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TITLE

# OBSERVATIONS OF FLUX TRANSFER EVENTS: ARE FTEs FLUX ROPES, ISLANDS, OR SURFACE WAVES?

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# Observations of Flux Transfer Events: Are FTEs Flux Ropes, Islands, or Surface Waves?

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**Flux transfer events (FTEs) are widely regarded as a signature of transient magnetic reconnection between the solar wind and magnetospheric plasmas. However, there is disagreement on what form this reconnection takes: Are FTEs tearing islands, or time-varying single x-line reconnection? We reexamine the evidence that first led to the suggestion that FTEs are related to a non-time-stationary reconnection process. In particular we discuss how the combination of field and plasma variations suggest that FTEs are magnetic flux ropes. Both time-varying single x-line reconnection and multiple x-line merging can produce a signature which 'mimics' that of a flux rope, but without the flux rope topology. Finally, we review the evidence that FTEs cannot be merely surface waves: their occurrence during southward IMF, mixture of solar wind and magnetospheric plasmas, leakage of energetic particles, accelerated plasma flows and peculiarities of the magnetic signature all point to a reconnection-related phenomenon.**

## Introduction

The magnetopause is the boundary of the terrestrial magnetosphere; it separates the terrestrial plasma and magnetic field from those of the solar wind. Consequently the magnetopause is the prime site for energy transfer from the solar wind to the magnetosphere. It has long been known that geomagnetic activity is linked to solar wind conditions. When the interplanetary magnetic field (IMF) has a southward orientation, opposite to that of the northward terrestrial magnetic field, there is enhanced energy input from the solar wind to the magnetosphere. When the IMF has a northward orientation, parallel to that of the Earth's field, little energy is transferred. *Dungey* [1961] was the first to suggest that magnetic reconnection at the magnetopause is the principal mechanism for energy transfer when the IMF is southward.

While there was at the time indirect evidence of the validity of Dungey's 1961 hypothesis, the first convincing *in situ* measurements of reconnection at the magnetopause came much later, after the launch of the ISEE spacecraft in 1977. ISEE plasma and magnetic field measurements revealed that the time independent tangential stress balance expected in a rotational discontinuity sometimes appears to hold across the magnetopause, consistent with quasi-steady state reconnection [*Paschmann et al.*, 1979, *Sonnerup et al.*, 1981]. But even under favorable conditions these steady reconnection signatures were not always observed, evidently reconnection occurs sporadically.

*Haerendel et al.* [1978] noted evidence in the HEOS 2 data that reconnection can occur at the high latitude magnetopause in a spatially and temporally limited manner. *Russell and Elphic* [1978] suggested that impulsive reconnection can occur at the low latitude magnetopause, based on ISEE observations of isolated but large scale disturbances of the magnetic field, plasma and energetic particle environment at and near the magnetopause. These disturbances are brief (1 – 2 minutes) and separated by a longer period of quiet (typically 8 minutes). What *Russell and Elphic* [1978] suggested, in effect, was a magnetopause analog to solar flares. Because of their episodic nature and their association with enhanced convective plasma flow, they were dubbed flux transfer events (FTEs).

Magnetic flux is transported in FTEs, that this flux transport is related to reconnection is suggested by both plasma and energetic particle data. Surveys by *Berchem and Russell* [1984] and *Rijnbeek et al.* [1984] showed that FTEs can occur all across the dayside magnetopause when the IMF is southward, but rarely when the IMF has a northward component. They are observed near magnetopause crossings where quasi-steady reconnection is found. FTEs may thus be an important, and possibly dominant form of reconnection at the magnetopause.

*Farrugia et al.* [1988] and *Sonnerup* [1988] have recently reviewed, respectively, the observations and theoretical interpretation of FTEs. Our goal here is to present observations of FTEs and to compare with the various hypotheses put forward to explain those observations. In particular we wish to test whether or not FTEs are actually magnetic flux ropes, as some of the theories suggest. In the process we shall visit the question of whether or not FTEs have anything to do with reconnection at all — can they be explained as mere surface waves on the magnetopause? We shall briefly review magnetic, plasma and energetic particle behavior in FTEs, and then discuss some of the hypotheses put forward to explain that behavior.

## FTE Observations

### *Magnetic Field Signature*

FTEs were first identified by *Russell and Elphic* [1978] as a particular signature in the magnetic field near the magnetopause. Examples of this signature can be seen in Figure 1, magnetic field data near a magnetopause crossing on 21 October, 1981. The data shown span the period 1200 to 1340 UT, during which the ISEE spacecraft passed from the magnetosphere into the magnetosheath. The magnetopause crossing is at about 1247 UT. The data have been cast into a coordinate system ordered with respect to the magnetopause surface: the N component is normal to that surface, while the L component lies in the plane of the magnetopause surface and is directed northward, the M component completes the right-handed LMN set. If the magnetopause were a simple one-dimensional current sheet, the field would change only in the plane of the current sheet, i.e., only in the L and M components.

Figure 1 shows that field variations are not confined to the magnetopause plane. Indeed, large variations in the N component indicate that the boundary is disturbed, or filamentary currents are present, or both. Some of these events are demarcated by hatched lines. The most striking feature is the tendency for these $B_N$ variations to be bipolar and to occur at rather regular intervals of about every six minutes. The bipolarity is almost without exception a positive followed by negative variation. These $B_N$ variations are often accompanied by an increase in the field strength, and by changes in $B_L$ and $B_M$ away from either the magnetospheric or magnetosheath orientation. These three-dimensional magnetic field variations indicate a localized breakdown in the planar structure of the magnetopause.

The persistence of the +/- bipolar $B_N$ signature in both the magnetospheric and magnetosheath FTEs in Figure 1 indicates that the field in both locations bends first away from the plane of the magnetopause, then toward it. This is the expected signature of a passing 'bubble' on the magnetopause, or alternatively of a filamentary current lying in the magnetopause and advecting northward. It is this very signature that caused *Russell and Elphic* [1978] to reject surface waves as an explanation of the FTE phenomenon (but this topic arises again later). The bipolar signatures in $B_N$ have the same +/- sense whether they are seen inside the magnetosphere, or in the magnetosheath. In order for a surface wave to produce both signatures, it must push the magnetopause only inward for magnetospheric FTEs and only outward for magnetosheath FTEs (or that outward localized displacement of the magnetopause produces no noticeable signature). The simpler explanation is that the FTE is a disturbance like a blister on the boundary, distorting both the southward magnetosheath and northward magnetospheric fields to produce the characteristic +/- $B_N$ signature if the blister were moving northward, and a -/+ signature if moving to the south. *Russell and Elphic* [1978] proposed that an isolated reconnected flux tube, topologically distinct from the surrounding magnetosheath and magnetospheric plasmas, would produce just such a signature.

Comprehensive surveys of the ISEE 1 and 2 magnetic field data by *Berchem and Russell* [1984] and *Rijnbeek et al.* [1984] showed that FTE signatures are seen with nearly equal frequency inside and outside of the magnetopause and that FTEs are observed almost exclusively when the magnetosheath magnetic field is southward. They also found that the bipolar $B_N$ component variation tends to be a [illegible] direct north of the magnetic equator while the opposite sense [illegible] reverse [illegible] found to the south. Figure [illegible] shows the distribution of FTE direct and reverse signatures on the dayside magnetopause. *Cailey et al.* [illegible] examined the convective electric field in FTEs and found that those with direct signatures were traveling northward and those with reverse southward.

*Elphic and Southwood* [1987] examined a case where spacecraft at widely separated sites, AMPTE UKS and ISEE 1 and 2, were passing through the magnetopause at roughly the same time. UKS, near noon LT and a few degrees above the equator, observed FTE signatures at the same time as ISEE 1 and 2, near the same local time but several $R_E$ to the south. The implication is that FTEs truly originate near the equator and convect away, north and south.

One important, but not widely appreciated ramification of FTE observations is that not all encounters by spacecraft with FTEs are equal. Some are grazing passages, and the $B_N$ signature then reflects merely the local plasma response to a passing disturbance on the magnetopause. Some, however, must be passages through the true reconnected magnetic flux, there we must expect the plasma and field signatures to be different from the grazing cases. In order to understand the interior structure of an FTE, it is important to study first the grazing cases.

*Farrugia et al.* [1987a] investigated the magnetic signatures of grazing FTEs and showed that they are approximately consistent with incompressible plasma flow about an impenetrable cylinder. The +/- $B_N$ variation corresponds to the deflection of plasma out of the way of the approaching cylinder, while the $B_L$ and $B_M$ variations follow from the draping of field over the cylinder and the plasma flow around it. This process is illustrated in Figure 3, adapted from *Farrugia et al.* [1987a]. For oblique cylinder orientations there is a peak in $B_L$. Consequently the field strength maxima so often seen in FTEs do not necessarily correspond to the core field of a twisted flux rope structure, but rather to the draping field around the FTE core region, the impenetrable cylinder. Strictly speaking, these results do not address the issue of what is inside the core, nor what produced it.

A comparison of predicted and observed magnetic field and convective plasma flow around an FTE is shown in Figure 4. The prediction is based on the incompressible flow/field assumption discussed by *Farrugia et al.* [1987a]. The data, in boundary normal coordinates, are from an FTE observed by ISEE 1 and 2 while in the magnetosphere at about 0700 UT on September 3, 1978. The convective plasma velocity ($\mathbf{E}\times\mathbf{B}/B^2$) is derived from electric and magnetic field measurements (see *Daley et al.* [1985]). We have scaled the abscissa to be a measure of spacecraft trajectory distance in arbitrary units assuming the FTE convects at a steady speed. Solid lines denote the best fit incompressible flow and field solution, while dotted lines denote the data.

The magnetic field variations appear to fit the model at least qualitatively, with the $B_N$ signature due to the northward passage of the FTE cylinder past the spacecraft. The negative/positive/negative variations in $B_M$ correspond to the cylinder being inclined by 51deg relative to the magnetospheric field, canted in the direction of the magnetosheath field. As expected for a northward-going FTE as seen in the magnetosphere, the convective flow component $V_N$ is in antiphase to the $B_N$ component. Likewise, the observed $+V_M$ flow is consistent with the expected reconnection flow based on the external magnetosheath field orientation. However, the details of the data are not in agreement with the prediction, suggesting the breakdown of one or more of our assumptions. Nevertheless, the qualitative agreement of field and flow with the incompressible model suggests that the notion of an FTE obstacle as a convecting cylinder is not completely unreasonable.

