also be present there. Satellites X_3 and X_4 would observe unidirectional streams away from the X-line if some reconnection continued after the burst which gave rise to the FTE. Note that satellites Y_3 and Y_4 would see bidirectional counterstreaming electrons on the edges of the reconnection layer: these would be produced at the X line, stream earthward, and mirror at low altitudes.

The magnetosphere signatures are shown in Figures 3c - 3e. Figure 3e is the reconnection explanation of the structure reported by Farrugia et al. [1988], which can be compared to Figure 2f, which is the corresponding prediction for the pressure pulse model. With the possible exception of the discontinuities in B_N in the latter, there are

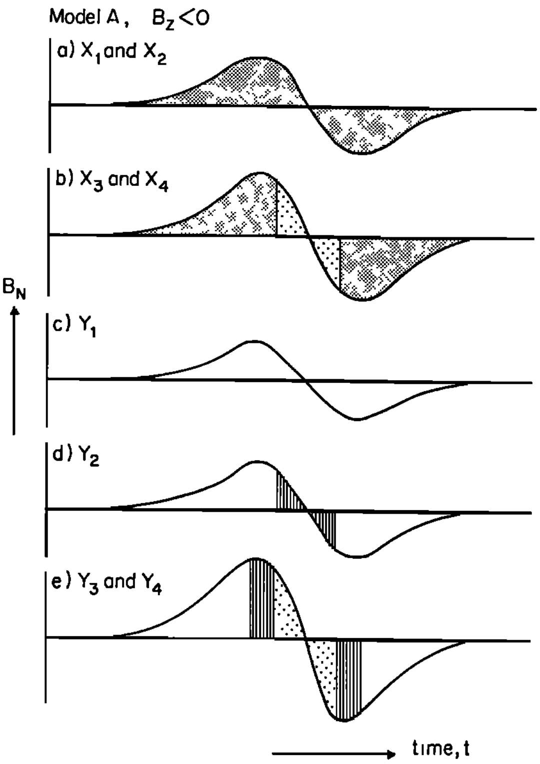

Fig. 3. Same as Figure 2, but for the reconnection model (A) and southward IMF (as in Figure 1c).

no significant differences, at least in the B_N and basic particle characteristics, to which we have confined our attention here. However, it should be noted that model A places the satellites X_4 and Y_4 in the reconnection layer at the event center, whereas for model B, Y_4 enters the magnetosheath. Hence high- resolution plasma observations which can differentiate between the reconnection layer and the magnetosheath/PDL or the magnetosphere/LLBL may offer discrimination of these two models.

Figure 1d shows the event for the pressure pulse model (B) during southward IMF, as presented by Sibeck [1990]. The vital difference, compared with the northward IMF case (Figure 1b), is that the boundary bulges out ahead of the indentation. The proposed mechanism for this is that the LLBL is thinner for southward IMF. This means that the region of higher plasma density does not extend as far into the magnetosphere and the speed of the fast mode compressional wave inside the magnetosphere is greater. The fast mode wave may then move faster than the dynamic pressure discontinuity in the magnetosheath, and it is proposed that this produces an outward bulge in the magnetopause which grows as the discontinuity propagates along the boundary. Behind the discontinuity the boundary is indented by the enhanced dynamic pressure, as in the northward IMF case. Figure 1d is of the same form as that given by Sibeck [1990] (his Figure 4), other than that the outer edge of the PDL has been indented to a greater extent to allow the magnetosphere satellite Y_4 to emerge into the magnetosheath proper, as postulated by Sibeck in his explanation of the Farrugia et al. [1988] "crater" FTE observations. Note that as the fast mode outruns the indentation, the boundary distortion will disperse.

The B_N signatures for this form of boundary perturbation are shown in Figure 4. All signatures are generally tripolar (and some are pentapolar) rather than bipolar. As discussed by Sibeck [1990], the draping caused by a trough in the boundary will be weaker than that for a crest, and the trailing deflections seen by satellites X_1 and X_2 are shown as weaker in Figures 4a and 4b for this reason. However, that they are weaker does not necessarily mean that they will not be detected. Sibeck shows field lines which would give tripolar signatures in his Figure 4 (and shows twin vortical flows in his Figure 2, which are equivalent to a tripolar signature, with outward, inward and then outward motions); however, in his discussion of signatures in his Figure 4 and text, he comments only on the outward and inward motions around a boundary crest and neglects completely the trailing (for these magnetosheath cases) outward motion and corresponding B_N deflection. One possible reason for neglecting this trailing B_N deflection may be that the fast mode speed inside the magnetosphere is so much greater than the magnetosheath flow speed that the boundary deformation shown in Figure 1d is highly dispersed, especially if the event is observed far from the point of initial impact on the magnetopause. This could mean that the trough arrived at the satellite so much later than the crest that its signature would not necessarily be associated with that of the crest.

The signatures in Figures 4a and 4b undoubtedly constitute "B_N activity," but one must consider whether they would be classed as FTE signatures or not. It could be argued that the tailing, positive B_N deflection would be too small to be detected (because of fluctuation levels in B_N outside the event or because of uncertainties in the derived boundary normal direction) and the event would then be

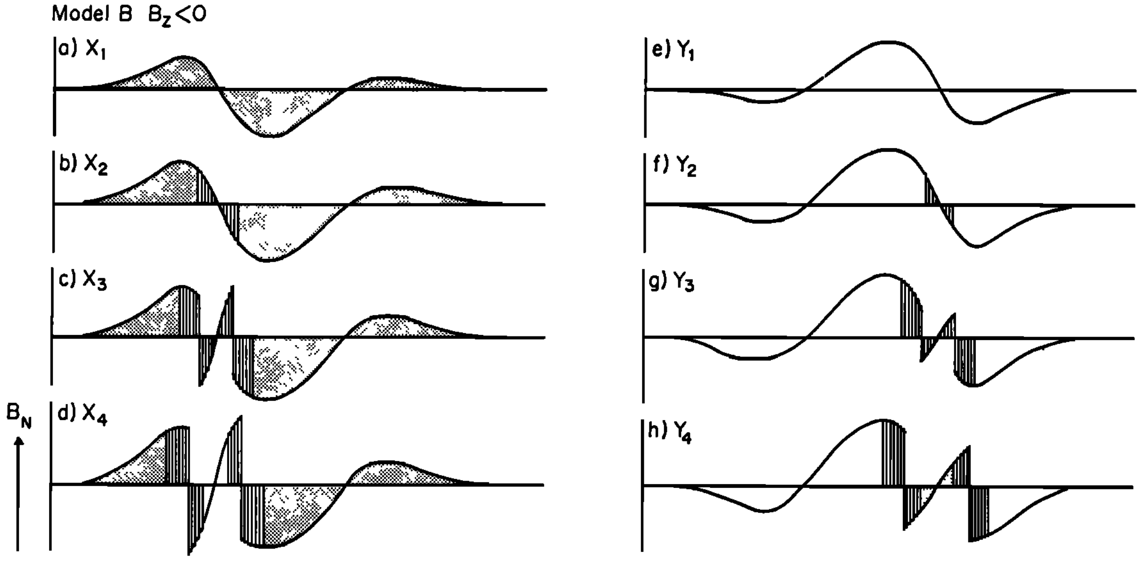

Fig. 4. Same as Figure 2, but for the pressure pulse model (B) and southward IMF (as in Figure 1d).

classed as a standard polarity, bipolar FTE. Alternatively, it is possible that the event would be classed as an irregular FTE. The third possibility is that such events are sufficiently tripolar that they would not have been classed as FTEs at all. In this paper, we will consider the implications of the first two alternatives, i.e., that the pressure pulse gave a signature which would have been classed, at least sometimes, as an FTE.

