RAL-92-060

Science and Engineering Research Council
Rutherford Appleton Laboratory
Chilton DIDCOT Oxon OX11 0QX
RAL-92-060

Magnetopause Signature of Magnetic Reconnection

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September 1992

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MAGNETOPAUSE SIGNATURES OF MAGNETIC RECONNECTION

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Lecture given to mini-Workshop on reconnection,
Oslo University, June 1992.

Abstract. Observations by satellites close to the magnetopause provide evidence of magnetic reconnection between the interplanetary magnetic field (IMF) and the magnetic field of the Earth. Two types of such reconnection have been discussed in the literature, namely quasi-steady reconnection and flux transfer events (FTEs). Particle distributions, of both solar wind and magnetospheric origin, and the stress-and energy-balance tests provide evidence of on-going reconnection, being consistent with transmission and reflection at an (almost) ideal MHD rotational discontinuity on open field lines (which thread the dayside magnetopause) produced by reconnection. However, such observations do not give information about the rate at which the reconnection proceeds. Signatures consistent with bursts of réconnection have been detected at the magnetopause and in the cusp/cleft auroral ionosphere. The recurrence rate of these flux transfer events (FTEs) has a mean value of 8 min.; however, the distribution of the intervals between FTE signatures is highly skewed, having mode, upper and lower decile values of 3.0 min., 1.5 min. and 18.5 min., respectively. A survey of 1 year's 15-second data on the interplanetary magnetic field (IMF) suggests that the derived distribution could arise from fluctuations in the IMF B_z component, rather than from a natural oscillation frequency of the magnetosphere-ionosphere system.

1. GENERAL PRINCIPLES

The dayside magnetopause is the current-carrying layer which separates the Earth's magnetic field (confined within the cavity of low plasma density called the magnetosphere) and the interplanetary magnetic field (IMF). The latter, exterior, field is of solar origin and is frozen into the flow of solar wind particles. Because that flow is supersonic, a bow shock forms upstream of the Earth. In the region of shocked solar wind plasma between the bow shock and the magnetopause (the magnetosheath), the IMF becomes

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draped over the magnetosphere. A great many studies indicate that when the IMF points southward, in the reference frame of the Earth's magnetic field (the Geocentric Solar Magnetospheric or GSM frame), reconnection between the IMF and the terrestrial field occurs, allowing the transfer of mass, momentum and energy from the solar wind to the ionosphere and the Earth's ionised upper atmosphere, the ionosphere. Figure 1 illustrates this situation, with the reconnection neutral line (hereafter called the "X-line") at the nose of the magnetosphere.

Figure 1 shows the X-line situated at low latitudes on the dayside. There are four main pieces of evidence that this is the case for southward IMF, each of which will be discussed further in this text: (1). accelerated flows of particles which have crossed the magnetopause (i.e. solar wind inside the magnetosphere and magnetospheric in the magnetosheath) are always directed away from low-latitudes (with a dawn-dusk flow component which depends upon the dawn-dusk (B_y) component of the IMF) (Cowley, 1984; Gosling et al., 1990a). (2). The average sense of the rotational field discontinuities at the magnetopause (defined from the so-called "stress-balance" test) reverses across the equatorial plane (Paschmann, 1984). (3). The average polarity of flux transfer event (FTE) signatures reverses across the equatorial plane (Berchem and Russell, 1984; Rijnbeek et al., 1984; Southwood et al., 1986). (4). the direction of energetic ion streams in FTEs indicates that open flux tubes in a given hemisphere thread the boundary in the same hemisphere (Daly et al., 1984).

Closed geomagnetic field lines connect the ionospheres of opposite hemispheres and do not thread the magnetopause (such as that marked c in figure 1). Reconnection at the dayside magnetopause merges a magnetosheath field line with a closed geomagnetic field line to generate a pair of open field lines which do thread the magnetopause (o in figure 1). In this way, reconnection produces a number of features at the magnetopause.

1. A tangential electric field in the magnetopause, the reconnection rate E_T. Integrated along the length of the X-line, this gives a voltage of typically 100 kV, observed as plasma circulation in the ionosphere and magnetosphere ("convection") (Cowley. 1984; Reiff and Luhmann, 1986).

2. A rotational discontinuity (RD) on the open field lines where they thread the magnetopause. Because the frozen-in condition is considered to break down only in the small diffusion region, away from the X-line this is an ideal MHD rotational discontinuity. This RD is clearly seen in the segment of the dayside boundary shown in figure 2.

3. A boundary-normal magnetic field, B_N. If ideal MHD does apply to the rotational discontinuity, the open field lines move away from the X-line at a speed V_F, given by:

$$V_F = E_T / B_N \tag{1}$$

It is important to note that the reconnection rate, E_T, does not specify the value of the field line speed. Indeed, applying conservation and mass to the inflow an outflow regions to the X-line yields:

$$V_F \sim B_{in} /(\mu_o \varrho)^{1/2} \tag{2}$$

where B_{in} is the magnetic field in the inflow region and ϱ is the plasma density. This means that, to first order, V_F is independent of E_T and an increase in reconnection rate causes a proportional increase in the boundary normal field B_N (equation 1), but does not alter the speed with which the field lines move away from the X line.

4. Accelerated plasma flows where the magnetopause current, J_m, is such that $\underline{J}_m.\underline{E}_T > 0$.

In practice we have not yet been able to measure either B_N nor E_T at the magnetopause directly. This is because we cannot determine the orientation of the boundary accurately enough. In addition the boundary is always moving (in the Earth's frame of reference) due to fluctuations of the dynamic pressure of the solar wind flow. The electric field E_T is in the frame of the boundary and the unknown boundary motions give great errors in any attempt to measure it by a lone satellite.

However, satellite observations have allowed us to detect the rotational discontinuity through the "stress-balance" test, and the accelerated flows are frequently observed.

2. THE STRESS-BALANCE TEST

Figure 3 shows an example of a typical magnetopause crossing, by the AMPTE-UKS satellite (from Smith and Rodgers, 1991). The top three panels show the three components of the magnetic field in boundary-normal co-ordinates, the fourth panel shows the total field. The lower four panels show the corresponding ion velocity measurements. The N component is in the outward normal direction to the magnetospheric boundary, estimated by minimum variance techniques. The L axis lies in the boundary plane and is aligned with the Earth's magnetic axis. The magnetopause can be identified as a decrease in the total field strength as the satellite moves outward (with an increase in the short-period variability of the field). In addition, the magnetosheath field points southward in this case, so B_L is negative; whereas it always will point northward ($B_L > 0$) within the magnetosphere. In this example, the spacecraft finally departs from the magnetosphere at about 14:36 UT. However, prior to this the satellite had entered the magnetosheath around 14:21 UT, before an outward motion of the boundary returned it briefly to within the magnetosphere.

The stress-balance test has been applied to this and a number of other satellite intersections with the dayside magnetopause (e.g. Paschmann et al., 1979; Sonnerup et al., 1981; Paschmann, 1984, Johnstone et al., 1986). The ideal cases have multiple encounters with the boundary caused by many oscillatory boundary motions, giving many measurements from the immediate vicinity of the magnetopause. For an ideal-MHD rotational discontinuity (RD) (Hudson, 1970), the particles are accelerated by the $\underline{J} \times \underline{B}$ force as they cross the current layer. Using the condition that the E_T is continuous across the boundary, we can derive the difference between the velocities on the two sides of the boundary:

$$\underline{V}_1 - \underline{V}_2 = \pm (\underline{B}_1 - \underline{B}_2).\ [(1-\alpha)/(\mu_o\ \varrho)]^{1/2} \tag{3}$$

where $\underline{V}$ and $\underline{B}$ are the plasma velocity and magnetic field, respectively and subscripts 1 and 2 refer to the two sides of the RD; α allows for the particle pressure anisotropy and is given by:

$$\alpha = (P_{||} - P_{\perp})\ \mu_o\ /\ B^2 \tag{4}$$

and the velocity at any point is given by

$$\underline{V} = \underline{V}_F \pm (\underline{B}/\varrho)\ [\varrho(1-\alpha)/\mu_o]^{1/2} \tag{5}$$

where $\underline{V}_F$ is the velocity of the field line. The sense of the plus or minus is determined by the sense of the boundary-normal field $\underline{B}_N$. Note that there is a reference frame in which the convective electric field E_T is zero - this frame is called the de Hoffman-Teller frame and moves with speed V_F along the boundary. Because equation (6) is a vector relationship, it also applies to any one component. For an ideal-MHD rotational discontinuity, the term in square brackets in (5) should be conserved (Hudson, 1970), i.e.:

$$\varrho(1-\alpha)/\mu_o = \text{a constant} \tag{6}$$

When applying the stress balance test to a direction i, V_i is plotted as a function of (B_i/ϱ) for all data taken close to the magnetopause (on both sides). The results show a clear linear relationship (Paschmann et al., 1979; Sonnerup et al., 1981; Paschmann, 1984, Johnstone et al., 1986). The intercept of the $(\underline{B}/\varrho)$ axis yield the component of the de Hoffman-Teller velocity, V_{Fi}. Figure 4 presents an example of the results showing the clear linear relationship. Note that it is assumed that the boundary does not change in character during the time of the satellite intersection (about 30 min.) and that there are no variations in the RD in the direction normal to the satellite path (i.e the RD is taken to be time-stationary and one-dimensional).

These results clearly show that the magnetopause is a rotational discontinuity which is indirect, but very strong, evidence for magnetopause reconnection. It is found that the boundary is usually an RD when there is large magnetic shear across it (i.e. when the IMF is strongly southward). However, at least one example of a tangential discontinuity for large shear has been published (Papamastorakis et al., 1984).