Another almost brute force demonstration of the FTE morphology comes from simultaneous observations of the magnetic fields on either side of the magnetopause. This was possible when ISEE 1 and 2 were at their greatest separations on the dayside in 1979, with one spacecraft in the magnetosphere, the other in the magnetosheath. *Farrugia et al.* [1987b] discussed these observations in detail. Figure 5 shows the observed variations of the magnetic field in the magnetosheath (ISEE 1) and in the magnetosphere (ISEE 2) for an FTE at 1358 - 1400 UT on November 9, 1979. The field vectors are shown in the L-N plane along trajectories parallel to the magnetopause surface, assuming that the FTE is convecting as a whole at 150 km/s from north to south (the spacecraft are south of the equator). The spacecraft are separated by 3300 km normal to the magnetopause, with ISEE 1 some 5000 km (~0.8 $R_E$) further north along the L direction.

ISEE 1, the more northerly spacecraft, observes the first disturbance of the oncoming FTE, a negative $B_N$ excursion (a). At the time of maximum negative $B_N$ on ISEE 1, ISEE 2 has begun a positive negative excursion (b). When the ISEE 1 $B_N$ signature passes through zero at the midpoint of the FTE, ISEE 2 is approaching its maximum negative excursion. As the ISEE 2 $B_N$ signature swings through zero, ISEE 1 is just past its maximum

positive $B_N$ excursion. Finally ISEE 1 is sensing the last vestige of its positive $B_N$ signature when ISEE 2 passes through its positive $B_N$ maximum. The combination of spacecraft separation normal to the boundary, along the boundary in the north-south direction, and the phase relationship between the two sets of $B_N$ signatures indicate that a structure much like an elongated blister is passing on the magnetopause.

*Plasma and Particle Observations*

The observed FTE magnetic field variation is not in itself necessarily evidence for reconnection. However, the observed plasma and particle signatures within FTEs are consistent with reconnection. *Daly et al.* [1981] found that energetic magnetospheric ions were streaming along the local magnetic magnetic field in FTEs, away from the Earth. *Paschmann et al.* [1982] found that the bulk properties of the FTE plasma are a mixture of tenuous, hot magnetospheric plasma, and the dense, thermal magnetosheath plasma. They also found that the FTE plasma was sometimes accelerated above the local magnetosheath speed. *Scudder et al.* [1984] have reported that a net parallel electron heat flux is found on one or both edges of magnetosheath FTEs; they ascribe the signature to ongoing reconnection. More recently, *Thomsen et al.* [1987] reaffirmed the view that FTE plasma is a mixture but also found significant modifications to the magnetosheath electron component, particularly heating preferentially parallel to the field. They found that the electron heat flux could be as readily explained by leakage of a hot magnetospheric component as by heating through reconnection. *Sibeck et al.* [1987] echoed this assessment for the energetic ions. Figure 6 shows the ion anisotropies as organized (a) by the merging model of ion escape and (b) by simple leakage through the boundary.

It is instructive to view FTE plasma and magnetic field data together. Figure 7 shows a pass through the magnetopause near the nose by AMPTE UKS, the same examined by *Elphic and Southwood* [1987]. The panels contain ion density, temperature, thermal pressure, and vector flow velocity, respectively. The bottom panels show magnetic field, both field and flow are in boundary normal coordinates. UKS is initially in the magnetosphere as evidenced by the low plasma density and high temperature; there is a brief exit to the magnetosheath between 1559 and 1602 UT, characterized by high densities and low temperatures. Thereafter UKS returns to the magnetosphere but has two encounters with boundary layer like plasma at 1604 and 1608 UT, the satellite does not exit the magnetosphere completely until 1610 UT.

There are flow bursts throughout the pass, with center times of 1559:30, 1601:45, 1604:30, 1607:15, 1610:30, 1611:00 and 1616:30 UT. The first two and the event at 1610:30 UT are associated with magnetopause current sheet crossings, and may reflect quasi steady reconnection. The others appear to be associated with bipolar variations in the $B_N$ component, a signature of FTEs. The magnitude of the plasma flow in each burst is considerably larger than the background magnetosheath flow speed of 40 – 80 km/s. All flow bursts are associated with ion thermal pressure maxima. Two possible explanations of this behavior are (1) Motions of the magnetopause, including undulations or small wavelength surface waves, carry a relatively steady state fast flow layer over the spacecraft, giving the illusion of temporal burstiness. (2) Rapid reconnection flows occur over a variety of time scales, from quasi steady to impulsive. In the former only quasi steady reconnection is required, along with surface motion of the magnetopause; however, the arguments advanced in the last section put this explanation in doubt. The second picture explains why there should be a $B_N$ signature in some events and not in others.

Figure 8 shows observations of an FTE by AMPTE UKS, adapted from *Rinbeck et al.* [1987], and illustrating some the plasma features of an FTE. Here selected moments of the ion distribution function, electron flux intensities and magnetic field variations are shown. The data begin at 1013 UT in the magnetosphere where the ion plasma has a roughly 1 keV temperature, and a density of about 1 $cm^{-3}$. The intensities of 0.2 and 1 keV electrons are comparable within a factor of 2. In region (1) the magnetic field gradually changes, the $B_N$ component making a positive excursion. At 1017 UT the plasma density begins to increase, the temperature to drop, and the flow speed to rise. In the region marked (2) the 12 eV electron intensity rises and the 1 keV intensity falls, indicating the presence of a more thermal population. The 200 keV electron intensity has a local maximum in this region. The magnetic field magnitude rises. In region (3) the plasma has the characteristic density and temperature. The magnetic field, though, is weaker by nearly 3 fold. The second half of the FTE is [illegible] the [illegible] at the ion perturbations are negative.

Taken together, the particle and field characteristics could be regarded as consistent with reconnection. Region (1) represents the disturbance region outside the reconnected flux tube. Region (2) corresponds to the separatrix layer, and the enhanced 295 eV intensity is a signature of the electron heat flux out of the reconnection site, similar to that reported by *Scudder et al.* [1981]. It is a possible indication that reconnection is still occurring somewhere along field lines connected to the observation point. Region (3) is near the core of the reconnected flux tube, with accelerated convective plasma flow away from the reconnection site, and the magnetic field in an orientation intermediate between that of the magnetosphere and the magnetosheath. Not shown here is the streaming of energetic ions out of the magnetosphere.

There may be reasons to doubt that the *Rijnbeek et al.* [1987] FTE is in fact a reconnection event. It may be nothing more than a brief exit from the magnetosphere into the magnetosheath while the IMF is northward (D. Sibeck, private communication, 1989). ISEE 1 and 2 were in the solar wind at the time, and observed a quite variable IMF with a strong radial component. These conditions lead to the development of upstream waves which, when processed by the bow shock and convected to the magnetopause, may cause pressure fluctuations and boundary motions.

*Paschmann et al.* [1982] noted that the plasma and magnetic pressures in an FTE often maximize at the center of the event. They found that this overpressure could be balanced by the tension associated with the Maxwell stress of field lines wrapped around the core region. Figure 9 shows their results. This relationship between tension and internal pressure implies that the FTE is a self balancing entity, and led to the supposition that at least part of the $B_N$ signature corresponds to a helically twisted outer field in FTEs (*Cowley* 1982, *Paschmann et al.*, 1982).

*FTE Occurrence*

We showed evidence earlier that even quasi-steady state reconnection may have some intrinsic time scale for growth and decay. FTEs have been interpreted as a highly time-dependent reconnection event. Sometimes quasi-steady reconnection and FTE's are observed on the same magnetopause pass. Are the two seemingly distinct forms of reconnection related? Is there an intrinsic time scale associated with the reconnection instability?

The quasi periodic occurrence of reconnection events, and in particular FTEs, suggests that the process has some intrinsic time scale for the buildup and release of free energy in the magnetopause current sheet. If so, there should be a relationship between the energy released in an FTE and the free energy buildup time: the longer the buildup time, the greater the energy available for release, and hence the greater the energy in the FTE. This process is analogous to proposed substorm mechanisms in the magnetotail, to the unsteady flow of water drops from a leaky faucet, and even to the occurrence of earthquakes. It is, in short, characteristic of a highly nonlinear dynamical system.

So we wish to explore the relationship between FTE (released) energy and the accumulated free energy since the last release. Because it is impossible to determine the total energy content of an FTE, we must use a measurable quantity which is in some way related to energy content. One possible parameter is simply FTE size, as characterized by the duration of the event. For this quantity to be a valid size parameter, we must assume that all FTEs travel at the same speed. To characterize the free energy accumulated at the magnetopause, we use the time since the last FTE. For this quantity to be a valid parameter we must assume that the last FTE released all free energy from the boundary, and moreover, that the free energy accumulation rates are always the same.

We have measured FTE durations and inter FTE times for events observed by AMPTE UKS or IRM and ISEE 1 and 2. These are shown in Figure 10. Two points emerge: (1) Most of the FTE's observed by AMPTE (and not close to the equator) have shorter durations; (2) Larger FTE's tend to be observed for longer inter FTE time. There is considerable scatter in the data, suggesting that our assumptions are not entirely good. Another parameter relating to FTE energy content would be an estimate of FTE cross section. A measure of the FTE cross section is the Lundquist, the ratio of the axial $B_N$ excursion to the Lundquist field. The larger the size of the FTE normal to the boundary, compared to its extent along the boundary, the larger the value of [illegible]. When normalized, FTE duration (a quantity proportional to the time of FTE flux in the boundary

normal direction. Figure 11 shows how this quantity varies with inter FTE time. Once again there is a trend suggesting that "larger" FTEs are found after longer energy accumulation times, and most of the AMPTE FTEs are smaller than the ISEE FTEs.

The correlation coefficients for the above trends are approximately [illegible]. There are many reasons for the scatter in Figures 10 and 11. Our simple measures of FTE size or energy content, and of the boundary's free energy accumulation time are crude. It is unlikely that all FTEs convect past the spacecraft at the same speed, the free-energy accumulation rate varies with IMF and solar wind dynamic pressure changes. Moreover, the quantity "Time Between FTEs" hides the fact that, if the last FTE was a small one, little free energy was removed from the boundary. Thus, a large FTE could follow a small one by a very short time.