In Figure 4a we see that satellite X_1 remains entirely within the magnetosheath, whereas in Figure 4b, X_2 enters the PDL. In Figures 4c and 4d the satellites (X_3 and X_4) pass through the magnetopause and hence observe almost discontinuous polarity reversals in B_N, as they encounter the northward field of the magnetosphere. It seems unlikely that such events would be classed as FTEs, unless they were regarded as two asymmetric, standard polarity FTEs of unusually short duration and short repetition period. This interpretation would not stand under inspection of the particle data.

Corresponding signatures are predicted on the magnetopause side of the boundary. Again, signatures for the satellites further from the boundary (Y_1 and Y_2) are generally tripolar. This time the weaker signature is a negative B_N deflection which precedes the larger part of the event. It is very difficult to see how this leading B_N deflection could be absent in this case, given that the outward bulge in the boundary is compressional and hence field lines close to the boundary would be expected to move outward as well. The discontinuities are apparent for Y_3 and Y_4 when they cross the magnetopause. Similar questions arise as to which of these signatures may have been classed as FTEs in the past, as for the magnetosheath cases.

3. Observed Magnetopause Signatures

Many observations of FTEs have been presented, and it is not the purpose of this paper to review them, nor to discuss individual cases in detail. This is because results for any one case may not apply to all, or even many other, cases. However, some of the characteristics of the observations are commented upon in the light of the above predictions.

3.1. Magnetosheath FTEs

All but a very few magnetosheath FTEs are observed when the IMF/magnetosheath field is southward [Berchem and Russell, 1984; Rijnbeek et al., 1984]. Many examples have been presented in the literature [e.g., Russell and Elphic, 1979, Figure 1; Rijnbeek et al., 1984, Figures 1 and 2; Berchem and Russell, 1984, Figures 2, 3, 4, 6, and 7; Saunders et al., 1984, Figure 1]. In most of these cases, no third deflection following the main bipolar deflection can be detected. However, examples of tripolar FTEs in the magnetosheath can be found. An example is Figure 5 of Berchem and Russell; however, it is interesting to note that this example is for positive sheath field, for which neither model predicts the tripolar signature. Observations by the ISEE spacecraft [e.g., Saunders et al., 1984, Figure 1] show that there is a rise in energetic ion and electron fluxes inside many magnetosheath FTEs, but a drop in the total electron densities. In the dynamic pressure model, these cases must be for satellites such as X_2 in Figure 1d (observing the sequence shown in Figure 4b); i.e., the satellite must enter the PDL but not pass through the magnetopause. This underlines the importance of the PDL to the pressure pulse model, which would not offer an explanation of the particle characteristics of magnetosheath FTEs if the PDL were only rarely present during southward IMF. Nor indeed would this model stand if the PDL were merely a depletion of the magnetosheath; there must be a layer of plasma of magnetospheric origin outside the point where the field inclination changes for model B to explain magnetosheath FTE signatures. Hence improved knowledge of the occurrence (as a function of IMF B_z) of the PDL and energetic particle layer outside the magnetopause as well as of the various particle characteristics inside FTEs is vital to test the pressure pulse model on this point.

Several tests are suggested for magnetosheath FTEs. The higher-resolution particle data from the AMPTE satellites could resolve plasma which was purely magnetospheric from that of the LLBL/PDL: if magnetospheric plasma was found in the center of the event (as shown in Figure 4d for satellite X_4), the B_N signature could no longer be bipolar for model B. Another observation of interest would be of magnetosheath FTEs during northward IMF. The particle data should not show any magnetosphere-like plasma for the pressure pulse model, as the B_N signature is due to the magnetopause (and with it the PDL and LLBL) being indented, away from the spacecraft. This would cause the field strength to drop in the event, whereas for an outward bulge in the boundary and southward IMF (giving the same B_N signature) it would increase.

3.2. Magnetosphere FTEs

The most detailed case studies of a magnetospheric FTE are those presented by Rijnbeek et al. [1987] and Farrugia et al. [1988]. These AMPTE observations show a clearly bipolar B_N signature and no discontinuity in B_N inside the event plasma boundary layer. To explain this the pressure pulse model must assume that the magnetosheath field was northward and that the B_L components were roughly equal on both sides of the magnetopause. Sibeck [1990] states that the IMF was northward during this event, but does not show any data to substantiate this assertion, which is vital to the pressure pulse interpretation.

For southward magnetosheath field, the magnetosphere signatures for the pressure pulse model would be expected to be generally tripolar. Because the dynamic pressure pulse model explains the magnetosheath FTEs in terms of Figure 1d, these signatures should be quite common. Possible examples are shown in Figure 3 of Rijnbeek et al. [1984] (particularly those at 0554 and 0603 UT), but the general level of B_N fluctuations makes it hard to discern if there are genuine third deflections in these case. However, for a satellite within the magnetosphere, the weaker, additional deflection (due to the trough in the boundary, rather than the crest, as seen from the magnetosphere) would preceed the main signature (see Figures 4e and 4f), whereas in both these experimental examples the first B_N deflection is the greatest.

Recently, Klumpar et al. [1990] have used plasma data from the AMPTE CCE spacecraft to suggest that the ion velocity distributions, composition, and flows inside magnetosphere FTEs are "unique to the FTE and unlike either the adjacent magnetosphere or nearby boundary layer or nearby magnetosheath." If confirmed, this inference would argue strongly against the pressure pulse model (B) and for the reconnection model (A) because the reconnection layer has distinct plasma properties. However, it has not been shown conclusively that the plasma data have sufficient resolution to support this inference.

3.3. Two-Regime FTEs

Farrugia et al. [1987b] have presented examples of what they term "two-regime" FTE observations. In these cases, FTEs are observed simultaneously on both sides of the magnetopause. Another example of such an event is shown here in Figure 5. The plot shows the magnetic field components (in boundary normal coordinates) during an outbound pass of the ISEE 1 and 2 satellites (heavy and light lines in the figure, respectively). The distance between the two spacecraft is 5227 km. If we define the separation vector as pointing from ISEE 2 to ISEE 1, it has components $\Delta X=-4993$ km, $\Delta Y=1108$ km, and $\Delta Z=-1077$ km in GSM coordinates. Hence ISEE 2 is sunward of ISEE 1 (ΔX is negative). From the best estimate of the plane of the magnetopause boundary, the separation of the spacecraft along the boundary normal is $\Delta N=-4717$ km and in the plane of the boundary is $(\Delta M^2+\Delta L^2)^{0.5}$ = 2252 km. From the B_L component, we determine that both spacecraft were within the magnetosphere around 0610 UT, and that by 0620 UT, ISEE 2 (light trace) is out in the magnetosheath but ISEE 1 is still within the magnetosphere: ISEE 1 appears to make a partial exit from the magnetosphere around 0623 UT, returning to the magnetosphere about 2 minutes later and exits abruptly at 0630 UT. Between 0625 and 0630 UT both satellites detect a standard polarity FTE. The boundary normal direction was determined in the normal manner as described by Russell and Elphic [1978]: the fact that ISEE 2 observed consistently negative B_N outside the event suggests there may be some error in this determination. The B_N variation observed by ISEE 2 is a classic bipolar form, with no hint of the trailing third deflection predicted generally for the magnetosheath and southward IMF by model B (Figure 4a or 4b). The ISEE 2 spacecraft