There are reasons for believing that the boundary is somewhat more complicated than a simple time-stationary, one-dimensional, ideal-MHD RD. Firstly, the instruments on the ISEE and AMPTE-UKS/-IRM satellites, which yielded the data used in the above applications of the stress-balance test, did not resolve the ion mass and hence ϱ had to be assumed. Paschmann et al. assumed that the magnetosheath ion gas was predominantly protons but that there was a few percent oxygen ions (of ionospheric origin) in the magnetospheric boundary layer. This yielded the required ϱ to give the ideal stress test results. However, recently Fuselier et al. (1992) have studied 27 magnetopause crossings by the AMPTE-CCE spacecraft, which could resolve the ion mass, albeit with low temporal resolution. They failed to find the O^+ ion concentrations invoked by Paschmann et al., such that the relation (6) did not hold (the values on the magnetospheric side of the boundary being consistently low). These results indicate that one of the assumptions may be invalid. However, in considering stress test results, it is important that all the relevant ion populations contributing to the total momentum on both sides of the boundary (transmitted and reflected) are considered. The results of Fuselier et al. do not include the ring current. Also the low temporal resolution may mean that relevant particles have been omitted or irrelevant ones included.

Other evidence that the boundary is not an ideal-MHD RD comes from the "energy-balance" test. This applies conservation of energy to the boundary, with the assumption that the heat conduction term is zero. In the boundary layer, the ion gas is seen to be heated in the field perpendicular direction. Such dissipation is not predicted for an ideal-MHD RD (Paschmann, 1984).

3. PARTICLE POPULATIONS AT THE MAGNETOPAUSE

Equation 3 shows that particles crossing the magnetopause will be accelerated. Observations reveal such particles in a narrow layer on the dayside magnetopause. These can be seen in the bottom panel of figure 3, which shows accelerated ion flows as the satellite passes through the current layer (marked by the changes in sense of the B_L component of the field). Panel 5 shows that these flows are primarily in the +L direction, i.e. northward. This locates the X-line as being somewhere to the south of the satellite which was 0.5 R_E (Earth radius) to the north of the magnetic equator. Corresponding results from the southern hemisphere place the X-line near the magnetic equator. Note also that the larger flow speeds in figure 4 also show the effects of this acceleration.

3.1 Ion velocity distributions in accelerated flow regions.

Magnetosheath particles incident on the RD at the dayside magnetopause will be partially transmitted into the magnetosheath, but some will be reflected back into the magnetosheath. Likewise, ring current and ionospheric particles incident on the boundary will be partially transmitted into the magnetosheath and partially reflected back into the magnetosphere. As the field lines evolve over the magnetopause, these field-parallel motions cause the ions to follow paths like those shown by the broad arrows in figure 2.

Cowley (1982) predicted the ion velocity distribution functions for all these populations at a RD magnetopause by assuming that there are three Maxwellian source plasmas: the magnetosheath, the ionospheric and the ring current. Each was taken to be half reflected by and half transmitted through the boundary and the particle pitch angle was assumed to be conserved on crossing the current layer. For simplicity, the fields on opposite sides of the boundary were taken to be antiparallel (this was later generalised by Gosling et al., 1990a). With these assumptions, Cowley predicted that magnetosheath particles injected into the magnetosphere along the field lines of the RD) will have a D-shaped distribution functions. These predictions are shown in figure 5. The D-shape is evident in the lower left plot.

Recent, high-resolution particle data from the magnetopause have confirmed the existence of these D-shaped distributions (Smith and Rodgers, 1991, Fuselier et al., 1991, Gosling et al., 1990b). An example of such a distribution is shown in figure 6. Smith and Rodgers (1991) detected this form of distribution for the accelerated flows shown in figure 3 and showed them to be consistent with Cowley's predictions. They also determined the field line velocity V_F using the stress-balance test and showed that it was equal to the lower cut-off velocity of the D-shaped distribution, as predicted in figure 5. Fuselier et al. (1991) exploited the mass-resolution of the AMPTE-CCE observations, by noting that He^+ ions are entirely magnetospheric in origin whereas He^{++} ions are almost all from the magnetosheath. Inside the magnetosphere, the He^{++} ions show the D-shaped distribution, whereas the He^+ ions show the incident and reflected populations predicted by Cowley. Outside the magnetosphere, in the magnetosheath, the accelerated, transmitted He^+ is observed, along with the incident and reflected He^{++}. These observations show that Cowley's assumption that half the incident population is transmitted and half reflected is broadly correct. The success of the ideal MHD RD in predicting all ion populations on both sides of the boundary is very striking.

3.2 Electron and Ion "Edges" and the Magnetic Separatrix.

Further evidence comes from comparing these ion distributions with those for the electrons. The electrons incident upon the boundary have much higher speeds than the ions, such that the acceleration due to the field line motion is negligible. In general, particles entering the magnetosphere with higher field-aligned speed will follow a path which is closer to the separatrix field line (S2 in figure 2). [The lower the particles' field-parallel velocity, the further it is moved along the boundary by the field line's motion (speed V_F) as it moves along it]. Hence the highest energy ions form an "electron edge" (E2 in figure 2), which is closer to the open/closed field line separatrix (S2) than the ion edge (I2) formed by the fastest-moving ions.

Figure 7 shows ISEE observations of the ion (top) and electron (bottom) distribution functions as the satellite moves out through the structure illustrated in figure 2. The left-hand pair are for a time when the satellite is earthward of the electron edge, E1. The satellite may also be inside the X-line separatrix (the open closed field-line boundary), but the data cannot determine if this is the case. In this region, both ions and electrons show distributions characteristic of the ring current. At a later time, the satellite observes the middle pair of distributions. The ion distribution is unchanged, showing that the satellite is still earthward of the ion edge (I2). However, the electrons show a bi-directional streaming population, interpreted as magnetosheath electrons flowing down the field line and a population injected at a slightly earlier time which has mirrored in the converging geomagnetic field lines and are observed travelling back towards the magnetopause. Hence the satellite is no longer earthward of the electron edge. Comparison with the ring current distribution shows the distribution has become oblate, as electrons with large field-aligned velocity are lost on these open field lines. At the third time, shown in the right-hand column, the ions show the injected D-shaped distribution function, showing the satellite has now crossed the ion edge (I2). The high-energy electrons are here all lost and only the injected and mirrored magnetosheath populations are seen. These observations show that the electron edge is found earthward of the ion edge, as predicted by consideration of an ideal MHD RD on open field lines evolving away from the dayside X-line.

4. FLUX TRANSFER EVENTS

Flux transfer events (FTEs) are characteristic signatures in the magnetic field observed by satellites close to the dayside magnetopause. They were discovered in data from satellites close to the magnetopause by Russell and Elphic (1978, 1979) and, independently, by Haerendel et al. (1978). Subsequently there have been a large number of case studies of these events (Paschmann et al., 1982; Saunders, 1983; Farrugia et al., 1987a, 1987b, 1988) and statistical surveys of their occurrence (Berchem and Russell, 1984; Rijnbeek et al., 1984; Daly et al., 1984; Southwood et al., 1986;

Elphic, 1990; Lockwood, 1991). Figure 8 shows a clear example of a bi-polar signature in the boundary-normal field which would be classified as an FTE signature. This example was detected by the AMPTE-UKS satellite (Farrugia et al., 1988) on 28 October 1984. The key features defining the FTE are the bi-polar variation in the boundary normal field, B_N, at the same time as a rise in the total field strength, B. Such signatures are usually interpreted as resulting from transient magnetic reconnection, however, it should be pointed out that this particular example has been qualitatively explained as a wave motion of the boundary (Sibeck, 1990). However, such an explanation does not appear to be valid for all FTEs because of the dependence of the occurrence statistics on the orientation of the IMF and magnetosheath field (Lockwood, 1991).

4.1 Recent Models of FTEs

There are several theoretical models aimed at explaining magnetopause FTE signatures, and Figure 9 shows arguably the most successful of those proposed to date, particularly in terms of explaining possible ground-based signatures (see review by Lockwood et al., 1990a). This model is based on a suggestion by Saunders (1983) and Biernat et al. (1987). Similar conclusions have resulted from a variety of subsequent work: Southwood et al. (1988) presented conceptual modelling; Scholer (1988) obtained similar results by 2-dimensional MHD numerical simulations; and Semenov et al. (1992) have presented an analytic derivation. All these studies invoke temporal variations in the reconnection rate, but not necessarily at a short ($\sim 1R_E$) neutral line, as described by Russell and Elphic when FTEs were first discovered and by a large number of the subsequent studies.

In order to understand this model we note that, as discussed earlier, all the evidence indicates that reconnection usually takes place quite close to the equatorial magnetopause (at the neutral line X in figure 1) when the interplanetary magnetic field (IMF) has a southward component. Application of conservation of mass and energy predicts that the angle between the two separatrices of the reconnection X increases with the reconnection rate, E_T. (This yields an increase in the boundary-normal field B_N, without increasing the field-line speed V_F, as predicted by equations 1 and 2). The time-dependent reconnection models predict that a variation in the reconnection rate therefore produces a pair of "bubbles" of mixed magnetospheric and magnetosheath plasma as the angle of the X widens and then narrows again. These are threaded by loops of the newly-opened flux produced by the reconnection burst, as shown in figure 9. The combined effects of the field curvature force (the so-called "magnetic tension") and of the magnetosheath flow moves these bubbles away from X and past spacecraft near to the magnetopause (e.g. S1 and S2), causing the observed component of the magnetic field normal to the magnetopause, B_N, to vary. For the event shown in the northern hemisphere in figure 9, this component points firstly away from, and then toward, the Earth as the bubble passes by. The same polarity of bi-polar signature in B_N is seen by spacecraft S1 in the magnetosheath as by S2, on the other side of the magnetopause, i.e. within the magnetosphere (Farrugia et al.; 1987a,b; Lockwood, 1991). Statistical surveys have shown that FTEs are observed almost exclusively when the IMF points southward, as measured in the undisturbed solar wind outside the bow shock by a satellite such as S3 in figure 9 (Berchem and Russell, 1984) and are mainly, but not exclusively, observed when the exterior magnetosheath field points southward (Rijnbeek et al., 1984). It should be noted that Berchem and Russell and Rijnbeek et al. also employed different classification schemes to identify FTEs.