Like unsteady water drops, there should be a relationship between the time since the last FTE and the time since the last one before that. This relationship, a kind of FTE strange attractor, would not be obvious until hundreds or thousands of FTEs had been observed, and then only under absolutely constant external conditions. In practice the external conditions are constantly changing. Thus, an intrinsically endogenic process (the quasi-periodic accumulation and shedding of free energy in the boundary) could be triggered irregularly by exogenic processes (solar wind pressure pulses, or changes in IMF orientation). A solar wind pressure pulse, for example, could pinch an initially stable magnetopause current sheet, drive it unstable, and produce a burst of reconnection.

## FTE Models

### *Transient Reconnection*

*Russell and Elphic's* [1978] original explanation for FTEs involved spatially and temporally limited reconnection. If a patch of the magnetopause were to become unstable to reconnection for a limited time the result would be a bundle of reconnected flux lines threading the magnetopause surface. The bipolar $B_N$ variation is the signature of draping of the surrounding fields around the reconnected flux tube, and the intermediate field orientation within the FTE is the core field of the flux tube. A mixture of magnetosheath and magnetospheric plasma would be seen in the open flux tube, and that mixed plasma would be flowing at a velocity different from the background magnetosheath flow. The sense of the FTE plasma velocity would be in approximate agreement with quasi-steady reconnection stress balance. On the other hand, a grazing encounter with the reconnected flux tube would not necessarily show such an agreement.

Because of the relationship between FTE internal pressure and tension forces discussed above, *Paschmann et al.* [1982] and *Cowley* [1982] argued that the FTE magnetic field must have a twist, like a magnetic flux rope. In this view a field aligned current flowing in the reconnected tube produces a net azimuthal field which helps to pinch the FTE tube. The resulting configuration is shown in Figure 12. *Saunders et al.* [1984] examined FTE magnetic and flow field variations and found they obeyed the Walén relation, as would be expected if the field twist were an Alfvén wave propagating along the FTE flux tube. However the sense of wave propagation on the magnetospheric side of an FTE was found to be different from that on the magnetosheath side. Consequently the field twist could not simply arise from shear in the plasma flow on the magnetosheath "end" of the reconnected flux tube.

It now appears that *Saunders et al.* were observing the disturbance flow discussed above, namely the perturbed flow of plasma about the outrushing FTE obstacle. As *Farrugia et al.* [1987] point out, this approximately incompressible flow field perturbation also obeys the Walén relation. Nevertheless *Sonnerup* [1987] argues there must still be a field twist within the reconnected FTE tube. The field aligned current producing the twist is related to the orientation of the magnetosheath field, and to the JxB forces acting on the kinked reconnected flux tube.

*Scholer* [1988] and *Lotko and Schunk* [1988] have introduced a kinetic view of FTEs as transient reconnection at [illegible]. Earlier work by *Sitnov et al.* [1987] and *Semenov et al.* [1988] on time dependent Petschek [illegible] has been taken up in *Scholer* [1988]. Figure 13 illustrates the transient reconnection process. The home [illegible] field and plasma flow at a field reversing current sheet. At t=0 the onset of reconnection at *X*

- Near the reconnection site the field and plasma have established the inflow and outflow characteristics of steady Petschek reconnection, while far from the reconnection site (near $z = 150$) the initial Harris equilibrium current sheet is undisturbed. In the intermediate region the field and plasma undergo a transition from static equilibrium to the dynamic expansion fan geometry. The transition field is bubble-like, and contains the accelerated plasma. Outside the bubble the ambient plasma and magnetic field are forced out of the way in a fashion that is qualitatively very similar to that described by *Farrugia et al.* [1987a] for incompressible flow about a cylindrical obstacle.

This transient single x-line reconnection scenario contains most of the observed attributes of FTEs, including the proper sense of the $B_N$ variation, accelerated plasma flow, energetic particle escape, and electron heat flux on field lines mapping to the reconnection site. Moreover, the statistically determined results for the sense of energetic ion anisotropy, the sense of the bipolar $B_N$ signature, and the convective flow direction that were successfully explained by the *Russell and Elphic* [1978] picture are still consistent with the updated model.

### *Multiple X-line Reconnection*

*Lee and Fu* [1985] advanced an alternative mechanism for creating FTEs at the magnetopause. As *Podgorny et al.* [1978] had done, they suggested that multiple x-lines due to tearing mode reconnection could produce magnetic islands at the magnetopause current sheet. But *Lee and Fu* pointed out that, if the magnetosheath and magnetospheric fields are not precisely antiparallel, the islands will contain a field component along the island's axis. The resulting overall field configuration is that of a magnetic flux rope, as illustrated in Figure 14. As the tearing mode saturates, the islands grow to some maximum size and are eventually convected away down the flanks of the magnetosphere, and the process begins anew.

Variations on the multiple x-line reconnection have been advanced. *Crooker* [1986] invoked antiparallel merging to produce a large single island-like structure at low latitudes. There are also questions concerning the role of Kelvin-Helmholtz in reconnection. *Labelle-Hamer et al.* [1988] have suggested that the tearing mode may feed off the K-H instability. There is also the possibility that the reverse takes place, that strongly sheared reconnection flows could drive K-H.

The multiple x-line scenario explains the observed magnetic field variations, energetic particle anisotropy, plasma acceleration, the global distribution of $B_N$ signatures and the episodic occurrence of FTEs. However the observed electron heat flux signatures of *Scudder et al.* [1984] may not be consistent with the tearing island picture. Multiple x-lines should produce multiple heat flux signatures, some nested within others. As an FTE passes across a spacecraft, electron heat fluxes both parallel and antiparallel to the field should be seen consecutively. FTE electron observations do not appear to support this. In fact, *Scudder* [1989] have recently shown preliminary evidence that, on a given magnetopause pass the magnetosheath FTE electron heat flux is parallel to the local field, while for the magnetospheric FTEs it is antiparallel. If confirmed, this observation cannot be explained by simple leakage, and it is not consistent with multiple-x line reconnection. Rather it points to a form of single x-line reconnection.

*Aan* [1988] has described a synthesis of the multiple and single x-line pictures. He suggests that any one x-line will be limited in longitudinal extent, so that along a given meridional cut through the magnetopause there is only one merging site. This is shown schematically in Figure 15. Each x-line may turn on and off intermittently producing an FTE signature.

### *FTEs and Solar Wind Pressure Pulses*

In the last few years a complex view of solar wind magnetosphere interactions based on the steady solar wind model has arisen. There is a view that parcels of solar wind plasma may impulsively penetrate the geomagnetic field during the FTE signature. *Cowan* [1987] has recently reviewed the impulsive penetration picture. We shall [illegible] of Gather. However, in the [illegible] The steady solar wind picture has received more attention.

Recently *Siscoe et al.* [1988] have reinterpreted observations [illegible] solar wind dynamic pressure pulses. That [illegible] magnetopause. [illegible] pulses could be responsible for initiating reconnection

the FTE **B** and $B_N$ variations for the same reasons that *Farrugia et al.* [1987a] described: the ambient magnetosphere plasma and field are forced to circulate about any traveling magnetopause disturbance. A convecting tearing island, a single-x-line "bubble" or a surface wave all distort the boundary and force the surrounding medium into motion. This process sends Alfven waves to the ionosphere and produces the vortices observed there (*Friis-Christiansen et al., 1988, Elphic, 1988*). But as discussed earlier, in order to produce FTE signatures in both the magnetosheath and magnetosphere, the surface disturbance must protrude both into the magnetosphere and into the magnetosheath.

In a further development of the pressure pulse idea, *Siscoe* [1989] has argued how such a double-peaked protrusion may occur. The pressure pulse, traveling along the magnetopause, sends a fast mode wave ahead of it. The increased total pressure in the fast mode wave sends the local magnetopause out of equilibrium: the boundary must move outward in response. Consequently the whole train of magnetopause disturbances is first an outward movement of the boundary associated with the leading fast mode wave, followed by an inward movement associated with the external pressure pulse. A spacecraft in the magnetosheath would sense the $+/-$ $B_N$ disturbance of the outward magnetopause protruberence, while a spacecraft in the magnetosphere would sense the disturbance associated with the external pressure pulse. The boundary motion and perturbed magnetic fields are shown schematically in Figure 16.

There are a number of open questions in the pressure pulse model. One is whether or not there is evidence for a fast mode wave ahead of the magnetosheath pressure pulse signature. In the ISEE data shown in Figure 5, and discussed by *Farrugia et al.* [1988] there was no indication of a field enhancement in the magnetosphere ahead of the magnetosheath $B_N$ signature. ISEE 2 was ideally placed to observe such an enhancement. Instead, the magnetospheric field maximum was inferred to coincide spatially with the one in the magnetosheath. Another question centers on how the pressure pulse can cause accelerated plasma flow, as is observed. FTEs are observed to occur almost exclusively during southward IMF; pressure pulses have no preference for southward IMF orientation.

## Discussion

Elements of each of the above scenarios may occur at the magnetopause at one time or another. The question is whether any one of them can explain the observed suite of FTE attributes. If one such model can be singled out, the question of FTE topology may be addressed. There is, however, the possibility that a combination of these models may apply.

The transient single x line picture appears to be able to reproduce the detailed characteristics and global statistics of FTEs. In addition it offers an explanation for the observed association between quasi-steady and impulsive reconnection. FTEs can be regarded as a very large modulation of the reconnection rate. The multiple x line scenario also explains the observed FTE characteristics, with the possible exception of electron heat flux. However, since there is some question concerning the origin of the electron signature, it cannot be used as a discriminator between the two reconnection scenarios. In this picture, quasi-steady reconnection proceeds poleward of the last tearing island.

Finally, the pressure pulse scenario offers an explanation for the apparently impulsive nature of FTEs, but does not invoke reconnection. In this case there is some question of how accelerated plasma flow arises, as well as whether or not the required fast mode wave is observed in the magnetosphere ahead of the magnetosheath pressure pulse. On the other hand, there may be times when a pressure pulse can mimic an FTE signature. Any boundary undulation, at least in the common few minute FTE time scale, could be identified as an FTE.

As stated above, while a single model explaining FTEs is desirable, it may be a combination of the above characteristics that relates to the formation of FTEs. The simplest explanation for many of the observed plasma and field characteristics of FTEs is a train of reconnection. Solar wind pressure variations may trigger the reconnection process on the magnetopause by forcing the magnetopause current sheet to thin and destabilize. Patches of thin current sheet may be forming more frequently than the conventional steady state FTEs. As pressure [illegible] reconnection rate. The reconnection rate of this site [illegible] the observed FTE signature as well as that of quasi-steady reconnection.