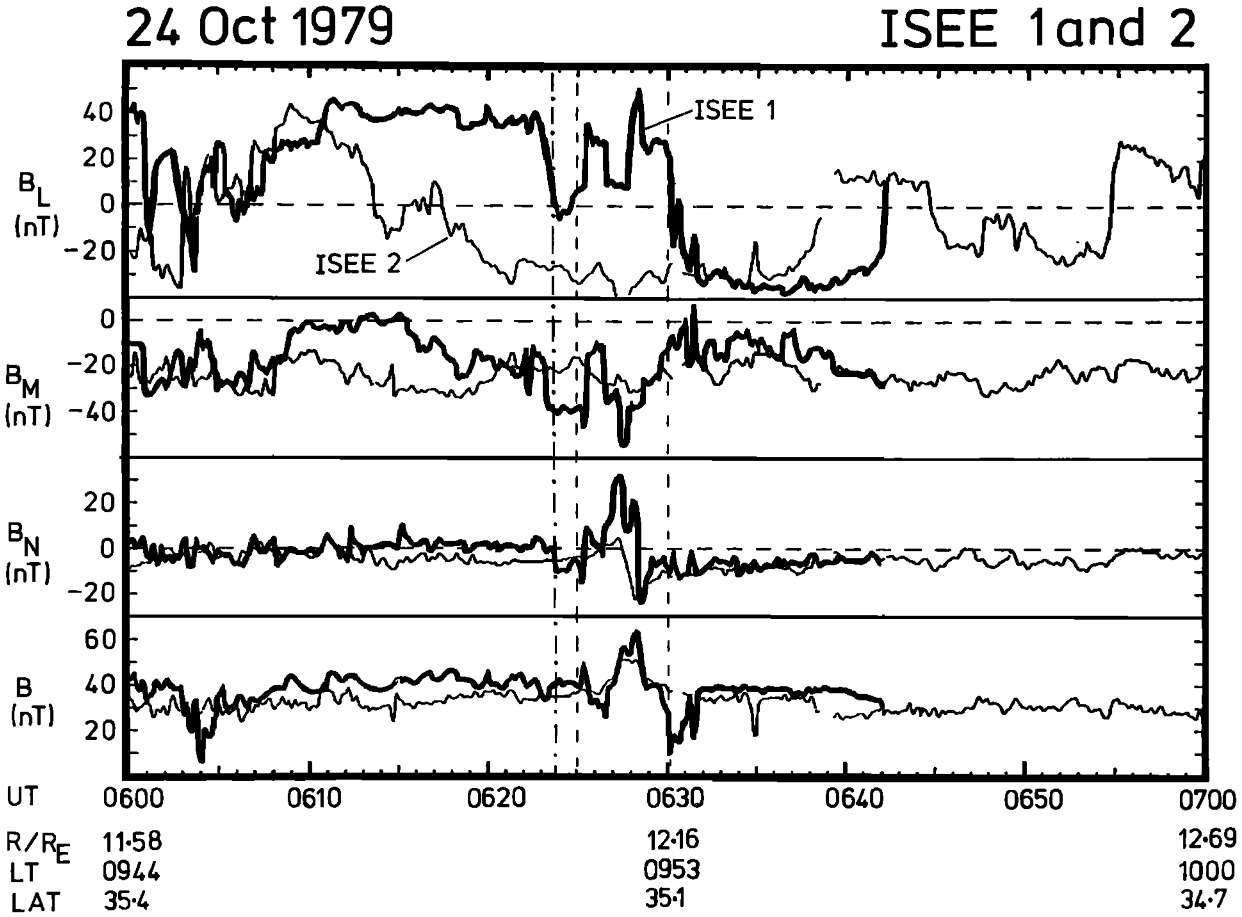

Fig. 5. A two-regime FTE observation by the ISEE satellites on October 24, 1974. Magnetic field components are shown in boundary normal coordinates as a function of time for ISEE-1 (heavy lines) and ISEE-2 (lighter lines). The dashed lines mark an FTE seen by ISEE 1 in the magnetosphere and by ISEE 2 in the magnetosheath (at 0625-0630 UT). The dot-dash line near 6:24 UT marks a partial and brief exit of ISEE 1 from the magnetosphere.

observed the magnetosheath field to be strongly southward. In the interval 0625-0630, ISEE 1 is within the magnetosphere (positive B_L) and also observes an FTE. In this case, there is a weak negative B_N deflection between 0623 and 0625 which, on its own, could be interpreted in terms of the preceding weak deflection for model B during southward IMF discussed in regard to Figures 4e and 4f. Thus far, we have confined our attention to the B_N signature; however, during the period 0623-0625 UT, B_L at ISEE 1 was negative or near zero (i.e., ISEE 1 made a partial magnetopause crossing in this period). This conflicts with the pressure pulse model where the third B_N deflection arises specifically because B_L is positive and the boundary is deformed. In addition, model B would predict that at 0623-0625 UT, ISEE 1 should be further from the magnetopause (which is then bulging out ahead of the indentation), whereas the data show that this satellite is almost exactly at the magnetopause in this interval. Hence the ISEE 1 data conflict with the idea that the ISEE 2 signature was caused by an outward bulge of the boundary. Note also that, despite the very close proximity of ISEE 1 to the magnetopause, no signature of the kind predicted in Figures 4g and 4h is observed.

One further test which can be applied has been described by Elphic [1990], namely to look at the timing of the deflections seen by the two spacecraft. Consider, first, that the separation vector between the two satellites were exactly normal to the boundary. For the pressure pulse model, the positive B_N deflection seen by ISEE 2 would then be coincident with a (weak) initial negative deflection at ISEE 1, and the negative deflection seen by ISEE 2 should coincide with the positive deflection seen at ISEE 1. Conversely, for the reconnection model, the two satellites would see the bipolar signatures simultaneously. The problem with this test is that, in general, the spacecraft are not aligned along the boundary normal and hence the exact timings of the B_N deflections depend upon the direction of motion and orientation of the event. Hence uncertainties in these directions, and in the orientation of the boundary, introduce uncertainties in this timing test [Elphic, 1990]. In Figure 5, both spacecraft observed standard polarity events in the northern hemisphere (i.e., northward moving), and ISEE 2 is roughly 1000 km northward of ISEE 1. Hence one would expect that the ISEE 2 signature would be delayed relative to that seen by ISEE 1. Calculation of this delay is vital for this test. The satellites are separated by ~2250 km in the boundary plane, and hence the event velocity and orientation in the boundary must both be known accurately. This would be best determined by at least one more nearby satellite, which will not be possible until the Cluster mission. Plasma data are not available for the event reported here, and hence we do not attempt this timing test in this paper. Farrugia et al. [1987b] and Elphic [1990] have used plasma flow measurements in two-regime events to define the event velocity and conclude that they are consistent in their phasing of signatures with model A.