Rijnbeek et al (1984) reported the number of FTEs observed by the ISEE satellites during the intervals between the magnetopause crossing and the FTE furthest away from the boundary in the time-series of the data. These intervals were typically of 30 min. duration and Rijnbeek et al. found that, on average, FTEs repeated at intervals of 7-9 min. Subsequently, this result has often been interpreted as showing that FTEs are a quasi-periodic phenomenon, with a mean period of about 8 minutes. This is further discussed in section 4.4.

4.2 Ionospheric Signatures of FTEs.

Recently, there has been much interest in identifying the signature of FTEs in the ionosphere (see Southwood, 1987; Cowley et al., 1991). One class of event, termed "dayside auroral breakup" is a particularly strong candidate (Sandholt et al., 1989). These events are observed using optical instruments in the midday auroral region (point I in figure 9) and are associated with bursts of plasma flow, as observed using the EISCAT radar (Lockwood et al., 1989). The patterns of motion and plasma flow associated with these events are consistent with them being regions of newly-opened flux. This is strong and direct evidence that they are indeed produced by bursts of magnetopause reconnection, as invoked by the time-dependent reconnection model to explain magnetopause FTE signatures. However, the optical observations of the noon aurora can only be made, in the northern hemisphere at least, from the Svalbard islands for a few weeks around winter solstice. In addition, clear skies, new moon, southward IMF and simultaneous radar observations are required. In only one experiment has it been possible to observe these ionospheric signatures in association with magnetopause FTEs (Elphic et al., 1990) and the statistics on the occurrence of these events is, as yet, limited.

A limitation of the magnetopause observations is that we cannot determine the event dimension along the magnetopause, in the direction perpendicular to the event motion. However, this can be done from ground based imaging and radar systems: because the ionospheric magnetic field (B_i) is effectively constant, it follows that if we can estimate the area of the region of newly-reconnected field lines in the ionosphere (A_i), we know the magnetic flux reconnected during the event ($F = B_i A_i$). Hence, if we can define the ionospheric signatures, we can evaluate the contribution of FTEs (F/τ, where τ is the event repetition period) to the average dayside reconnection voltage and to the consequent transfer of mass, energy and momentum from the solar wind to the magnetosphere. Initial studies of this type indicate that bursts of enhanced reconnection (i.e. FTEs) can be major, and possibly the dominant, mechanism of this solar wind-magnetosphere coupling (Lockwood et al., 1990a;b).

In the absence of sufficient combined ionospheric and magnetopause observations, a method often used in attempts to identify ionospheric phenomena which may be associated with magnetopause FTE signatures is to search for quasi-periodic events during southward IMF, with a mean repetition period close to that for the magnetopause signatures (e.g. Lockwood et al., 1989). However, Rijnbeek et al. only quoted the average number of FTEs in certain periods for a selected data set. Inspection of various examples in the literature (cited above) shows magnetopause signatures classified as FTEs repeat with a range of periods, not just the average of 8 min. Hence it is important to know the distribution of the intervals between magnetopause FTEs, to allow comparison with the corresponding distribution for any one type of ionospheric signature, if an association is to be confirmed.

4.3 Cusp Ion Precipitation and FTEs

Cusp precipitation is magnetosheath-like plasma seen in the noontime auroral ionosphere by particle detectors on low-altitude polar-orbiting satellites (see Newell et al., 1989). The field-parallel component of the injected D-shaped ion distributions (with about 15 degrees of pitch angle) would reach the ionosphere without mirroring and would be detected as cusp (or the adjacent higher-energy cleft) particles. Traditionally, the cusp particles have been described as a steady stream of injected particles, dispersed by a steady convection electric field in the magnetosphere. However, recently, Lockwood and Smith have proposed that the cusp particles are ionospheric signatures of FTEs (Lockwood and Smith, 1989, 1990, 1992; Smith and Lockwood, 1990; Smith et al., 1992). In this "pulsating cusp" model, a steady reconnection rate yields the traditional steady-state cusp model, but variations in the reconnection rate yield a cusp which is a series of FTE signatures. In most respects, the satellite data cannot determine if the reconnection rate is steady or not because of the inherent spatial/temporal ambiguity of the data. However, the Earth is a relatively slowly-moving observing platform, and the ground-based observations described in the previous section imply considerable temporal variation in the particle injection and momentum transfer.

The Southwood et al./Scholer/Semenov model of FTEs is very important in this model because it allows the X-line projection in the ionosphere to be elongated and cover up to about 1500 km, instead of the 100 km. predicted for the original Russell and Elphic FTE model. Hence FTEs could be variations of the cusp as a whole, not simply small-scale features embedded within the cusp. Lockwood and Smith (1989, 1990) showed how individual cusp intersections could be explained as FTE signatures and Smith et al. (1992) used the characteristics of dayside auroral breakup events (see 4.2) to predict the observed occurrence statistics of the cusp (Newell et al., 1989).

Smith et al. (1992) and Cowley et al. (1991) noted that the energy of precipitating magnetosheath ions in the cusp decreases with the time elapsed since the reconnection time of the field line when the ions first gain access to the magnetosphere. Hence pulses of reconnection would give spatially contiguous regions of cusp precipitation on the newly-opened field lines produced, but the ion energy would decrease discontinuously between the two. Hence these authors predicted that the ion energy dispersion would show discontinuous jumps. Independently, Newell and Meng (1991) presented examples of cusp ion spectrograms which showed exactly the behaviour predicted by Smith et al. and Cowley et al.

Lockwood and Smith (1992) have inverted the theory presented by Smith et al. and Cowley et al., to give a method of quantifying the reconnection rate at the magnetopause as a function of time. The results show that the cusp spectrograms presented by Newell and Meng resulted from pulses of reconnection, roughly one minute in duration and of order 10 min. apart. Between these pulses the reconnection rate was almost zero. Hence for these periods at least, the reconnection occurred only in large pulses.

4.4 The "periodicity" of FTEs.

It remains unclear if the rate of FTE occurrence reflects a natural oscillation period of the magnetosphere-ionosphere system under the influence of steady interplanetary conditions, and/or is caused by variations in the solar wind or IMF impinging upon the magnetosphere. It is known that the reconnection rate is strongly influenced by the magnetic shear across the dayside magnetopause and hence by the north-south component (in G.S.M. coordinates) of the IMF, B_z (see reviews by Cowley, 1984, and Reiff and Luhmann, 1986).

Lockwood and Wild (1992) have recently evaluated the distribution of inter-FTE intervals (τ) from the same dataset as employed by Rijnbeek et al. (1984). They found that the distribution of τ values was not substantially different for FTEs observed within the magnetosphere from that of FTEs observed within the magnetosheath and hence they aggregated the two together. However, by treating magnetosheath and magnetosphere data separately Lockwood and Wild excluded intervals between an FTE being observed on one side of the boundary, and a second FTE being observed on the other side of the boundary later in the pass. This is important because the characteristic FTE signature may not be observed if the satellite is very close to the magnetopause (Farrugia, 1989) and hence the time between two such events could be the sum of several inter-FTE intervals. The failure to detect an FTE very close to the boundary is because the time-dependent reconnection models predict loops of newly-opened field lines giving field lines which bulge away from the current layer to either side. However, at the centre of the current layer, the only signature would be the boundary normal field threading the magnetopause (which cannot be determined because the boundary orientation is not known with sufficient accuracy). What will be seen here are the accelerated ion flows produced as particles cross the rotational discontinuity in the field (e.g. Gosling et al., 1990a). However, these particles tell us only of the existence of ongoing reconnection, they do not tell us about the rate of reconnection. Hence the term "quasi-steady" reconnection is often misused: the detection of accelerated flows over a prolonged period tells us that there is "quasi-continuous" reconnection, not that it is steady in rate.

Figure 10 shows (n/N), where n is the numbers of cases for which τ had values in 1-minute bins and N is the total of 621 intervals, as a function of the inter-FTE interval, τ. The mean value of this distribution is $<\tau> = 8$ min., very similar to the mean recurrence time found by Rijnbeek et al. (1984). However, the distribution is highly skewed, with the lower decile being just 1.5 min. and the upper decile being 18.5 min. The mode value of the distribution is 3 min. We note that this form of distribution is also inherent in the scatter plot of a smaller set of FTE signatures presented by Elphic (1990). It can be seen that the mean value of the intervals (8 min.) is not marked by any significant peak in the distribution.

Figure 10 implies that the mean repetition rate of 8 min. is not a natural oscillation period of the ionosphere-magnetosphere system. Lockwood and Wild investigated the possibility that the reconnection rate variations simply reflect the variations of the B_z component of the IMF. If averaged over several substorm cycles, the dayside reconnection rate equals the voltage appearing across the ionospheric polar cap, plus only a very small contribution from "viscous-like" interactions (see discussion by Lockwood and Cowley, 1992). Statistical surveys show that this voltage depends upon the IMF B_z component, being small when the IMF is northward and increasing with increasing magnitude of southward IMF (see reviews by Cowley, 1984, and Reiff and Luhmann, 1986). Hence the average dayside reconnection rate increases with the magnetic shear across the dayside magnetopause and the magnitude of the IMF B_z component, when it is negative. This average behaviour also appears to apply on somewhat shorter time scales (about 5 min.), explaining the rapid response of dayside ionospheric flows to the appearance of increased magnetic shear across the magnetopause (Etemadi et al., 1988; Todd et al., 1988; Lockwood et al., 1989; Lockwood and Cowley, 1992). The FTE model demonstrated in figure 9, invokes increases in reconnection rate as the cause of magnetopause FTE signatures. The reasons for such increases in the reconnection rate are not specified (e.g. Scholer (1988) imposes a pulse of anomalous resistivity in his simulations, Semenov et al (1992) impose a pulse of tangential electric field).