During northward IMF there is less total current (and lower current density) flowing in the magnetopause, and the boundary may be stable to reconnection even when pressure pulses force it to thin.

Finally, the question of whether FTEs are magnetic flux ropes has not been answered. If the multiple x-line scenario obtains, then FTEs must have a rope-like structure. In the transient single x-line picture, the field topology is not that of a rope. However, it has certain rope-mimicking qualities. The pressure pulse/surface wave model does not alter the magnetopause field topology.

## SUMMARY AND CONCLUSIONS

In order to address the question of FTE origin, structure and topology, we have reviewed their salient observational features and statistical attributes. In particular we have focused on their magnetic, plasma and energetic particle signatures. We have also discussed the occurrence of FTEs, their quasi-periodic nature and how that might be a clue to their origin. Finally we have discussed three basic hypotheses put forward to explain the physics of FTEs.

The magnetic signature of FTEs includes a distinctive bipolar signature in the component normal to the magnetopause surface. Roughly, the direct (+/-) signature is found north of the equator, while the reverse (-/+) is found to the south. The same sense is found inside as outside the magnetosphere, and the direct signature corresponds to northward-going plasma, the reverse to southward. There are other field variations which suggest that at least some FTE signatures are due to grazing encounters with the FTE obstacle and do not correspond to passage through the reconnected flux tube at all. Consequently the field strength maxima often observed in FTEs can be ascribed to the draping or disturbance field around the FTE obstacle. Observations of FTE fields when two spacecraft are on either side of the magnetopause strongly suggest that the FTE obstacle is a bubble-like structure (as opposed to a single indentation of the boundary). FTEs are found to occur preferentially when the local magnetosheath field has a southward orientation.

Plasma and particle observations tend to support the reconnection picture of FTEs. The combination of accelerated plasma flows, energetic particle anisotropies consistent with the emptying of a newly opened magnetic flux tube, and the mixture of magnetosheath and magnetospheric plasmas all point to a reconnection-related phenomenon. The observation of electron heat flux at the outer edge of magnetosheath FTEs may also support this interpretation, though the heat flux may just be magnetspheric leakage. Cases where no plasma acceleration is observed may correspond to grazing encounters with the reconnected flux tube. Finally, the observational agreement between the total (thermal and magnetic) pressure maxima within FTEs and the inferred external magnetic tension in the $B_N$ field component points to a localized, self-pressure-balancing entity.

FTEs were first interpreted as a spatially and temporally-limited form of reconnection: each FTE a single flux tube connecting magnetosheath and magnetospheric fields. More recently it has become clear that FTE signatures can arise simply from the sudden and extreme modulation of the reconnection rate at a single x-line; there is no reason why they should be limited in longitudinal extent. Multiple reconnection sites can also produce a flux rope form of tearing island having the attributes of an FTE. There are few convincing ways to discriminate between the two forms of reconnection. At present the best hope is to use electron heat flux observations; but even this is possibly ambiguous. Though surface waves were initially rejected as an explanation for FTEs, pressure pulse-driven boundary motion has recently been advanced as a means of producing an FTE-like signature. At a minimum, this view implies that not all $B_N$ bipolar signatures are due to transient reconnection.

FTE characteristics, taken together, strongly suggest a reconnection-related origin. However, since FTE identification is based largely on the $B_N$ magnetic signature, it is possible to find many cases lacking one or more of the other FTE characteristics. For example, in a grazing encounter little or no plasma acceleration would be observed. By the same token, a $B_N$ signature caused by a solar wind pressure pulse will probably not be accompanied by other characteristics of transient reconnection; it is possible to misidentify FTEs.

Nevertheless, in the case of FTEs possessing the requisite reconnection behavior the evidence points toward intermittent reconnection modulated at some characteristic (1 - 2 minute) time scale, with a recurrence interval

of several times the modulation time scale (5 - 10 minutes). What remains unknown is the reason for these two time scales, which are far longer than the Alfvén travel time across the magnetopause current sheet. Rather, the modulation timescale is more like the time required for a fast mode wave to transit the dayside magnetosphere while the recurrence interval is approximately the time for an Alfvén wave to propagate along the geomagnetic field to the ionosphere, and return.

Possibly the phenomena of solar wind pressure pulses and transient reconnection are related. If upstream measurements reveal a pressure pulse associated with every FTE at the magnetopause, this does not necessarily mean that FTEs are pressure pulses. Instead the pulse may thin the magnetopause current sheet, destabilizing it to reconnection. The reconnection event may be short-lived or long, depending on the free-energy available in the current sheet. In any case only the transient part of the event causes the FTE signature. The recurrence rate of reconnection bursts may be externally-driven or a function of the coupled magnetopause/ionosphere system. Future work on FTEs may reveal that localized reconnection is modulated by the global magnetospheric system.

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## Figure Captions

Fig. 1. ISEE 2 magnetic field data for a crossing of the magnetopause on October 21, 1980. The data are shown in boundary normal coordinates, where N is the inferred direction normal to the magnetopause surface, and L is the projection of the earth's dipole on that surface. M then completes the right-handed LMN system. The magnetopause crossing can be seen as the sudden transition at 1217 UT from $B_L < 0$ (magnetosphere) to $B_L > 0$ (magnetosheath). Throughout the interval there are noticeable disturbances in the $B_N$ component, each lasting 1 - 2 minutes and separated by about 6 minutes. Four of these signatures can be seen in the magnetosheath, indicated by hatching. Most of the $B_N$ variations are bipolar: a positive followed by a negative excursion, and many are associated with local enhancements of the field strength.

Fig. 2. Distribution of FTE's across the dayside magnetopause. The different symbols denote the two observed senses of $B_N$ variation: the direct sense is (+/-), the reverse sense (-/+). There is a very clear tendency to find direct cases to the north and dawnward, while the reverse cases are found to the south and duskward. This result implies that direct FTE's represent northward going reconnected flux tubes and reverse FTE's southward going flux tubes. Moreover, the distribution of direct and reverse signatures is the same whether the FTE is observed in the magnetosphere or in the magnetosheath. The inset shows an angular histogram of FTE occurrence as a function of IMF orientation. FTE's are observed preferentially when the IMF is southward.

Fig. 3. Much of the observed magnetic field variation associated with an FTE can be qualitatively explained as the disturbance field around an impenetrable obstacle, shown here as a cylinder. *Farrugia et al.* (1987a) compared the expected signatures of grazing impacts with such an obstacle to observed magnetic signatures of FTEs. Shown here is the field disturbance discussed by *Farrugia et al.* The top panel is a view down at the plane of the magnetopause, illustrating how the ambient field drapes about the cylinder traveling in the X direction. The lower panel is an orthogonal view, looking along the cylinder axis and illustrating the perturbations which give rise to the $+/-$ $B_N$ component and the peak in the $B_L$ component.

Fig. 4. Comparison of best-fit model and measured field and convective (E x B) plasma flow perturbations due to the grazing passage of an FTE. The data are from a magnetospheric FTE observed by ISEE 1, cast into boundary normal coordinates. The model magnetic field predicts an enhancement of the $B_L$ component at closest approach, a tripolar $+/-/+$ variation in the $B_M$ component, and the usual $+/-$ bipolar $B_N$ variation. The data generally follow this behavior, but the phases and amplitudes are in slight disagreement. The model convective flow field predicts primarily a $+/-$ $V_N$ signature as expected for a northward moving cylinder, the data do show this. The other flow components show less agreement, however. While the predicted $V_M$ variation is a tripolar $+/-/+$ variation, the observed signature shows largely a $+$ $V_M$ flow increase commencing at about the FTE midpoint. The departures from the incompressible plasma prediction probably reflect both a breakdown in the incompressible assumption and in the geometry of the obstacle, which is not expected to be a cylinder.

Fig. 5. FTE magnetic field variations in the $B_L$ - $B_N$ plane, as observed by ISEE 1 (magnetosheath) and ISEE 2 (magnetosphere) while the two spacecraft were separated by more than 0.5 $R_E$. The vertical trajectories of the spacecraft represent an assumed 150 km/s advection speed from north to south. The separation in $L$ (pointing from ISEE 2 to 1) is 3800 km, and in $N$ it is 3300 km.

Fig. 6. A comparison of the distribution of energetic ion anisotropies parallel (dots) and anti-parallel (open circles) to the local magnetic field, (a) assuming the merging model and (b) based on leakage. In the merging model, the data have been organized by folding the $B_y$ cases about noon, so that the distribution of events corresponds to a duskward and southward IMF. For the leakage model, the positions are just as they were observed. *Sibeck et al.* argued that the observed sense of anisotropy corresponds to escape of magnetospheric particles onto magnetosheath field lines at roughly 1500 LT, where the Parker spiral field lines drape closely about the magnetopause. The anisotropy observations are from *Daly et al.* (1984), the diagram is from *Sibeck et al.* (1987).

Fig. 7. Plasma ion and magnetic field data from AMPTE UKS for magnetopause crossings on September 19, 1984. The velocity and field are in boundary normal coordinates. As can be seen in the $B_L$ component, the crossings occur at 1530:30, 1602:00 and 1611:00 UT, and accelerated flows are observed at these times. Rapid flows are also seen associated with the FTEs at 1604, 1607, 1611 and 1617 UT. The accelerated plasma flows appear to occur in a quasi-periodic manner, every 2 to 3 minutes. Each flow burst is associated with a maximum in the thermal pressure.

Fig. 8. AMPTE UKS observations of an FTE on October 28, 1984 (adapted from *Rijnbeek et al.* 1987). Top panels show the ion bulk flow, temperature, and density measurements. Middle panels show electron intensities at 12.5 and 180 eV, respectively, characteristic of magnetosheath, transition and magnetospheric populations, respectively. The bottom panels show the magnetic field in boundary normal coordinates. Region 1 corresponds to the draping of magnetosheath field lines about the FTE proper, while Region 2 marks the transition from magnetosphere to magnetosheath-like plasma, with the dramatic peak in the 12.5 eV intensity in Region 2. Finally, Region 3 is characterized by magnetosheath-like plasma and a mixed magnetospheric-magnetosheath field orientation. [illegible] Parker spiral [illegible] Sibeck [illegible] in the magnetosphere [illegible] northward IMF [illegible] and pressure [illegible]

Fig. 9. Comparison of the total overpressure in FTEs versus the inferred magnetic tension due to the presence of an azimuthal field component, represented by the observed $B_N$ signature. These results, from *Paschmann et al.* [1982], suggested that FTEs have a pinch like structure reminiscent of a magnetic flux rope.