To conclude this section we note that one can interpret most available observations, at least qualitatively, in terms of either model, by invoking a certain satellite path through the event and attributing certain unsatisfactory features (such as the lack of a fully tripolar B_N signature) to measurement uncertainties and others (such as the lack of discontinuity in B_N at the magnetopause) to chance occurrences. We have only considered the B_N variation and a broad description of the particle characteristics. More detailed analysis is required to see if other characteristics are explicable quantitatively using either model. However, we do not rely on such arguments here. Model B is particularly unsatisfactory as an explanation for two-regime observations by the ISEE satellites and of high-resolution plasma measurements within magnetosphere FTEs by AMPTE CCE, but neither of these tests has yet proved conclusive. We also note that recently, R.C. Elphic et al. (The search for pressure pulses observed in conjunction with flux transfer events: an AMPTE/ISEE case study, submitted to Geophysical Research Letters, 1990) have carried out a superposed-epoch study of 16 FTEs, observed on either side of the magnetopause by the ISEE spacecraft during a single pass. They found no consistent variation in the total magnetosheath pressure (the sum of magnetic, thermal, and dynamic pressures), as observed simultaneously by the AMPTE IRM and UKS satellites. Their analysis strongly argues against model B, for this pass at least. However, completely unambiguous discrimination between the two models in individual cases may require the data from the four-spacecraft Cluster mission.

4. Occurrence Statistics

The problem with case studies of the type given in the previous section is that one can never be sure that any given event is not unusual in some way, i.e., that it is not one of a subset of FTE observations which is relatively rare. This means that even if a particular event does discriminate between the two models, conclusions about FTEs in general cannot be drawn. The main evidence that FTEs are due to transient reconnection comes primarily from the statistical surveys of Berchem and Russell [1984] and Rijnbeek et al. [1984] (the latter results were also confirmed by Southwood et al. [1986] and Smith and Curran [1990]) that FTEs occur predominantly when the IMF/magnetosheath field is southward. In fact, these surveys indicate that southward IMF is almost a necessary and sufficient condition for FTEs to occur.

However, care must be taken concerning the procedures adopted in these surveys of magnetopause data. Berchem and Russell studied only magnetosheath FTEs observed by the ISEE 1 and 2 satellites and compared with the IMF observed by the ISEE 3 and IMP 8 satellites. These authors made allowance for the propagation delay from the satellites in the interplanetary medium to the magnetopause and the uncertainties inherent in its calculation. They found that magnetosheath FTEs were virtually only observed when the IMF was southward. This is readily explained by the reconnection model. However, the magnetosheath FTEs could also be explained by the dynamic pressure pulse model, but only if certain further assumptions are made. Principally, these are that (1) the bipolar B_N signatures in the magnetosheath predicted in Figures 2a and 2b for northward IMF cannot be detected (no matter how large the incident pressure pulse) and (2) nor can the second positive deflection (i.e., the third part of the generally tripolar signature) predicted in Figures 4a and 4b for southward IMF. The first of these assumptions will be studied in section 4.3; the second was discussed earlier.

Rijnbeek et al. [1984] studied both magnetosphere and magnetosheath FTEs, also observed by ISEE 1 and 2, but used no IMF data. Because simultaneous observations in the magnetosheath and just inside the magnetosphere were (and still are) rare, these authors classified the magnetopause crossings according to the B_L component of the magnetosheath field observed on the same magnetopause crossing. Hence for magnetosheath FTEs, B_L was observed immediately before and after the event (within the event, B_L is perturbed by the event itself). However, for magnetosphere FTEs the magnetosheath field was observed at some time before/after the magnetosphere observations (for inbound/outbound passes, respectively). The crossings were classed as $B_L < 0$ or $B_L > 0$ if B_L was stable for the half-hour period immediately before/after the magnetopause crossing (for inbound/outbound passes), excluding any brief variations within FTEs themselves: if B_L varied within this period, the crossing was classified as "intermediate B_L." Rijnbeek et al. also classified both the magnetosheath and magnetosphere segments of each magnetopause crossing as either showing at least one FTE or not showing any FTEs, using slightly more relaxed FTE definition criteria than employed by Berchem and Russell. The results are summarized in Tables 1 and 2. For $B_L < 0$, 85.4% of crossings showed at least one magnetosphere FTE, and 91.2% showed at least one magnetosheath FTE: for $B_L > 0$, these figures fall to 20.5% and 14.5%, respectively. The explanation of the results for magnetosheath FTEs in terms of dynamic pressure changes would be as discussed above for the Berchem and Russell study, given that the polarity of the magnetosheath B_L at the subsolar magnetopause is expected to be the same as that of the IMF B_z component [Crooker et al., 1985].

TABLE 1. The Total Number of Magnetopause Crossings, N and the Number Showing One or More Magnetosphere FTEs, n, From the Survey by Rijnbeek et al. [1984]

B_L Polarity	N	n	n/N	P_c
$B_L > 0$	39	8	0.205	0.04
$B_L < 0$	41	35	0.854	0.93
Intermediate	17	10	0.588	
Total	97	53	0.546	

P_c is the occurance probability, corrected for the expected variability of the polarity of B_L (see text).

TABLE 2. The Total Number of Magnetopause Crossings, N and the Number Showing One or More Magnetosheath FTEs, n, From the Survey by Rijnbeek et al. [1984]

B_L Polarity	N	n	n/N
$B_L > 0$	55	8	0.145
$B_L < 0$	57	52	0.912
Intermediate	22	13	0.591
Total	134	73	0.545

For his model, Sibeck [1990] predicts that magnetosphere FTE signatures of the kind shown in Figures 2d, 2e, and 2f will occur for northward IMF, indeed he models the event described by Farrugia et al. [1988] specifically by assuming the IMF was northward. Because there is no reason for the occurrence of solar wind dynamic pressure pulses to depend on the polarity of IMF B_z (and indeed a recent statistical survey by Bowe et al. [1990] indicates that it does not), these northward IMF magnetosphere FTEs should be as common as either the magnetosheath FTEs or the magnetosphere FTEs observed during southward IMF. On page 3764 of his paper, Sibeck correctly states that Berchem and Russell studied only magnetosheath FTEs and that Rijnbeek et al. used no simultaneous IMF observations. He therefore concludes that "the dependence of magnetospheric FTE occurrence on the simultaneous IMF is unknown." This statement may be strictly accurate but is highly misleading as it invites the reader to dismiss the Rijnbeek et al. results for magnetosphere FTEs without providing any explanation of them. Given that the magnetosheath B_L at the subsolar magnetopause is a much more direct indicator of the likelihood of reconnection than the IMF upstream of the bow shock (the latter often observed at considerable distances from the Earth), it is only the lack of simultaneous observations which can be considered to be a problem. In section 4.2 we correct Rijnbeek et al.'s results to allow for the probability that the magnetosheath B_L changed sense between the time that it was observed and the time that FTEs were (or, alternatively, were not but could have been) observed within the magnetosphere. To do this we must look at the stability of the polarity of the magnetosheath field. This is assumed to be the same as that for the IMF B_z, which is discussed in section 4.1.