As a first attempt to investigate whether the distribution of FTE repetition periods might reflect some variability in the IMF, an analysis of the distributions of periods when the IMF B_z remained either above or below certain thresholds was carried out. The IMF data were transformed into the G.S.M. co-ordinate system. The periods for which the hourly average of the IMF was southward (i.e. $<B_z> < 0$) were selected. This selection was carried out because FTEs occur almost exclusively when the mean IMF is southward (Berchem and Russell, 1984): it reduces the dataset by a factor of almost exactly two because the distribution of the hourly averages of B_z is almost exactly symmetrical about zero. The times of all transitions of the IMF across a threshold value B_{zT} were then defined in the 15.339-second resolution IMF data, i.e. transitions from $B_z > B_{zT}$ to $B_z < B_{zT}$ were identified, as were all the transitions in the reverse direction across this B_{zT} threshold. From these transition times, the duration of each period when the IMF B_z was greater than this threshold were evaluated. The analysis was repeated with a requirement that α successive 15.339-second samples on the other side of the threshold were needed to terminate an interval, i.e. that (α-1) such samples were not considered significant. In addition to the $\alpha=1$ case presented here, the analysis was repeated for $\alpha=2$, $\alpha=3$ and $\alpha=4$. The results were found to be largely independent of α, for the range of periods which are of concern here which is roughly 2 - 30 min.

Figure 11 shows the distribution of interval lengths for one year's 15.339-second IMF data from the IMP-8 satellite for which the IMF B_z was greater than B_{zT} = -2 nT, but the hourly average of B_z was negative (crosses). It can be seen that the number of cases, c, in each range between t and (t+15.339 sec.) increases monotonically with decreasing period length, t, at all values. No significant change in the shape of the distribution was found if the threshold value, B_{zT}, were altered, but the total numbers of the counts differed. Figure 11 also shows the distribution of FTE repetition intervals, as plotted in figure 10 (solid line). The scaling factor used to compare the two distributions largely reflects the different total intervals of the two datasets. It can be seen that the distributions are very similar in form for periods at and above 3 min.

In comparing these two distributions, a number of factors concerning the detection of FTEs must be considered. Firstly, if the interval between FTEs were too small, the events would not be classed as FTEs, even with the shorter duration criterion. Close to the magnetopause, extended variations in the reconnection rate with periods of less than about 1 minute would almost certainly give signatures classed as "B_N activity", rather than as a series of FTE signatures with very small inter-FTE intervals. Two isolated FTEs, with a short period between them, could also be classified as a single event. Another factor is that many of the FTEs included in the survey were detected at more than about $1R_E$ from the magnetopause. In such cases, the satellite does not detect the bipolar signature in the boundary normal field B_N because it has intersected the loops of newly-opened field lines within the FTE bubble. However, a bipolar B_N signature is still observed as the satellite moves through the regions in which the ambient magnetosheath or magnetospheric field is draped over the FTE bubble (Farrugia et al., 1987a). Rapid variations in the reconnection rate would give multiple bubble-like structures which were very close together (Farrugia, 1989), and the structure would be increasingly smoothed out with increasing distance from the magnetopause. Hence we would not resolve all the FTEs and we should not expect the FTE distribution to reflect the very rapid variations in the IMF B_z component. Hence there are a number of reasons for the divergence of the two curves at low periods, as shown by figure 11.

In addition, we note that the very rapid variation in IMF B_z may not propagate through the bow shock and across the magnetosheath to be reflected in variations of the southward magnetosheath field at the nose of the magnetosphere. If the magnetosheath does act to filter out the higher frequency variations in this way, that too would contribute to the difference between the two curves in figure 11.

Hence we can state the distributions are, at least, not inconsistent with the simple hypothesis that when the IMF B_z is less than a certain threshold, the reconnection rate is larger and an FTE is produced. When B_z is greater than this threshold, reconnection may cease or may continue, but at a lower and more steady rate and these intervals account for the inter-FTE periods. Note however, that because virtually the same shape distribution was obtained for different thresholds (B_{zT} of -4nT and -6nT were employed as well as the -2nT shown in figure 11), this analysis does not tell us that there really is such a threshold, nor what value it has.

This comparison does not consider the B_x and B_y components of the IMF and, in addition, there will be spectra of variations in solar wind speed, density and dynamic pressure. Hence the results presented do not prove that the reconnection rate is simply modulated by the value of the southward component of the IMF to give FTEs. However, the results do indicate that FTEs may simply reflect part of a spectrum of reconnection rate variations, which could simply reflect changes in the interplanetary medium.

CONCLUSIONS

The discovery of accelerated ion flows provides very strong evidence for reconnection between the geomagnetic field and the interplanetary magnetic field. The stress-balance test shows quantitatively that the acceleration is produced by an almost-ideal MHD rotational discontinuity about the magnetopause current layer. Hence although the boundary normal field and the tangential electric field cannot yet be measured because of instrumental constraints, we can detect the rotational discontinuity produced by the reconnection.

The rotational discontinuity away from the reconnection neutral line may not be exactly like an ideal MHD discontinuity because the mass conservation law appears to be violated and there is dissipation, with heating of the ion gas. However, the former observation has a number of other possible causes, including instrumental limitations, three dimensional reconnection geometry and time-dependence.

A kinetic description of the particle behaviour of plasma on open field lines, produced by the reconnection, is remarkably successful is predicting the ion distribution functions on both sides of the boundary, for all ion species. Comparison with stress-balance test results show that the ions are accelerated by the predicted amount. The electron distribution functions are also well explained, at least qualitatively. These particle data underline the value of the ideal MHD description of the rotational discontinuity away from the reconection diffusion region (the X-line).

Magnetopause signatures called flux transfer events are well explained in terms of bursts of reconnection. Recent models which allow this to occur along an extended (of order 10 Earth radii) neutral line are successful in explaining putative ionospheric signatures of FTEs, such as dayside auroral breakups and associated flow bursts. The cusp precipitation is also well explained by this model and analysis of cusp ions provides a unique measure of the reconnection rate as a function of time. The observation that the reconnection can all occur in a series of discrete pulses supports FTE models which invoke time-varying reconnection.

Lastly, a survey of magnetopause FTE signatures indicates that their mean repetition period of 8 min. is not a natural oscillation period of the ionosphere-magnetosphere system, and may simply reflect the variability of the interplanetary magnetic field.

Acknowledgements
The author thanks Prof. S.W.H Cowley and Dr. M.F. Smith for many valuable discussions. He is also grateful to the organisers and sponsors of the Oslo reconnection workshop for making such a stimulating meeting possible.

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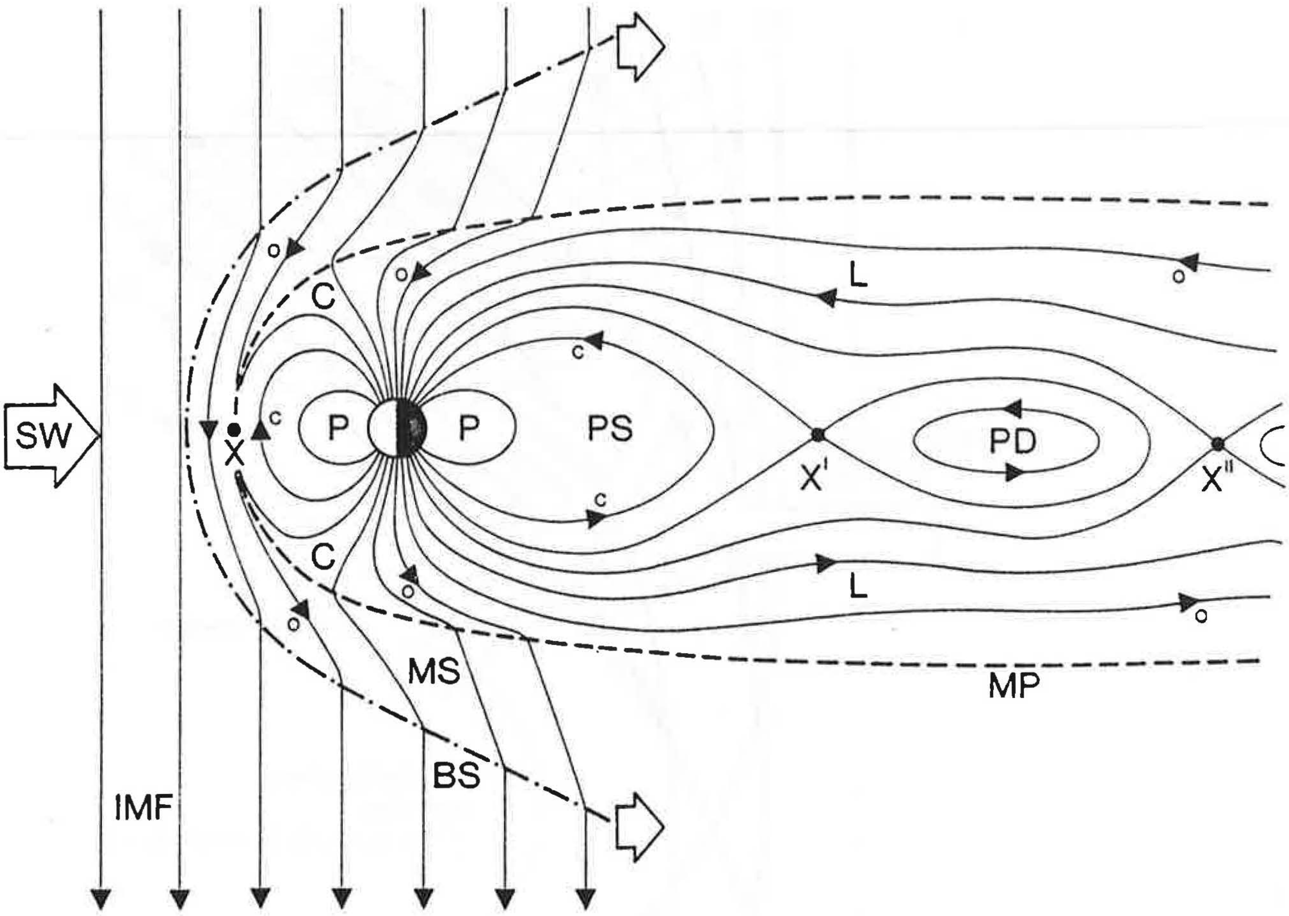

SW - Solar Wind; IMF - Interplanetary Magnetic Field; BS - Bow Shock;
C - Cusp; MS - Magnetosheath; MP - Magnetopause; L - Tail Lobe; PD - Plasmoid;
PS - Plasma Sheet; P - Plasmasphere; o - open field line; c - closed field line.