Fig. 10. FTE durations versus inter-FTE time. FTE duration is defined as the time between the extrema of the bipolar $B_N$ signature; inter-FTE time is simply the time elapsed since the last FTE. If duration is an indication of FTE size, hence energy content, and inter-FTE time is an indicator of magnetopause free energy accumulation time, then longer accumulation times lead to larger FTEs. Most of the AMPTE FTEs, sampled at lower latitudes, are smaller than those at ISEE.

Fig. 11. Another FTE "size" measure versus inter-FTE time. The product of duration and $\Delta B_{N/}$ [illegible] is a measure of FTE size normal to the magnetopause surface. Once again, larger FTEs appear to be associated with longer inter-FTE times.

Fig. 12. Schematic diagram of an early interpretation of FTE structure. A bundle of flux tubes is shown having reconnected between the magnetosheath (foreground) and the magnetosphere (background). This isolated reconnected flux tube is shown accelerating upward and to the left, as shown by the arrow. It is disturbing the surrounding environment, as can be seen in the magnetosheath field lines draped over the flux tube. There is also a field-aligned current flowing in the flux tube, shown by the smaller arrow. This current produces the twisted field structure inferred from magnetic field and plasma measurements. Not shown here is the downward-going counterpart FTE below and to the right of the diagram. From *Paschmann et al.* [1982].

Fig. 13. Snapshot of magnetic field lines and plasma flow vectors from one time step of a two-dimensional MHD simulation of transient reconnection by *Scholer et al.* [1988]. The configuration began as a stable neutral sheet. Finite and spatially-limited resistivity was then imposed near the origin. Near the reconnection site the field and plasma have established the inflow and outflow characteristics of steady Petschek reconnection, while far from the reconnection site (beyond Z = 140) the initial equilibrium current sheet is undisturbed. In the intermediate region the field and plasma undergo a transition from static equilibrium to a standing expansion fan geometry. The transition field is bubble like, and contains the accelerated plasma.

Fig. 14. *Lee and Fu's* [1985] picture of multiple x-line reconnection at the magnetopause when there is a finite field component along the x-lines. As the tearing mode develops the tearing islands contain an axial field component, and the overall structure of the islands is that of a magnetic flux rope. Eventually the islands develop nonlinearly and are convected away, then the process repeats. Poleward of the islands the signature of quasi-steady reconnection would be observed.

Fig. 15. *Kan's* [1988] synthesis of single and multiple x-line formation. X-lines (bold lines without arrows) are limited in longitude and turn on intermittently. Along any meridional cut (lines a, b, and b-) there is at most one x-line. Lines with arrow heads are current flow lines.

Fig. [illegible]. Schematic diagram of the magnetopause response to an isolated solar wind pressure pulse. The local magnetosheath pressure maximum forces a localized inward displacement of the magnetopause. A fast mode wave can travel more rapidly in the magnetosphere and so runs ahead of the magnetosheath pressure pulse. However the higher pressure in the fast mode wave pushes the magnetopause outward. In this way a single pressure pulse can produce an outward deflection on the magnetosheath side and an inward deflection on the magnetospheric side. From [illegible] [1989].

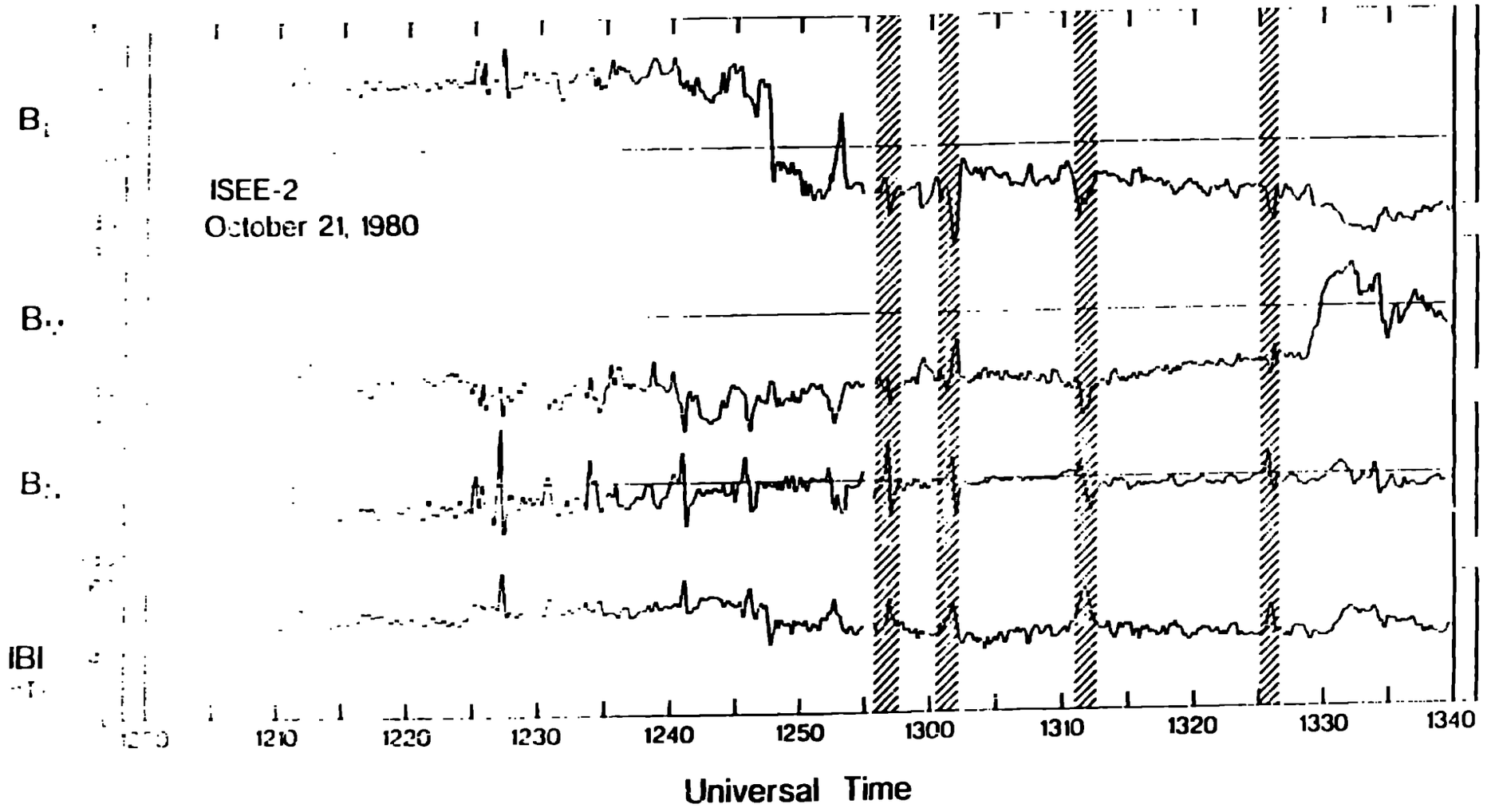

ISEE-2
October 21, 1980
1210
1220
1230
1240
1250
1300
1310
1320
1330
1340
Universal Time