4.1. The Stability of the Polarity of IMF B_z

Two recent studies, by Rostoker et al. [1988] and Hapgood et al. [1991], have investigated how long the IMF B_z component maintains a given polarity. Rostoker et al. used 9 months' IMF data of 15-s resolution whereas Hapgood et al. employed 1-hour averages of the data from 24 years. Because of its higher time resolution, we mainly invoke the results of the former study here. Rostoker et al. gave the number of periods, n_τ, during which the IMF B_z maintained the same polarity continuously for an interval of between τ and $(\tau+\Delta\tau)$. They used bin lengths $\Delta\tau$ of 5 min and 1 hour. The average duration of one of these periods is $(\tau+\Delta\tau/2)$ and hence the total duration of all of them is $n_\tau.(\tau+\Delta\tau/2)$ and the probability of the IMF being in one of them is $n_\tau.(\tau+\Delta\tau/2)/T$, where T is the total period of observations used in the study (452 hours). Hence the probability that the polarity of B_z is stable for a time, t, less than some value t_1 (which is a multiple of $\Delta\tau$) is

$$P\{t<t_1\} = \sum_{\tau=0}^{t_1-\Delta\tau} n_\tau(\tau+\Delta\tau/2)/T \tag{1}$$

and the probability that it is stable for at least t_1 is

$$P_1\{t\ge t_1\} = 1 - P\{t<t_1\} = 1-\sum_{\tau=0}^{t_1-\Delta\tau} n_\tau.(\tau+\Delta\tau/2)/T \tag{2}$$

Figure 6a shows a histogram of $P_1\{t\ge t_1\}$ as a function of t_1, from the hourly n_τ values given by Rostoker et al. This is very similar to the results obtained by Hapgood et al. Rostoker et al. did not differentiate between periods of continuously southward and continuously northward IMF in their study, whereas Hapgood et al. did but found no detectable differences in the results. The dashed line in Figure 6a shows the results for 5-min values (only given for the first hour), which are also shown on an expanded time scale in Figure 6b.

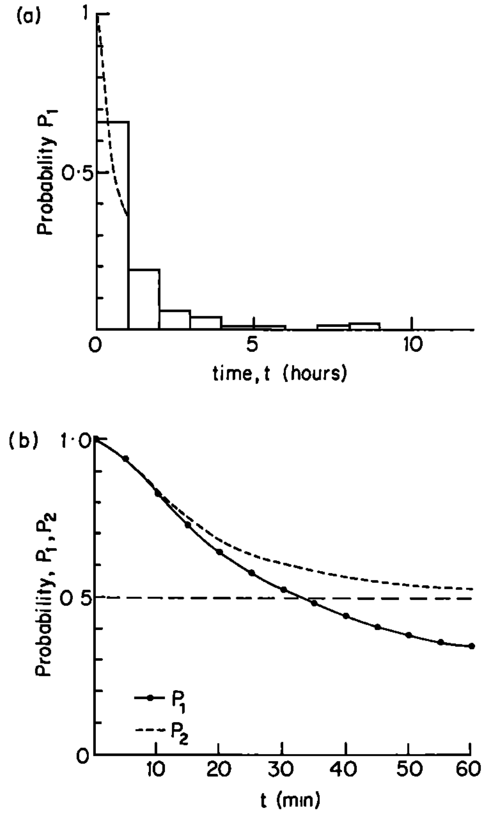

Fig. 6. Probability $P_1\{t\ge t_1\}$ that the IMF maintains a given north-south polarity for an interval exceeding t_1, as a function of t_1: for (a) hour and (b) 5-min intervals of t_1. The dashed line in Figure 6a is that shown in Figure 6b for comparison. The dashed line in Figure 6b is $P_2\{t=t_1\}$, the probability that the IMF has the same north-south polarity at times t=0 and $t=t_1$.

The dashed line in Figure 6b is the probability that the IMF has the same sense of B_z at time $t=t_1$ as at time t=0, $P_2\{t=t_1\}$. This is the probability that the B_z changed sense n times in the interval t_1, where n is zero or any even number. At larger t_1, $P_2\{t=t_1\}$ exceeds $P_1\{t\ge t_1\}$ because there is an increased probability that B_z has changed back to its original polarity. The dashed line shows that after about 1 hour, $P_2\{t=t_1\}$ approaches 0.5, i.e., the IMF is almost as likely to have the opposite sense as the same sense it had at time t=0. But for periods of less than 30 min it is more likely to have retained its original polarity. This is the justification of the classification employed by Rijnbeek et al. In the following subsection, we quantify the effects of IMF variability on the results of Rijnbeek et al.

4.2. Magnetosphere FTE Signatures

Rijnbeek et al. [1984] found that the mean interval between FTEs within the magnetosphere, for crossings where at least one FTE was observed, was 7.1 min and that on average there were 3.7 magnetosphere FTEs in each such crossing. This means that, on average, the satellite could observe magnetosphere FTEs (with their definition of events) while the satellite was within 3.7×7.1 = 26 min of passing through the magnetopause.

Rijnbeek et al. classified crossings according to the L component of the magnetosheath magnetic field observed in the 30-min period immediately before/after the magnetopause crossing (on inbound/outbound passes): we will call this value B_L' in order to distinguish it from the value prevailing when FTEs could have been observed in the magnetosphere (within 26 min of the magnetopause crossing on average); we will call the latter B_L. We need to allow for the probability that the magnetosheath field L component changed sense during the crossing, i.e., that $B_L'/B_L<0$ at any time. To do this we must consider inbound and outbound passes separately.

From Figure 6b we find that the probability that the IMF B_z, and hence the B_L in the subsolar magnetosheath, was stable for 30 min (t_1=30 min), $P_1\{t\ge30\}$, is 0.53. For $B_L'<0$ this yielded N = 41 crossings in Rijnbeek et al.'s survey. For a subset of these $B_L'<0$ crossings, B_L would have swung to positive after the satellite had entered the magnetosphere on inbound passes or swung to negative before it exited the magnetosphere on outbound passes. Let us consider the hypothesis that $B_L>0$ prevents magnetosphere FTEs (i.e., that they are produced by magnetic reconnection). Taking first inbound passes we note that during crossings with magnetosphere FTEs they recur every 7.1 min, on average; so to be sure of a northward IMF swing in B_L preventing an FTE it must occur within 7 min of the magnetopause crossing. The probability of B_L being stable for 30 min, but then switching polarity in the next 7 min is

$$P\{37\ge t\ge30\} = P_1\{t\ge30\} - P_1\{t\ge37\} \tag{3}$$

If no FTEs are to be observed within this crossing, B_L must then remain positive until the satellite is sufficiently deep into the magnetosphere that it would not detect an event. This requires an average interval of 26 min. Generally, we must also allow for the travel time of the FTE from the X line to the satellite. In Rijnbeek et al.'s survey, the average distance of the crossings to the GSM equatorial plane is 5 R_E, and for a mean FTE speed of 175 km s^{-1} we obtain a rough estimate of 3 min for this travel time. Hence if B_L remained positive for at least 26-3=23 min after the magnetosphere crossing, it would prevent an FTE being observed. If the B_L change took place at exactly the time of the crossing it would therefore have to remain positive for the subsequent 23 min, but if it took place 7 min after the crossing, it would have to remain positive for only the next 16 min. On average, we therefore require B_L to remain positive for about 20 min: the probability of which is $P_1\{t\ge20\}$. Assuming that the probability of any interval of stable B_z polarity is independent of the duration of the previous interval, the probability of the whole sequence is

$$\begin{aligned} P_{in} &= P_1\{t\ge20\}\,.\,P\{37\ge t\ge30\} \\ &= P_1\{t\ge20\}.[P_1\{t\ge30\} - P_1\{t\ge37\}] \end{aligned} \tag{4}$$

Considering outbound passes, we require B_L to have been positive for 20 min (on average) prior to the crossing, but to then swing to negative in the subsequent 7 min, immediately prior to the magnetopause crossing, and remain negative for 30 min. By analogy to equation (4) the probability of this sequence is

$$P_{out} = P_1\{t \geq 30\} \,.\, [P_1\{t \geq 20\} - P_1\{t \geq 27\}] \qquad (5)$$

From Figure 6b, $P_1\{t \geq 20\} = 0.65$, $P_1\{t \geq 30\} = 0.53$, $P_1\{t \geq 37\} = 0.47$, and $P_1\{t \geq 27\} = 0.56$. Hence from equation (4), $P_{in} = 0.039$, and from equation (5), $P_{out} = 0.048$. For an equal number of inbound and outbound passes, the probability of the required sequence of B_L variation to give no magnetosphere FTEs, but negative B_L', is the average of P_{in} and P_{out}. In Rijnbeek et al.'s survey this corresponds to N_1 passes, where

$$N_1 = N \,.\, [P_{in} + P_{out}]/2P_1\{t \geq 30\} \qquad (6)$$

and from Table 1, N = 41. Hence $N_1 = 3.37$.