Figure 1. *Schematic cross section of the magnetosphere for a southward-directed interplanetary field (IMF), showing a reconnection X-line in the dayside magnetopause: c is an example of a closed field line, o is an open field line. The table gives the code letters for the various magnetospheric regions (from Lockwood and Coates, 1992).*

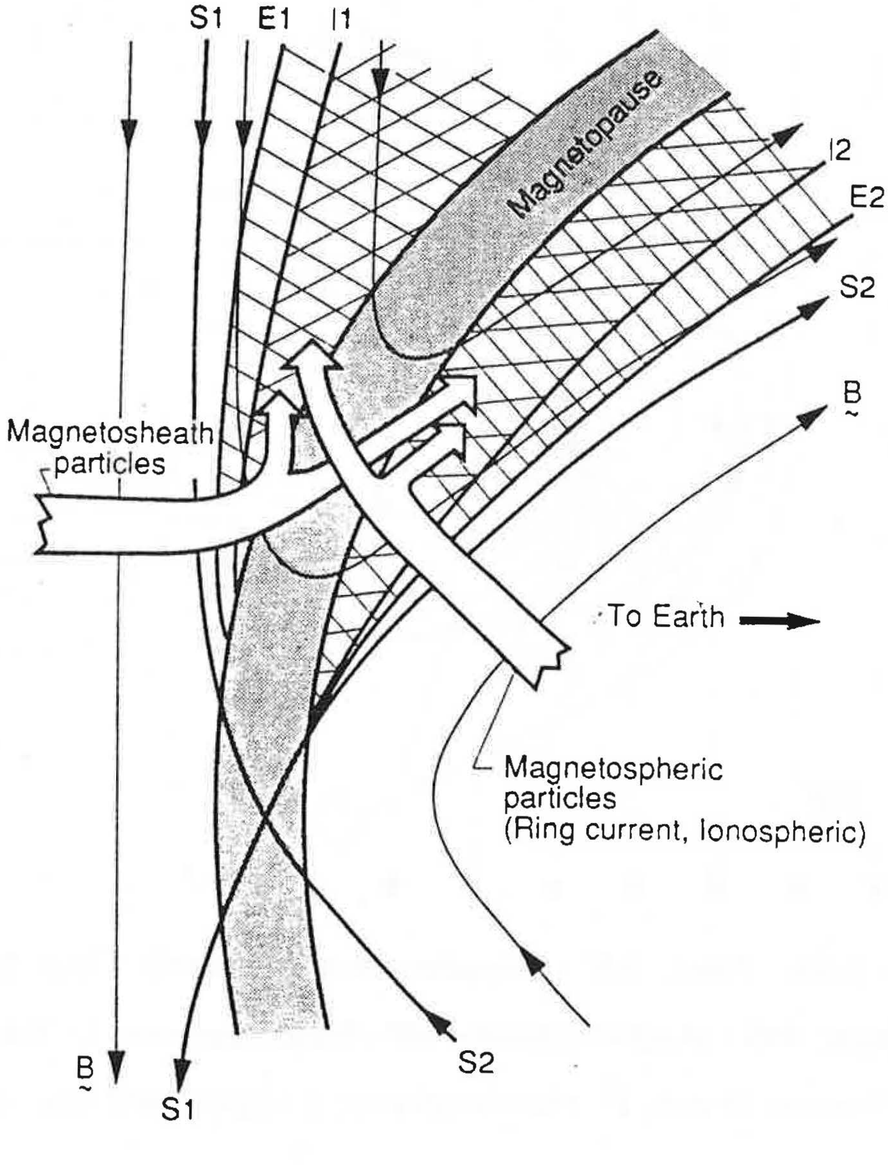

Figure 2. *A segment of the dayside magnetopause showing open field lines, with a rotational discontinuity in the current-carrying magnetopause, contracting away from the X line (where the separatrix field lines S1 and S2 meet) (from Gosling et al., 1990c)*

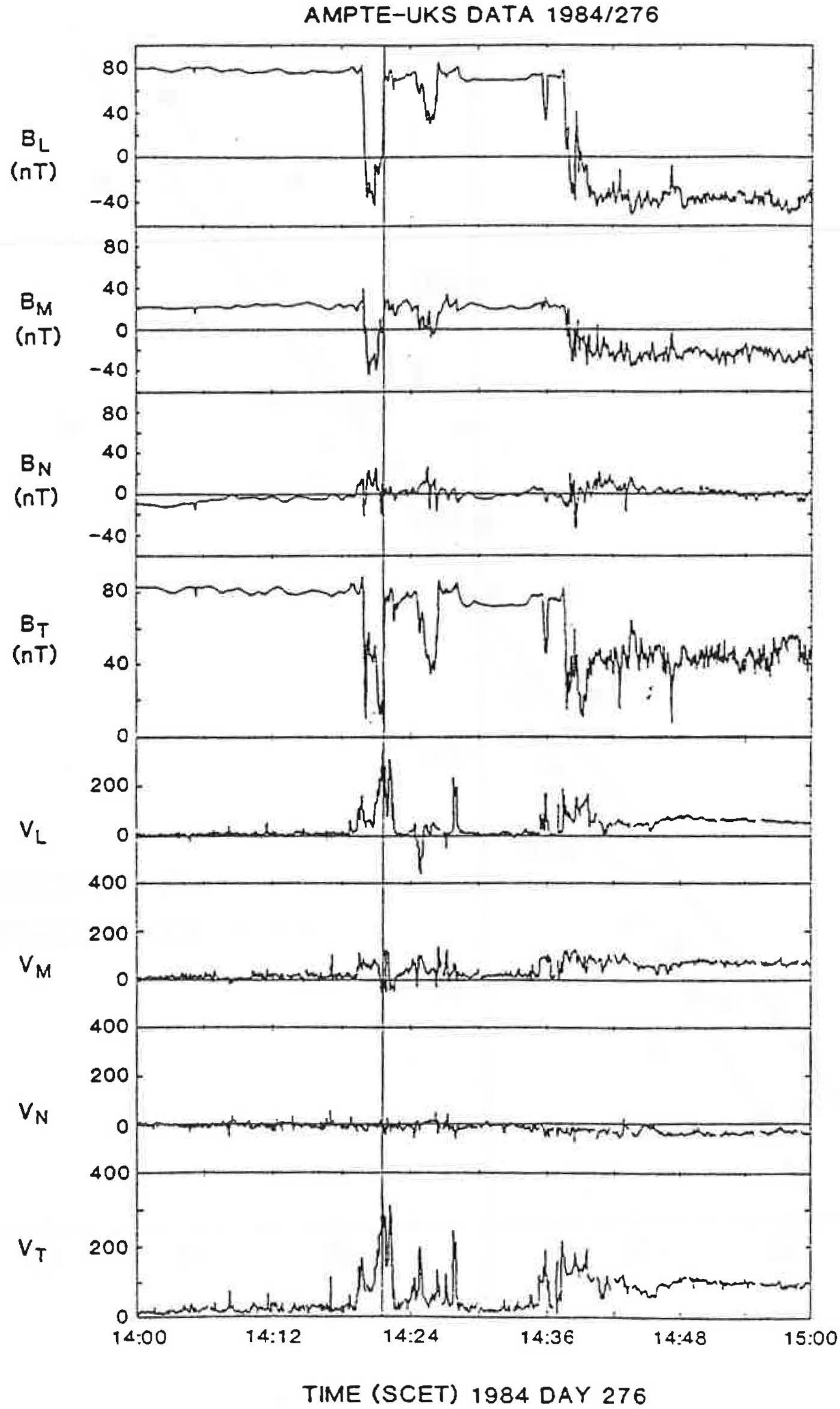

Figure 3. *A magnetopause crossing by the AMPTE-UKS satellite on 2 October 1984. See text for details (from Smith and Rodgers, 1991).*