Fig. 1

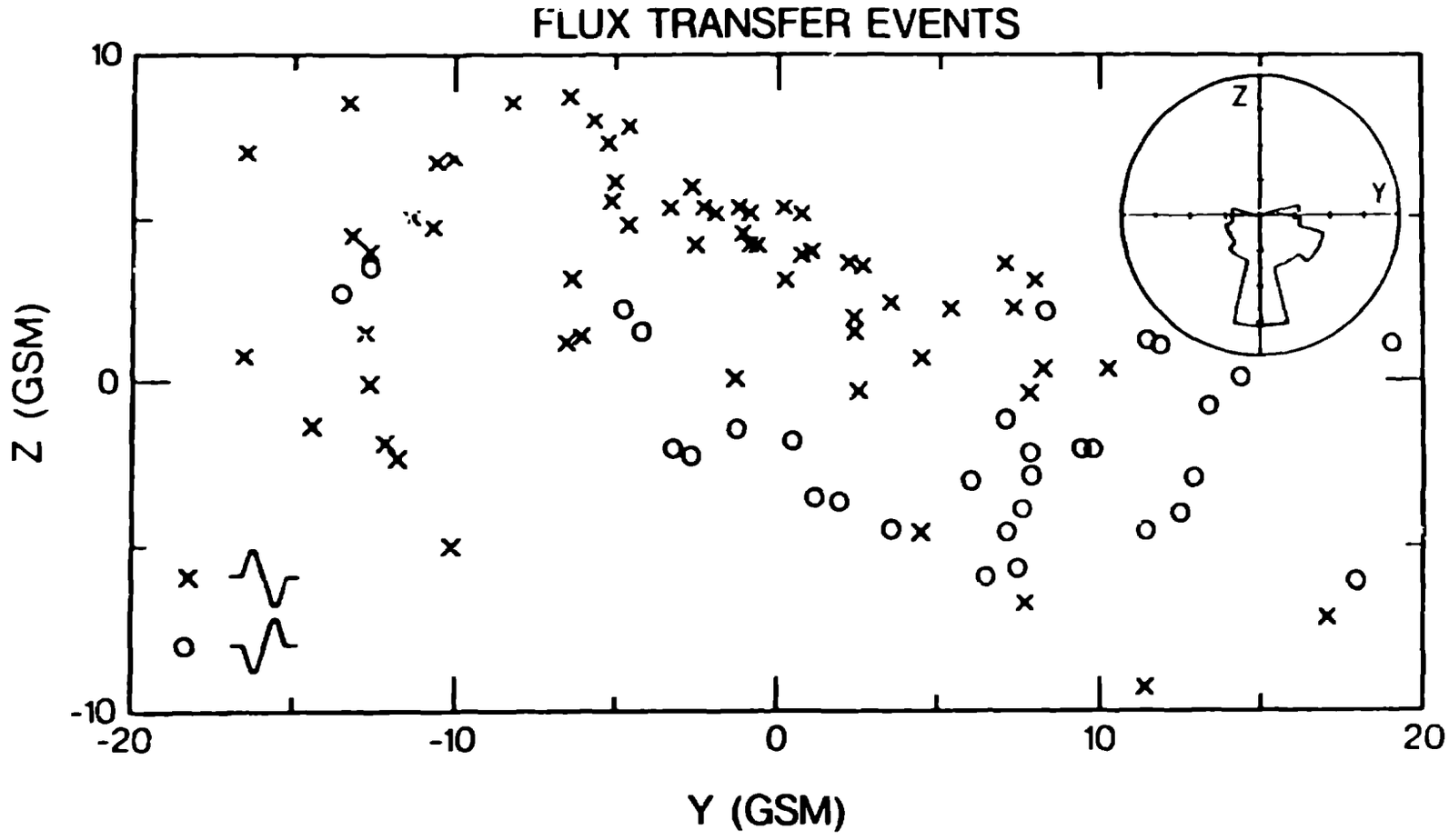
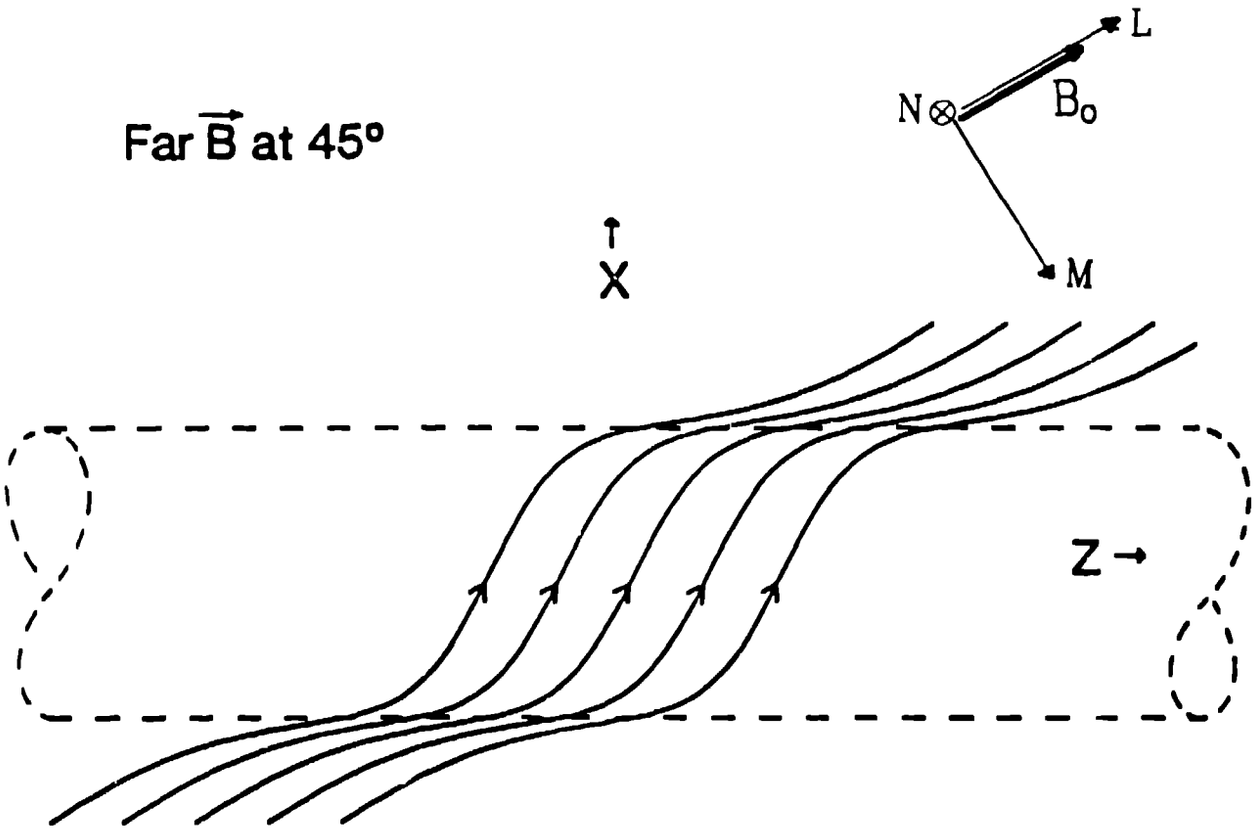



Fig. 2



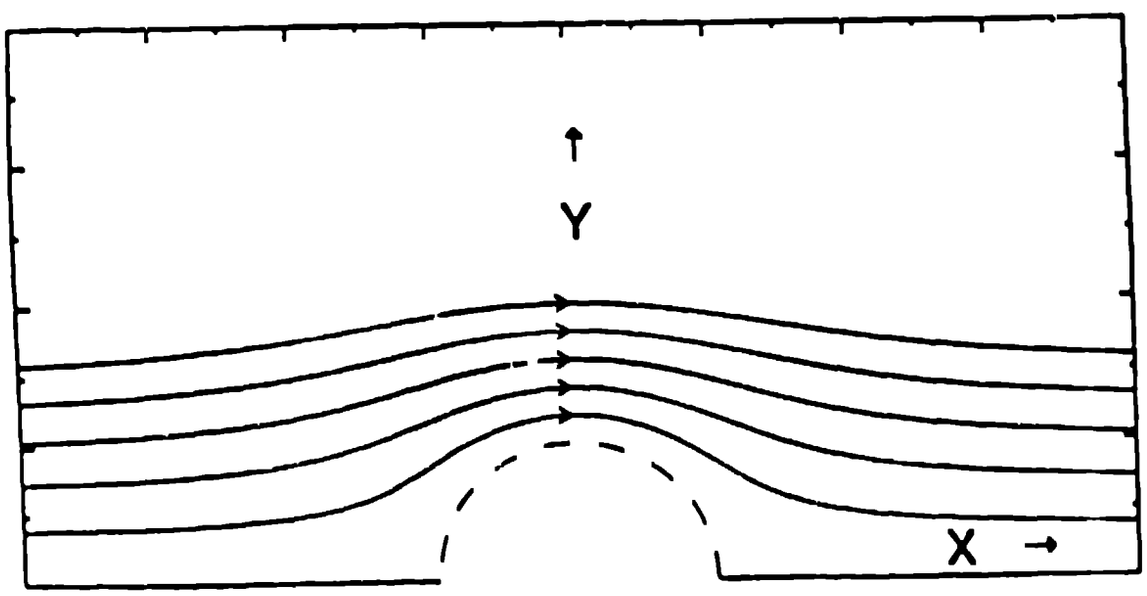




Fig. 3

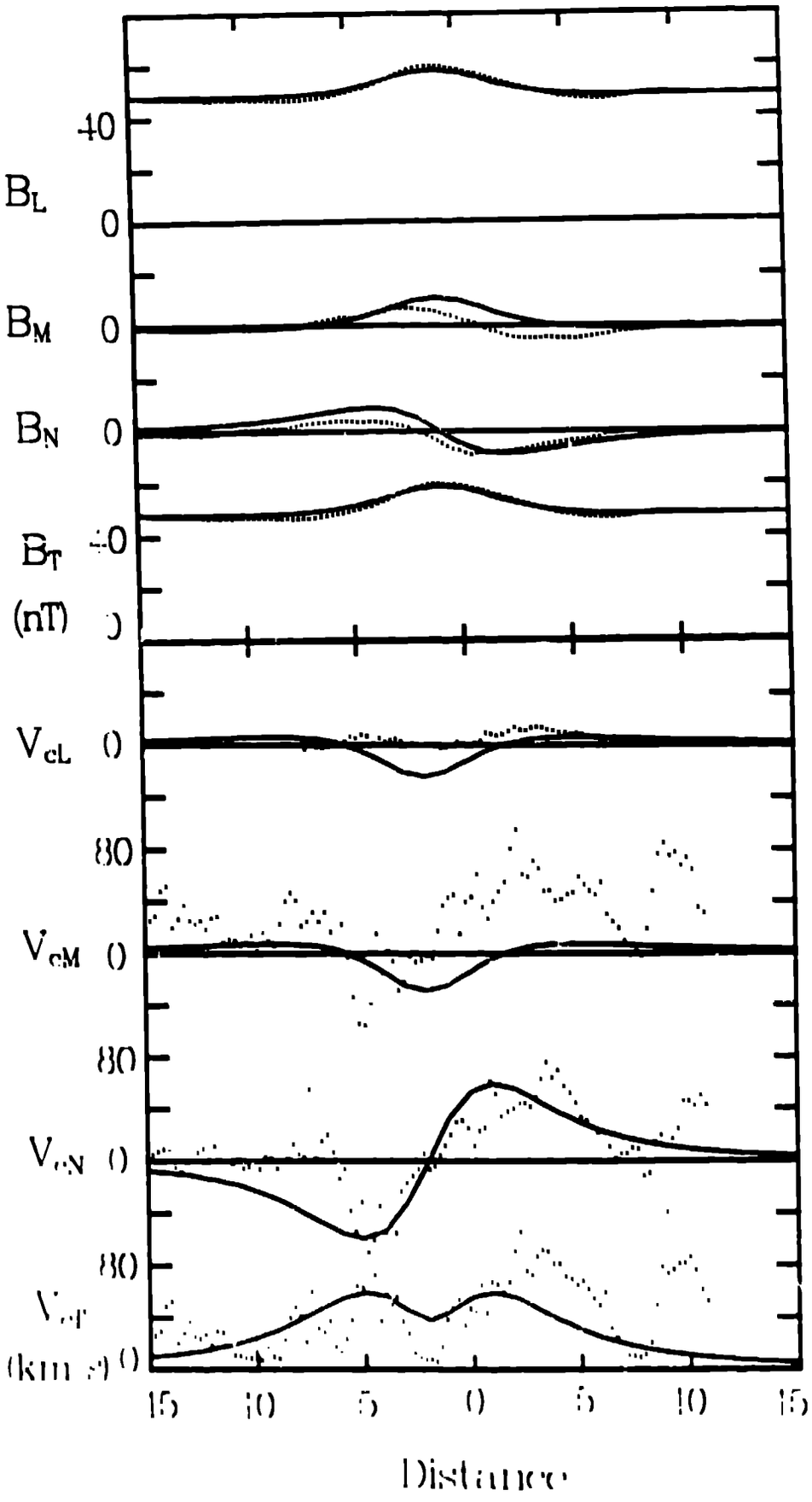

40
$B_L$
0
$B_M$
0
$B_N$
0
$B_T$
40
(nT)
0
$V_{cL}$
0
80
$V_{cM}$
0
80
$V_{cN}$
0
80
$V_{cT}$
(km/s)
0
15
10
5
0
5
10
15
Distance