Hence from the total of N (= 41) $B_L'<0$ passes discussed by Rijnbeek et al., we should subtract $N_1 = 3.37$, for which we would expect B_L to have turned to positive on inbound passes or turned from positive on outbound passes, in such a way that it prevented an FTE occurring while the satellite could have detected a magnetosphere FTE. This gives a corrected occurrence probability of the n crossings with at least one magnetosphere FTE for $B_L<0$ of

$$P_c = n/(N - N_1) \qquad (7)$$

From Table 1, n = 35, and hence P_c is 0.930. This corrected occurrence probability of passes with at least one FTE appears in the last column of Table 1. This is closer to the probability of observing a magnetosheath FTE under the same ($B_L<0$) conditions of 0.912 (see Table 2) than the uncorrected value (0.854).

Similarly, we can correct the $B_L' > 0$ passes to allow for the subset of them for which B_L was negative while the spacecraft was in the magnetosphere. From Table 1, we find that $P\{t \geq 30\}$ now corresponds to N = 39 crossings.

Again, we consider first inbound crossings. In order for the satellite to detect an FTE, the magnetosheath B_L must have turned negative within (26-3-X) min of the magnetopause crossing, where 3 min is the mean travel time of the FTE from the X line to the satellite, as before, and X is the interval of southward sheath field which is required to reconnect an FTE. The probability that the B_L remained positive for the 30 min that the satellite was in the magnetosheath and for at least the subsequent (23-X) min when it could have produced detectable FTEs is $P_1\{t \geq 53-X\}$. The probability that it was stable for 30 min and then changed sense in the subsequent (23-X) min is therefore

$$P\{53-X \geq t \geq 30\} = P_1\{t \geq 30\} - P_1\{t \geq 53-X\} \qquad (8)$$

The probability of the sheath field turning southward and remaining southward for long enough to generate an FTE is therefore

$$P_{in}' = [P_1\{t \geq 30\} - P_1\{t \geq 53-X\}].P_1\{t \geq X\} \qquad (9)$$

On outbound passes, an FTE could have been observed if B_L was negative for an interval of X minutes, ending up to (26+3) min prior to the magnetopause crossing. To classify the pass as $B_L'>0$, B_L must have then turned positive in the 29 min before the magnetopause crossing. The probability of this is

$$P\{29+X \geq t \geq X\} = P_1\{t \geq X\} - P_1\{t \geq 29+X\} \qquad (10)$$

After the crossing, the sheath field must be positive for 30 min. If B_L turned positive 29 min before the crossing, it must remain positive for 59 min; if it turned positive at exactly the time of the crossing, it must remain positive for the next 30 min. The average of this range is 45 min, and hence the joint probability of this sequence of B_L and of the generation of at least one magnetosphere FTE is approximately

$$P_{out}' = [P_1\{t \geq X\} - P_1\{t \geq 29+X\}].P_1\{t \geq 45\} \qquad (11)$$

The time taken to reconnect an FTE has been estimated to be of the order of 2 min [see Lockwood et al., 1990], which would imply X = 2 min, but it is possible that a more prolonged period of southward IMF may be required before the reconnection can commence. In this paper, we also therefore consider X = 7 min, the mean repetition period of FTEs. From Figure 6b, $P_1\{t \geq 2\} = 0.94$, $P_1\{t \geq 7\} = 0.90$, $P_1\{t \geq 51\} = 0.38$, $P_1\{t \geq 31\} = 0.52$, $P_1\{t \geq 46\} = 0.40$, $P_1\{t \geq 36\} = 0.48$, and $P_1\{t \geq 45\} = 0.41$. Hence from equations (9) and (11), $P_{in}' = 0.141$ and $P_{out}' = 0.172$ for X=2, and $P_{in}' = 0.117$ and $P_{out}' = 0.172$ for X=7.

From equation (6), and for N = 39 (Table 1), this corresponds to N_1' of 11.52 crossings for X=2 and 10.56 crossings for X=7. Of these N_1' crossings, $N_2' \approx N_1'.P_c$ will show FTEs, where P_c is the corrected probability of a $B_L<0$ pass having at least one magnetosphere FTE. This yields N_2' of 10.71 and 9.60 passes with FTEs for X of 2 min and 7 min, respectively. Both these numbers are greater than the n = 8 actually observed by Rijnbeek et al. [1984]. In other words, the IMF appears to have turned southward (such that it triggered at least one FTE) less often in Rijnbeek et al.'s survey than we would have predicted. One reason for this may be that a more prolonged period of southward IMF is required to generate the first of a sequence of FTEs. Such an effect has been simulated by Ogino et al. [1989]. This would strongly affect inbound passes and would reduce P_{in}' and hence N_2'.

The corrected ocurrence frequency is

$$P_c = (n-n_2')/(N-n_1') \qquad (12)$$

From Table 1, n = 8 and N = 39; hence we derive P_c' values of -0.099 and -0.056, for X = 2 and X = 7, respectively, i.e., $P_c = -0.08 \pm 0.02$. We can allow for a "priming time" of southward IMF before the first of a sequence of events can be triggered by taking X=20 min for the first event [Ogino et al., 1989]. Equation (9) then yields $P_{in}' = 0.02$ and hence from (6) $N_1' = 7$ (giving $N_2' = 6.6$) and from (12) $P_c = 0.04$. This is the value quoted in Table 1. These P_c estimates are all close to zero, and we conclude that all of the $B_L'>0$ crossings which Rijnbeek et al. observed to show at least one magnetospheric FTE can be explained in terms of the IMF changing sense while the satellite was in the magnetosphere. This is not the same as the magnetosheath results presented by Rijnbeek et al. [1984] (Table 2 shows that there was a probability of 0.145 of observing at least one magnetosheath FTE during $B_L>0$), but is very similar to those presented by Berchem and Russell [1984]. The differences between the results of the two surveys must be attributed to the less stringent FTE definition criteria used by Rijnbeek et al., and from the above discussion we would infer that the effect of this is most marked in the magnetosheath.

We conclude that allowing for the variability in the polarity of the magnetosheath B_L component, the Rijnbeek et al. results are consistent with magnetosphere FTEs being present 93% of the time when the magnetosheath field points southward, but being almost entirely absent when the sheath field is northward.