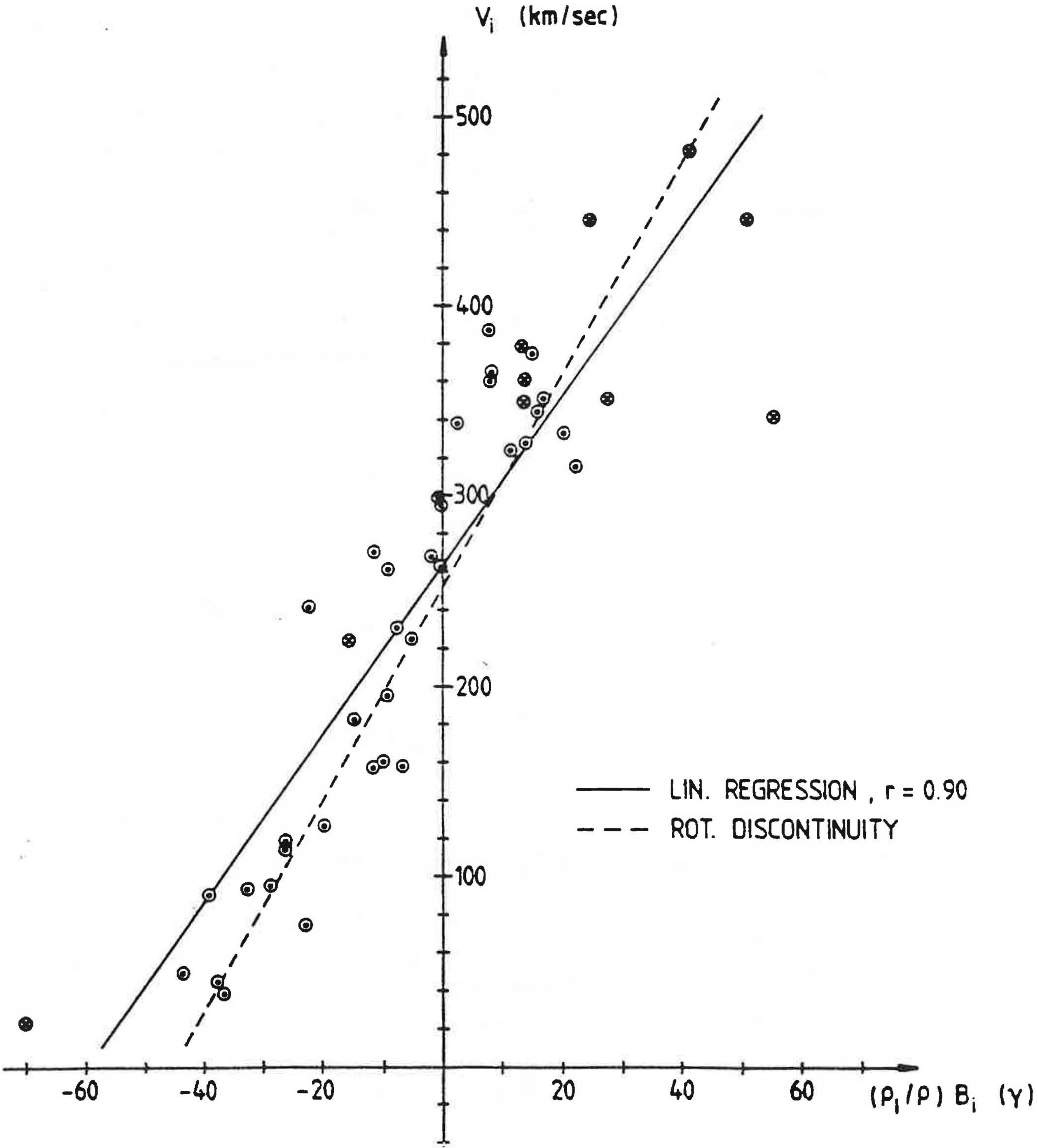

Figure 4. *Results of the stress-balance test applied to a pass of the ISEE spacecraft on 8-September 1978 (from Paschmann et al., 1979).*

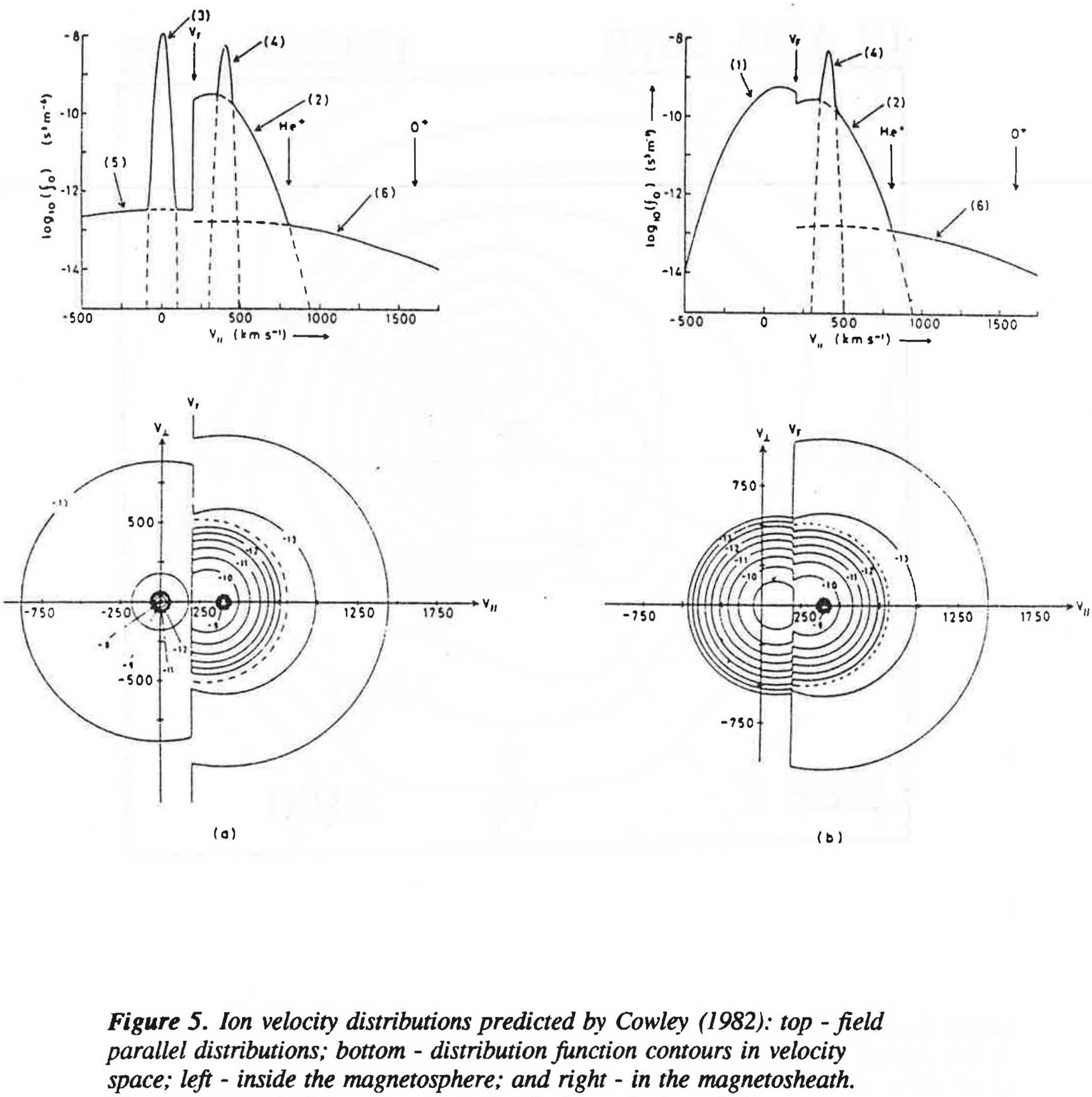

Figure 5. *Ion velocity distributions predicted by Cowley (1982): top - field parallel distributions; bottom - distribution function contours in velocity space; left - inside the magnetosphere; and right - in the magnetosheath. The source populations are magnetosheath, ionospheric and ring current (labelled 1, 3 and 5, respectively) while corresponding the accelerated populations are 2, 4 and 6.*

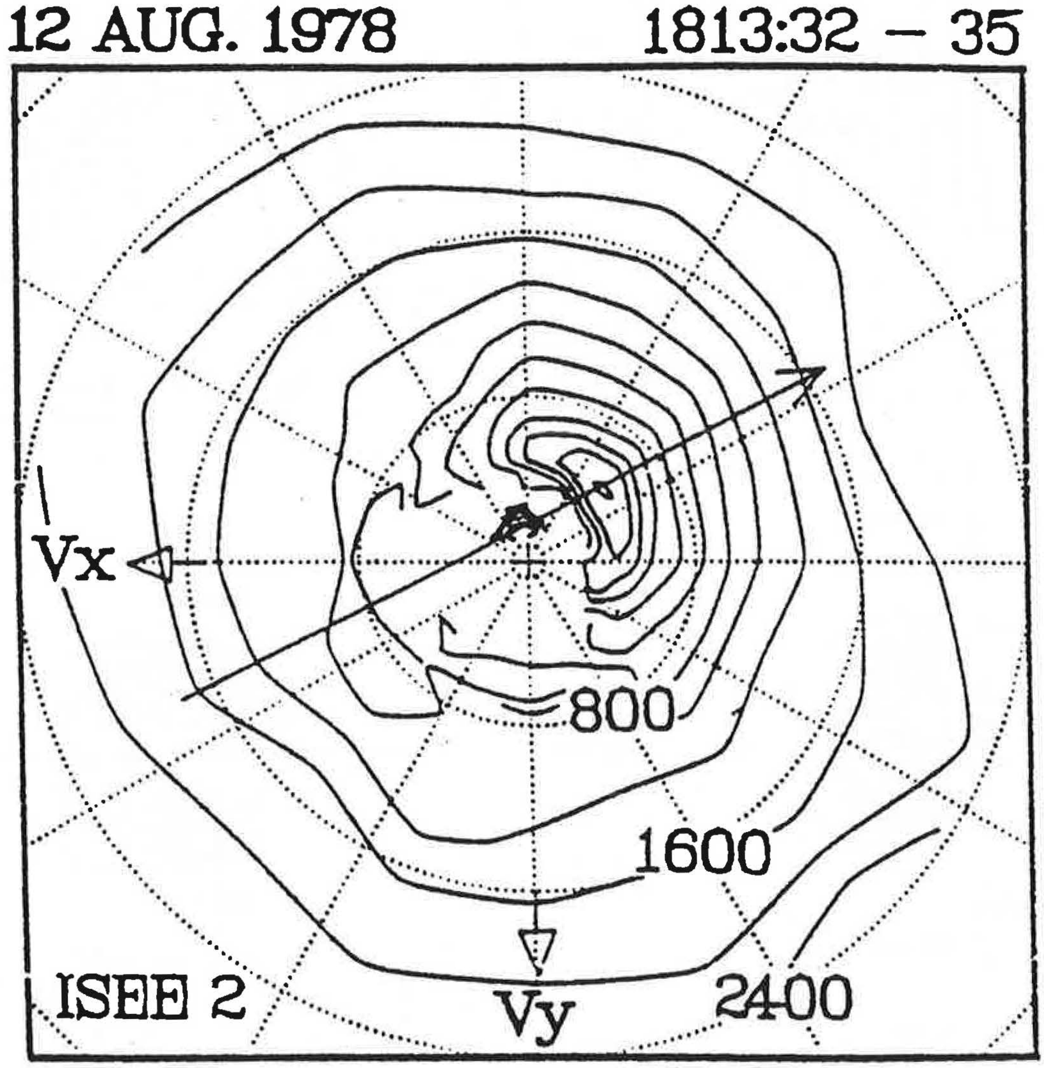

Figure 6. A two-dimensional ion velocity distribution function observed in the low-latitude boundary layer of the magnetosphere by the ISEE-2 satellite on 12 August 1978. The plot is in the GSE X-Y frame and the projection of the magnetic field direction on the XY plane is given by the arrow. The contour levels are of constant phase-space density separated logarithmically. The dotted circles are labelled in km s^{-1} (from Gosling et al., 1990b).