Fig. 1

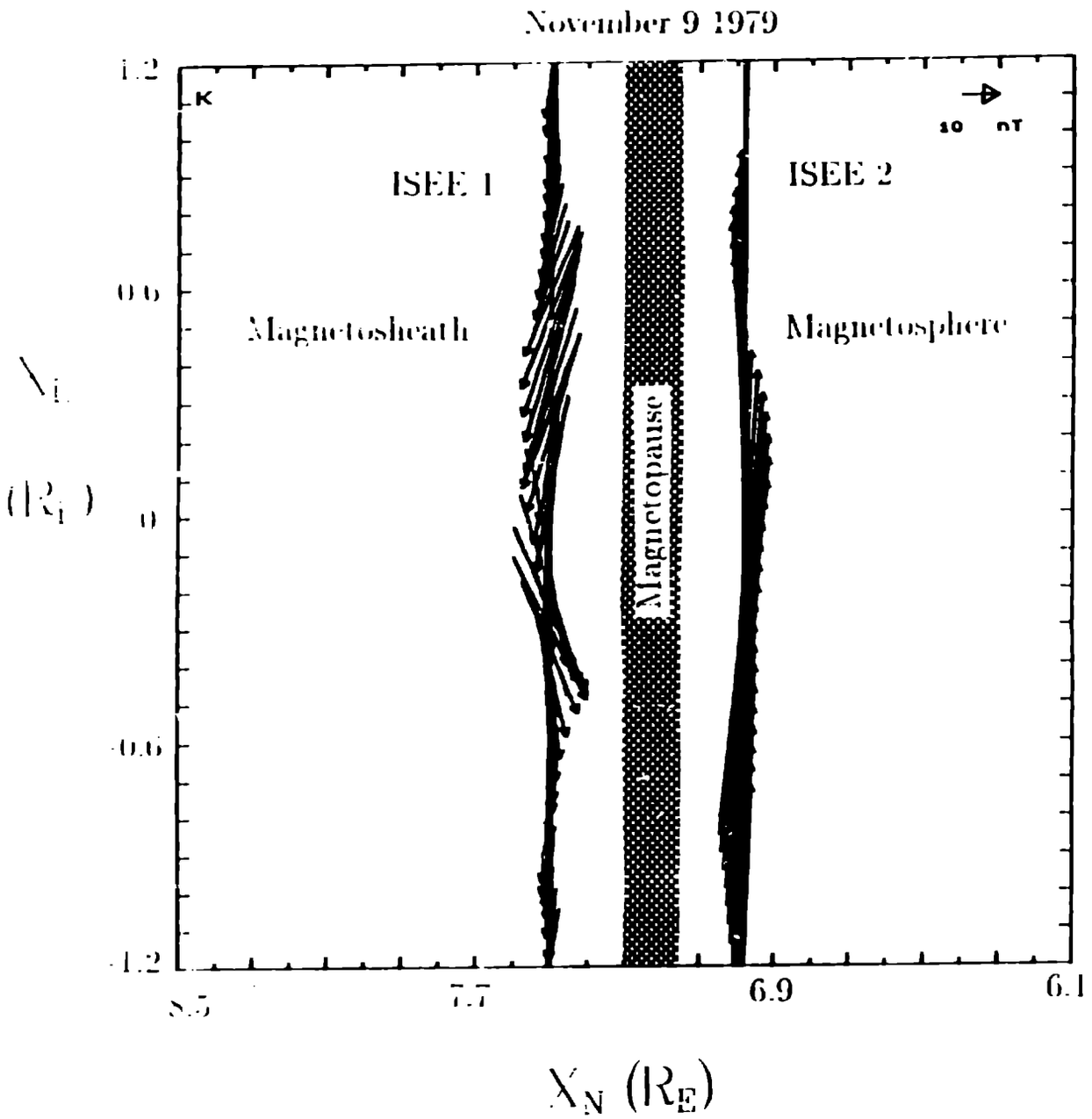

November 9 1979
1.2
0.6
0
-0.6
-1.2
K
10 nT
ISEE 1
ISEE 2
Magnetosheath
Magnetopause
Magnetosphere
$Y_N$ ($R_E$)
8.5
7.7
6.9
6.1
$X_N$ ($R_E$)

Fig. 5

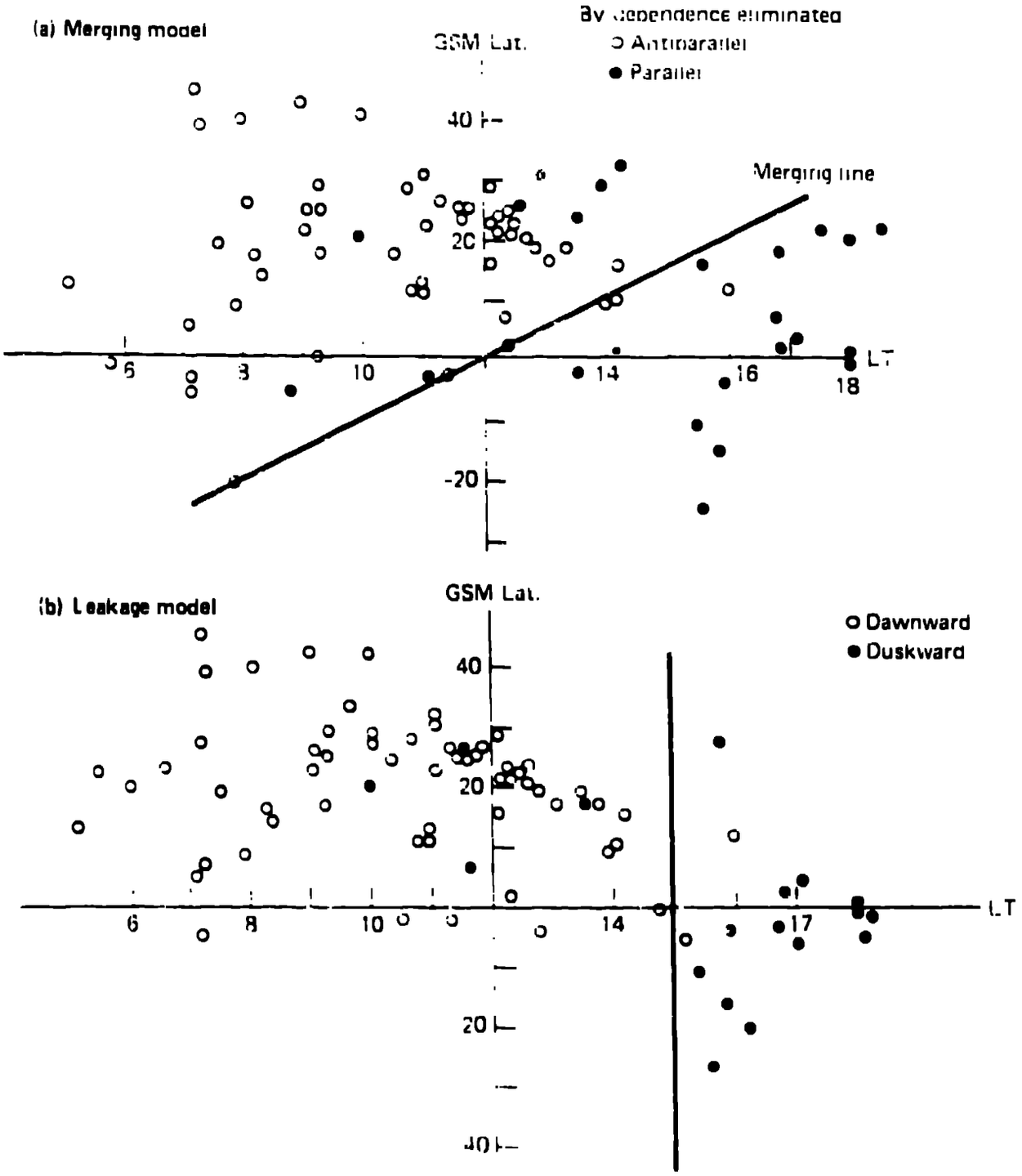

(a) Merging model
By dependence eliminated
GSM Lat.
Antiparallel
Parallel
40
20
-20
Merging line
6
8
10
14
16
18
LT
(b) Leakage model
GSM Lat.
Dawnward
Duskward
40
20
20
40
6
8
10
14
17
LT