Now we consider the probability of obtaining the Rijnbeek et al. [1984] result if the signatures were in fact caused by dynamic pressure changes. Because there is no correlation between the occurrence of dynamic pressure pulses and magnetosheath B_L polarity, the occurrence of the magnetosphere events would then be uncorrelated with both B_L and B_L'. The bottom row of Table 1 shows that the overall probability of observing a crossing with at least one magnetospheric FTE is 0.546 and the probability of the magnetosheath field being southward is 0.5 (because the distribution of magnetosheath B_L is symmetric about zero). Because these would be uncorrelated for this model, the probability of both occurring is $p = 0.5 \times 0.546 = 0.273$. The reason why FTEs should be grouped into passes with several events whereas other passes have none is not clear: it must be postulated that there are periods of the required variability in dynamic pressure (to produce FTE signatures) and these must be slightly more common than periods where such variability is absent (probabilities of 0.546 and 0.454, respectively).

Consider the results obtained when $B_L'>0$, for which N = 39. If the Rijnbeek et al. survey was repeated many times, we would expect a spread in the results for n. Using the binomial distribution (i.e., assuming magnetopause crossings are statistically independent from each other) the mean number of crossings for which a magnetosphere

FTE signature would be expected is N.p = 10.56, and the standard deviation of the distribution would be $\sqrt{}$[N.p.(1-p)] = 2.78. Hence by observing n = 8, Rijnbeek et al.'s result is 0.922 of a standard deviation away from the mean. From the binomial distribution, the probability of any value of n is

$$P(n) = \frac{N!}{n!.(N-n)!} p^{n}.(1-p)^{(N-n)} \tag{13}$$

and hence the probability P(8) = 0.1 (note that this is quite high as unity is the probability of any n and the probability of the integer closest to the mean, P(11), is 0.14). Hence the $B_L' > 0$ results are not greatly inconsistent with the pressure pulse model.

Repeating this analysis for the $B_L' < 0$ observations, we have N = 41, giving an expected mean value of 11.11 and a standard deviation of 2.85. Hence the observed value of n = 35 is 8.4 standard deviations from the mean. The probability of this is P(35) = 9.6 x 10^{-15}.

We conclude that the Rijnbeek et al. result of low occurrence frequency of magnetosphere FTEs for northward magnetosheath field is not inconsistent with the dynamic pressure pulse theory. However, the probability that their result for a southward orientation is a chance occurrence is negligible.

4.3. Magnetosheath FTE Signatures for Northward IMF

In the study by Berchem and Russell [1984], virtually no FTEs were observed in the magnetosheath when the IMF was northward. In the Rijnbeek et al. [1984] study, only 14.5% of northward magnetosheath field crossings gave any magnetosheath FTEs. The difference between these two results may well be due to the less stringent definition of an FTE employed by Rijnbeek et al. However, Figures 2a and 2b indicate that FTE signatures should, in general, be present in the magnetosheath for a northward field orientation for the dynamic pressure pulse model. Sibeck [1990] points out that the signatures for this trough in the boundary (as seen from the magnetosheath) will be weaker than those for the field draped over a crest in the boundary. In addition, the dynamic pressure increase postulated to cause the indentation of the boundary may be due to enhanced plasma density (rather than its speed), and hence at constant temperature the thermal pressure will be enhanced and, if there is pressure equilibrium, the magnetic pressure and hence magnetic field will be reduced [Burlaga, 1968; Sibeck, 1990]. Consequently, the FTE signature in the magnetosheath will be weak, and hence such events may not have been classified by Berchem and Russell. In addition, the total field may decrease, and hence the event would not be classified as an FTE, as both Rijnbeek et al. and Berchem and Russell identified FTEs by their rise in total field as well as the B_n signature.

This explanation of the lack of FTE signatures in the magnetosheath for the dynamic pressure pulse model during northward IMF is illustrated schematically in Figure 7a. However, this is not consistent with the interpretation of "crater" magnetosphere FTEs put forward by Sibeck: this point is illustrated in Figure 7b. Because this interpretation requires the satellite Y_4 to pass through the PDL and enter the magnetosheath, the field line marking the boundary between the PDL and the magnetosheath must also be indented, and the satellite X_2 in Figure 1b, for example, would move from being within the PDL to being within the magnetosheath at the event center. The total field strength would be lower in the magnetosheath than in the PDL and, as indicated in Figure 1b, a drop in the magnetic field would be expected at the event center. This would explain the drop in field strength at the centre of crater FTEs observed by satellite Y_4, as reported by Farrugia et al. [1988]. However, the satellite X_2 must also observe a bipolar FTE B_n signature as demonstrated in Figure 2b.

In addition, at least some satellites which were initially outside the PDL (i.e., X_1) would likewise observe an FTE signature, of the kind shown in Figure 2a. If we consider Figure 7b, with unit length along the boundary perpendicular to the plane of the diagram, we see that the magnetic flux crossing the segment x of the path of satellite Y_4 must equal that crossing the width d in the magnetosheath outside the indentation. Hence

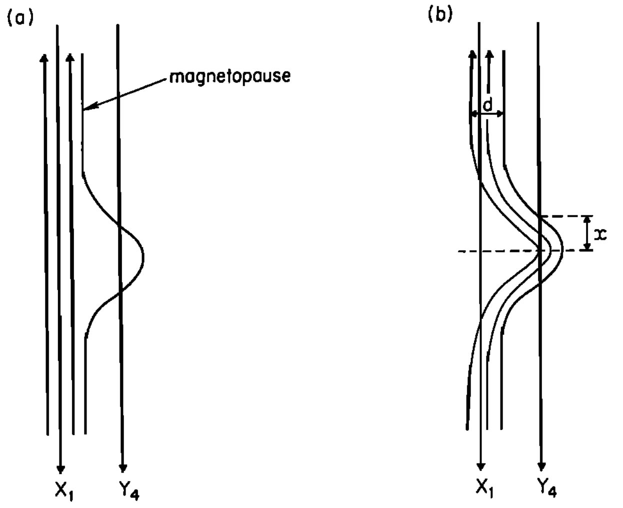

Fig. 7. Magnetopause and magnetosheath field deformation for the northward IMF and the pressure pulse model. (a) No FTE signature is detected by satellite X_1 in the magnetosheath. (b) A "crater" FTE signature is seen in the magnetosphere by satellite Y_4, and an FTE signature is observed by X_1 in the magnetosheath. The distances x and d are discussed in the text.

$$d.B_L = \int_{x} B_N \, dX = V . \int_{\tau} B_N \, dt \tag{14}$$

where V is the event velocity and τ is the interval between Y_4's passing through the magnetopause and reaching the center of the event (i.e., traveling the distance x in the frame of Figure 7b). For the event described by Farrugia et al. [1988] and modeled by Sibeck [1990], the integral with respect to time on the right-hand side of equation (1) is 320 nT s, and the event velocity, V, is 200 km s^{-1}. The L component of the magnetic field at the center of the event is B_L = 50 nT: as this is in the magnetosheath at this time for this model, we can, as a first approximation, employ this value for the sheath B_L. Equation (12) then yields d = 0.2 R_E. This value may be an underestimate, as the sheath field inside the event may be compressed ahead of the pressure pulse and then the value of B_L used will be a maximum. Any satellite X_1, which is within a distance d of the magnetopause, would detect a bipolar B_N signature (at least similar to that shown in Figure 2a) and a rise in total field of roughly the same magnitude as that observed in the magnetosphere by Farrugia et al. The value of 0.2 R_E is again a minimum because satellites at greater distances will also probably see some signature.

The event observed by Farrugia et al. is typical, in that its known dimension along the magnetopause (that along its direction of motion) is about 2 R_E and that perpendicular to the magnetopause is about 0.5 R_E. Hence we assume that the detection distance of d = 0.2 R_E is a reasonable average for all sizes of detectable FTEs [Saunders et al., 1984].