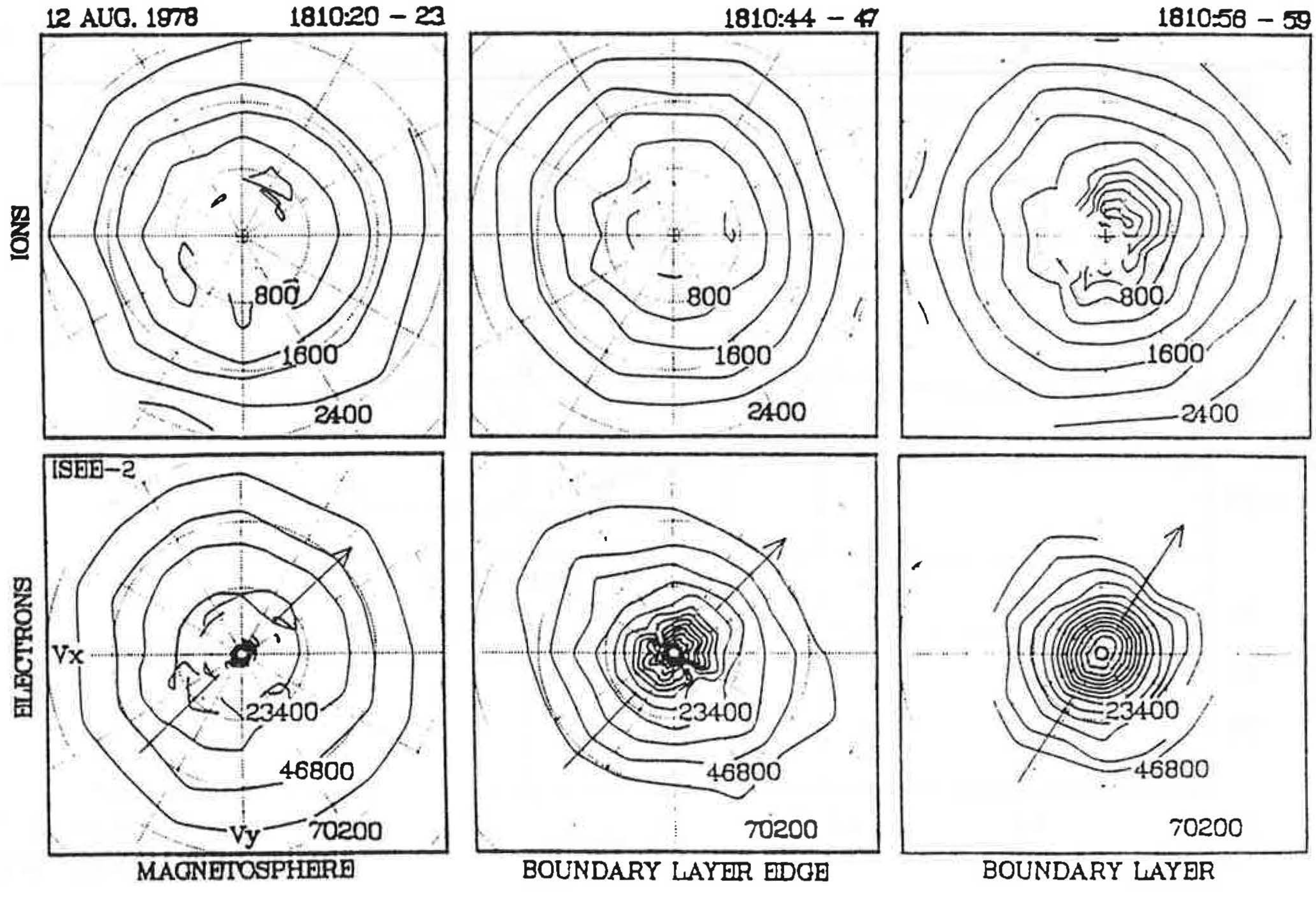

Figure 7. *Ion (top) and electron (bottom) velocity space distribution functions observed at three times by ISEE when close to the magnetopause on 12 August 1978. See figure 6 for details. (after Gosling et al., 1990c)*

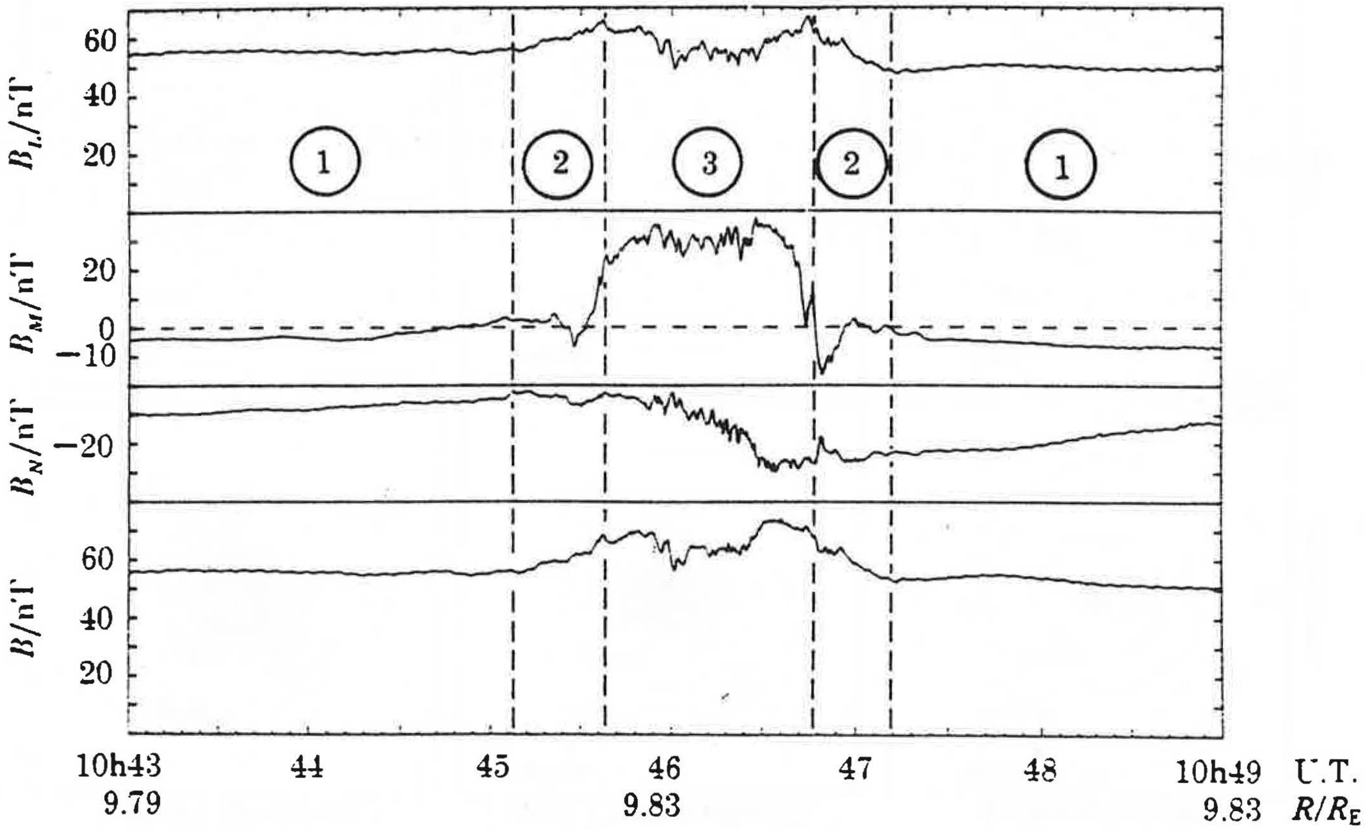

Figure 8. A magnetopause flux transfer event signature observed on 28 October 1984 by the AMPTE-UKS satellite (from Farrugia et al., 1988)

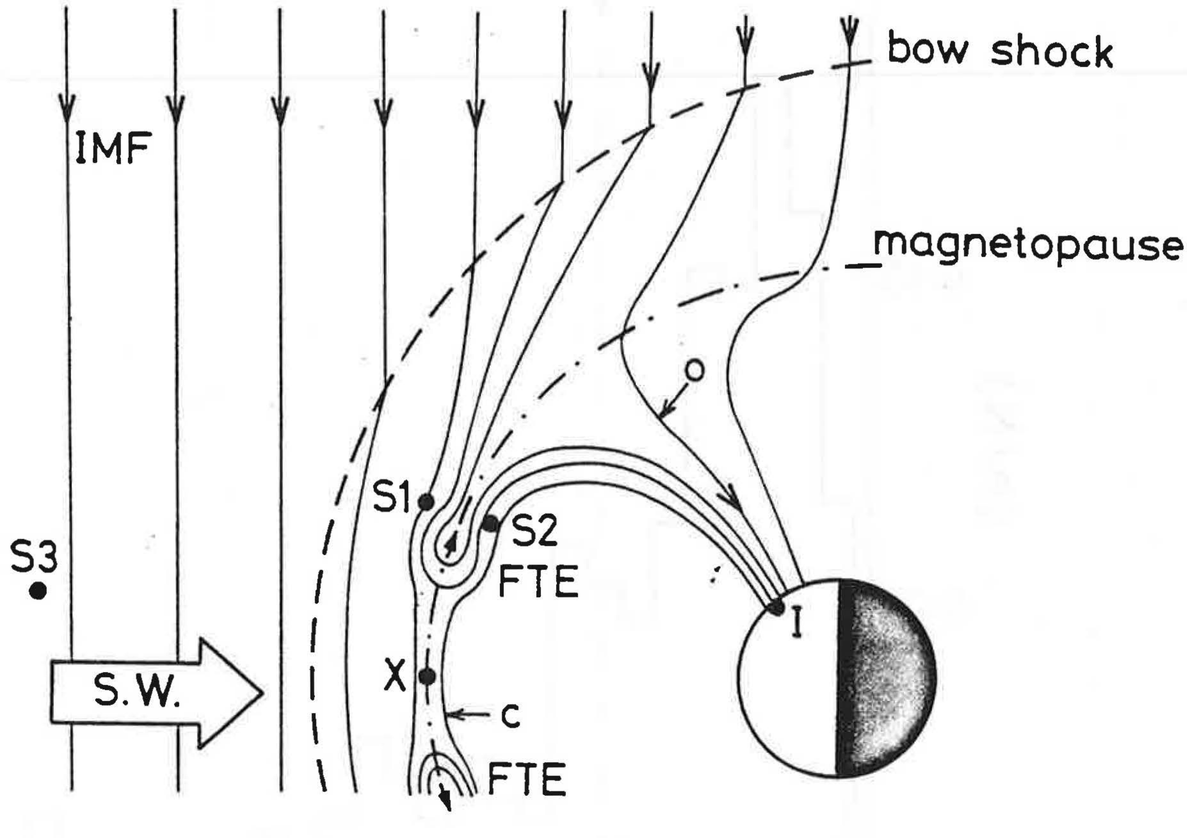

Figure 9. Schematic illustration of the Southwood et al./Scholer/Semenov et al. model of the production of magnetopause FTEs, as observed by satellites close to the magnetopause, either in the magnetosphere (such as S2) or in the magnetosheath (S1). S3 marks a typical location of an IMF monitor, X is the position of the reconnection X-line in the dayside magnetopause and I is the ionospheric footprint of the newly-opened field lines (from Lockwood and Wild, 1992).

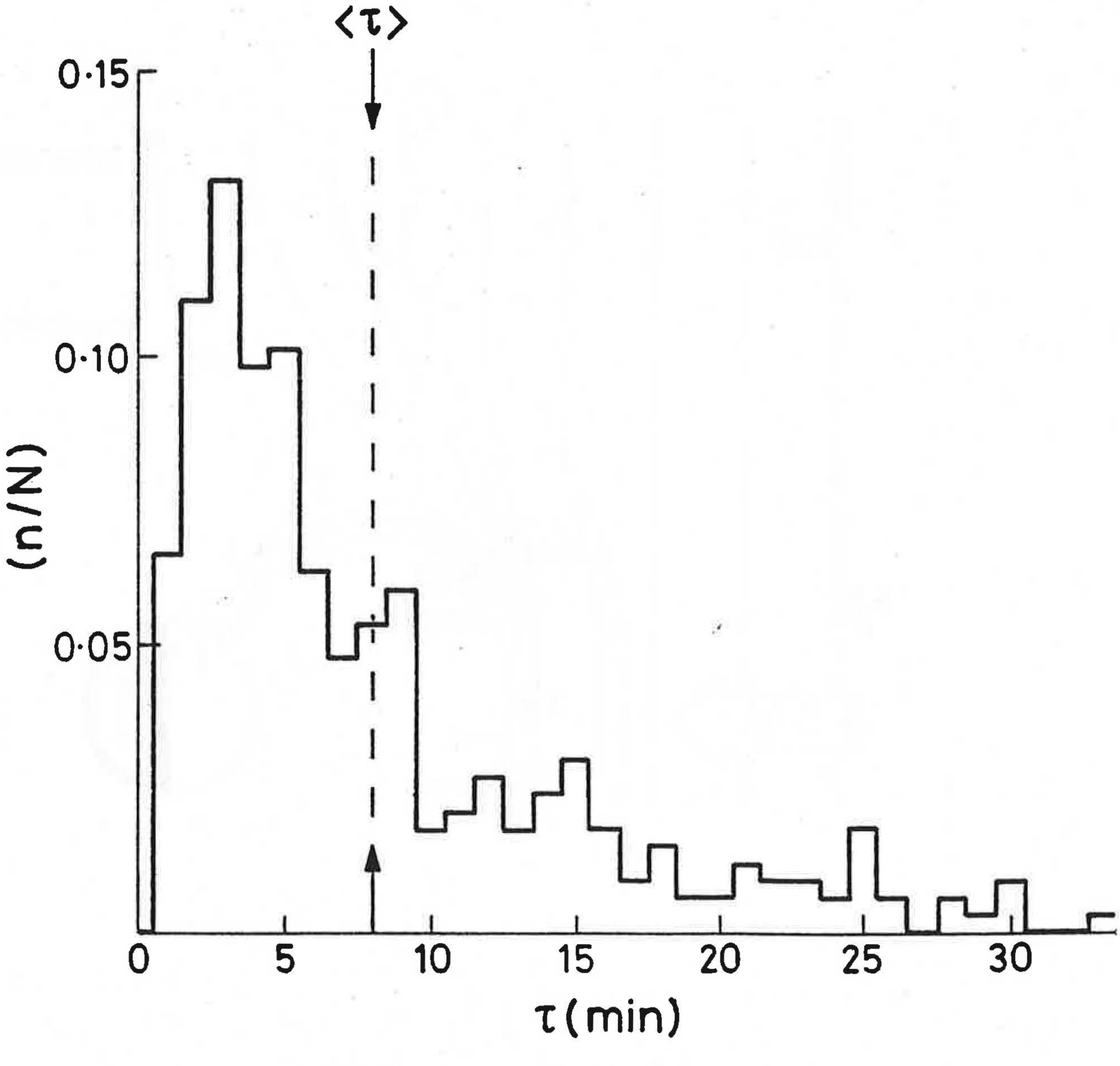

Figure 10. The distribution of inter-FTE intervals from the ISEE magnetopause data. The number of cases, n, for each 1-minute bin of the interval length, τ, is shown, normalised by the total number, N = 341 (from Lockwood and Wild, 1992).

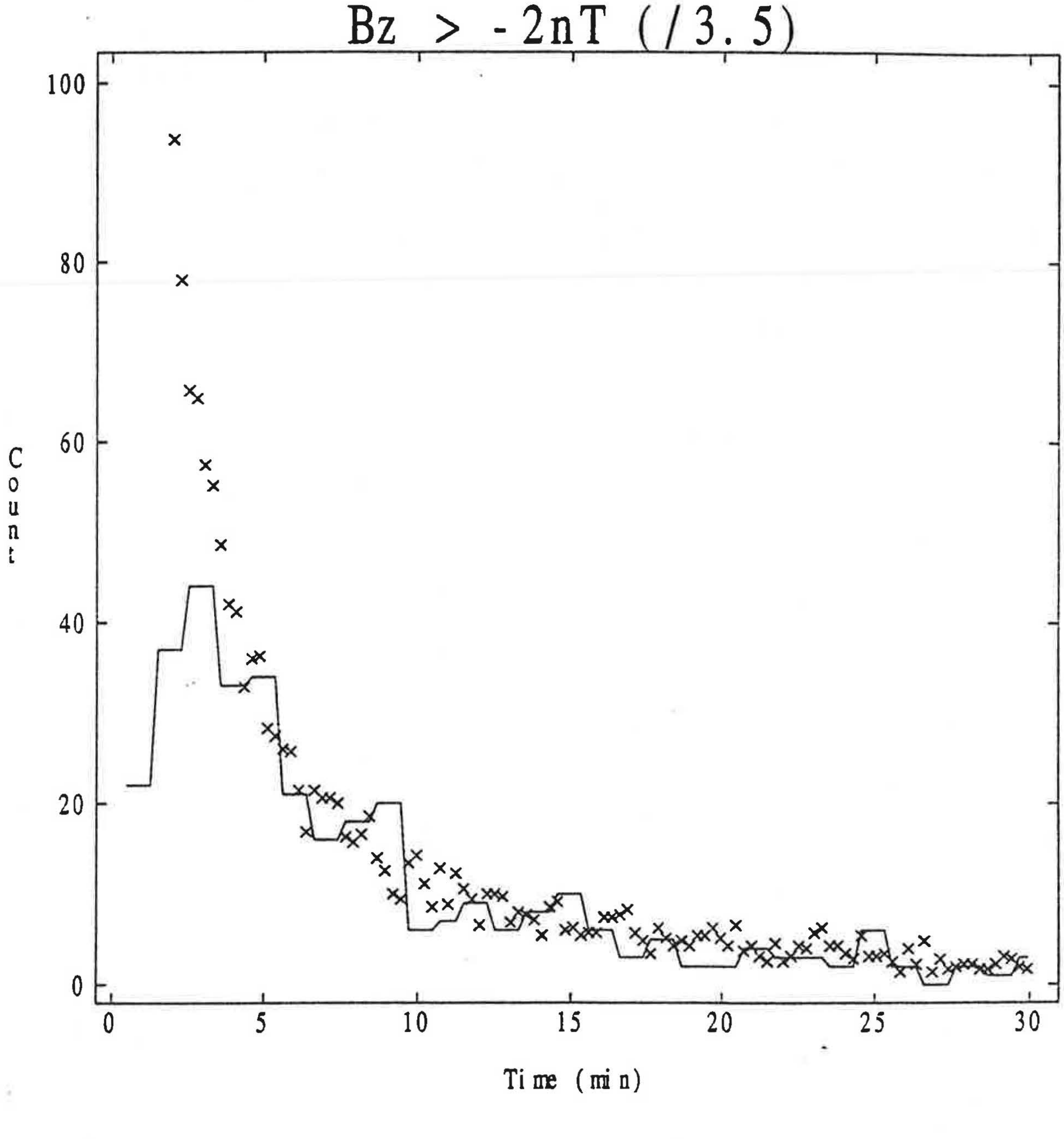

Figure 11. *The distribution shown in figure 10, plotted as a continuous line, and the distribution of durations of intervals of IMF $B_z > B_{zT} = -2nT$ (crosses). The axis labelled "count" gives the number of cases, n, of inter-FTE intervals in 1-minute bins, and the number of periods of IMF $B_z > B_{zT}$ in 15.339-second bins, the latter divided by a scaling factor of 3.5. (from Lockwood and Wild, 1992).*