The velocity of the ISEE 1 and 2 spacecraft normal to the magnetopause is typically v_{sat} = 2 km s^{-1}. Hence the spacecraft are within this mean detection distance, d, of the magnetopause for an interval d/v_{sat} = 10.67 min on each magnetopause crossing. In crossings with at least one FTE within the magnetosphere, Rijnbeek et al. found that the average recurrence time is 7.1 min. Hence for model B we would expect to see an average of at least 1.5 FTEs in the magnetosheath during such crossings, and Rijnbeek et al. would have classified each such crossing as showing at least one magnetosheath FTE. As discussed in section 4.2, for the dynamic pressure pulse theory, the probability of observing such a crossing during northward IMF is 0.273, and the hence the mean number of magnetosheath FTEs during northward IMF crossings should be at least 1.5x0.273=0.41.

We can compare these expectations with the results of Rijnbeek et al. and Berchem and Russell. Rijnbeek et al. found magnetosheath FTEs in 8 out of 55 cases when the magnetosheath field was northward, whereas the above prediction would have yielded 55×0.273 = 15. Again, using the binomial distribution we estimate the standard deviation of the spread of results from such surveys to be 3.3, and hence the observed number of 8 is 2.33 standard deviations from the expected mean. The probability of this is P(8) = 0.012, which can be compared with the probability of observing the expected mean number, P(15), of 0.12. Considering that the predicted mean is a minimum estimate (as the value of d employed was a minimum), it is unlikely that the Rijnbeek et al. results for magnetosheath FTEs during northward B_L can be explained by the pressure pulse model.

Berchem and Russell sorted their data into 12° bins of the IMF in the Y-Z GSM plane. If we take seven of their bins covering the elevation angle of the IMF vector, θ, from -6° to 90° (i.e. B_z is northward or weakly southward), there are a total of 17 magnetosheath FTEs in 126 crossings, i.e., 0.134 per crossing. If we take the results for $6° < \theta < 90°$ (i.e., purely northward IMF), we find no FTEs in 59 passes. Taking the first result (for $-6° < \theta < 90°$), with the predicted probability of observing a northward IMF, magnetosheath FTE of 0.41 for the dynamic pressure pulse theory, we would expect at least 0.41×126 = 51.66 FTEs. From the binomial distribution the expected standard deviation is 5.52, and hence the observation of 17 is more than 6.28 standard deviations from the mean. For the second result ($6° < \theta < 90°$), we would expect at least 0.41×59 = 24.2 FTEs. From the binomial distribution, the standard deviation is 3.78, and hence the observation of no FTEs is more than 6.4 standard deviations from the mean, the probability of which is $P(0) = 6.8 \times 10^{-9}$ (compared with the probability of observing the expected mean number P(24) of 0.105).

5. Conclusions

The dynamic pressure model of FTEs, as proposed by Sibeck [1990], contains a number of assumptions: examples are the existence of the PDL; the thicker LLBL during northward IMF, and the effects of a thicker LLBL on the magnetopause response to a dynamic pressure changes. Evidence in favor of these assumptions is certainly not conclusive; however, it has not been the aim of this paper to question them. Rather, they have been accepted, and the implications of the model have been assessed. It is found that most individual examples of FTEs can, at least qualitatively, be explained by invoking a certain path of the satellite relative to the magnetopause and the corrugations invoked in the model. There are a number of unsatisfactory features. For example, B_N signatures predicted are tripolar (rather than bipolar) for southward IMF; however, it could be argued that the third B_N deflection would be too small to be detected and some events may have been classified as "irregular" FTEs.

There are exceptions, however. Most notably, "two-regime" events [Farrugia et al., 1987b] are not completely satisfactorily explained by the dynamic pressure pulse model. These observations require a pair of spacecraft to be close to, but on either side of, the magnetopause, which is a relatively rare occurrence. Likewise, combined ISEE-AMPTE observations of the magnetosheath and magnetopause do not reveal the postulated pressure pulse (R.C. Elphic et al., The search for pressure pulses observed in conjunction with flux transfer events: an AMPTE/ISEE case study, submitted to Geophysical Research Letters, 1990). All these observations are relatively rare, and hence there is the problem that they do not tell us if these events were exceptional or if FTEs in general are inconsistent with the pressure pulse model.

The chief evidence that FTEs are a reconnection phenomenon comes from the observed dependence of their occurrence on the north-south component of the IMF. This evidence is presented in a number of papers, but we have mainly referred to the original two, by Berchem and Russell [1984] and Rijnbeek et al. [1984]. These employed data from the ISEE 1 and 2 spacecraft, but the results of Rijnbeek et al. [1984], in particular, have been broadly reproduced in surveys of the magnetopause data from the AMPTE UKS and IRM satellites [Southwood et al., 1986; Smith and Curran, 1990]. The ISEE surveys concluded that southward IMF (or equivalently magnetosheath field) was almost a necessary and sufficient condition for FTEs both in the magnetosphere and in the magnetosheath. The AMPTE data give similar results, but with lower FTE occurrence frequencies, a fact usually attributed to the lower latitudes of the AMPTE magnetopause crossings.

The dynamic pressure model explains the occurrence of magnetosheath FTEs by postulating that only during southward IMF does the magnetopause bulge outward ahead of the compression caused by the pressure pulse. On the other hand, "crater" FTEs in the magnetosphere (as presented by Farrugia et al. [1988]) are explained as northward IMF events. The occurrence of magnetosphere FTEs should not depend upon the IMF orientation according to this theory, and Sibeck dismisses the results of Rijnbeek et al. and Southwood et al. on the grounds that the IMF was not simultaneously observed.

Rijnbeek et al. sorted their ISEE data according to the orientation of the magnetosheath field observed during a half-hour period earlier/later in the inbound/outbound magnetopause crossings (as did Southwood et al. [1986] and Smith and Curran [1990] for their AMPTE data). This paper has investigated the likely effects of the polarity of the IMF B_z (and hence sheath field B_L) switching during the crossing. Although this will be a relatively rare occurrence, an example has been reported [Sibeck et al., 1990], and it is found that such cases will indeed have influenced the statistical surveys of magnetosphere FTEs. It has been shown that the data are consistent with magnetosphere FTEs occurring practically exclusively when the sheath field points southward, similar to the results for magnetosheath FTEs as a function of IMF polarity presented by Berchem and Russell. It is found that Rijnbeek et al.'s results for magnetosphere FTEs during northward sheath fields could possibly be explained in terms of the pressure pulse model; however, the probability of obtaining their result for southward sheath fields is miniscule (10^{-14}).

Another problem for the dynamic pressure pulse model is that some FTEs should have been observed in the magnetosheath for northward IMF, when the satellite is close to the magnetopause. A conservative estimate of the probability of this occurring shows that the number of crossings with magnetosheath events and northward field, as observed by Rijnbeek et al., is significantly lower than would be expected for the dynamic pressure model. The probability of Berchem and Russell's result of a very low number of FTEs in the magnetosheath for northward IMF is also negligible (10^{-8}).

In conclusion, even if we accept that most individual cases of FTE observations (at least those by single spacecraft without high-resolution plasma instruments) could be explained by the dynamic pressure pulse model, it does not provide a satisfactory explanation of the occurrence of FTEs. Indeed the results of surveys of FTE occurrence as a function of IMF/magnetosheath field are in gross disagreement with this model.

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M. Lockwood, Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, England, U. K.

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