Fig. 6

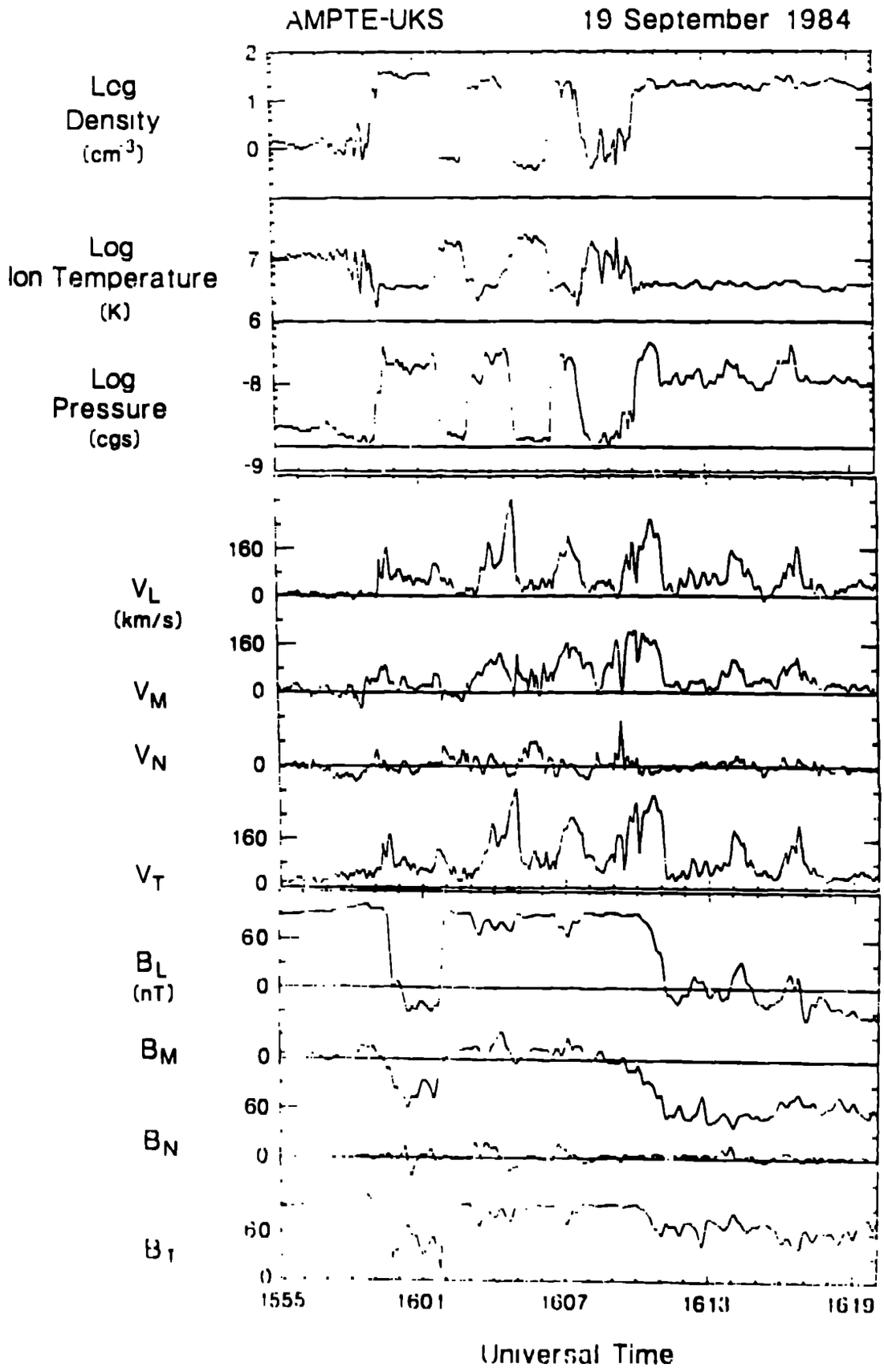
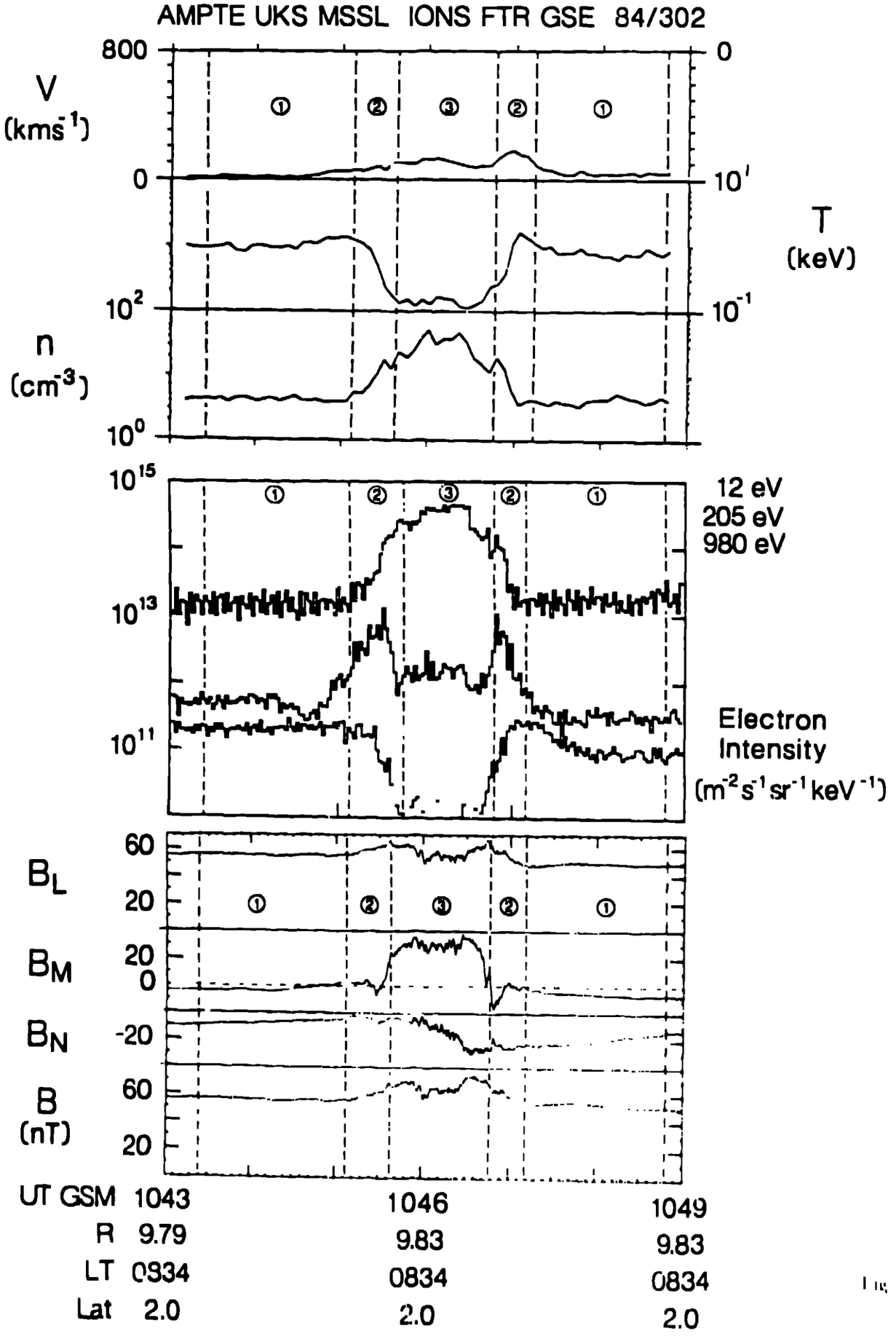

AMPTE-UKS
19 September 1984
Log Density (cm⁻³)
2
1
0
Log Ion Temperature (K)
7
6
Log Pressure (cgs)
-8
-9
V_L (km/s)
160
0
V_M
160
0
V_N
0
V_T
160
0
B_L (nT)
60
0
B_M
0
B_N
60
0
B_T
60
0
1555
1601
1607
1613
1619
Universal Time

Fig. 7


AMPTE UKS MSSL IONS FTR GSE 84/302
V
(kms$^{-1}$)
800
0
T
(keV)
$10^{1}$
$10^{-1}$
n
(cm$^{-3}$)
$10^{2}$
$10^{0}$
$10^{15}$
$10^{13}$
$10^{11}$
12 eV
205 eV
980 eV
Electron
Intensity
(m$^{-2}$s$^{-1}$sr$^{-1}$keV$^{-1}$)
$B_L$
60
20
$B_M$
20
0
$B_N$
-20
B
(nT)
60
20
UT GSM 1043 1046 1049
R 9.79 9.83 9.83
LT 0834 0834 0834
Lat 2.0 2.0 2.0

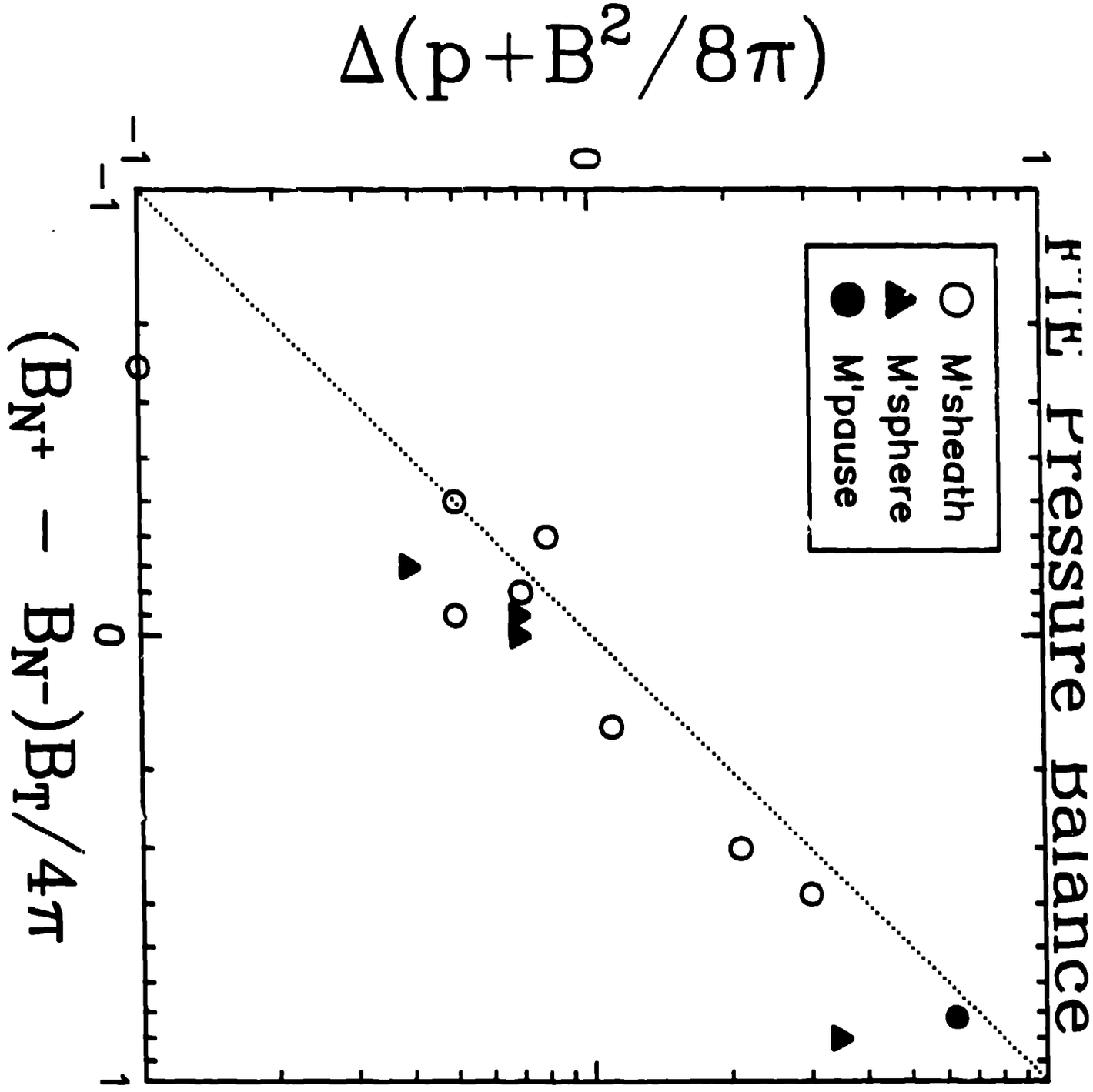



Fig. 9

Paschmann et al. [1982]

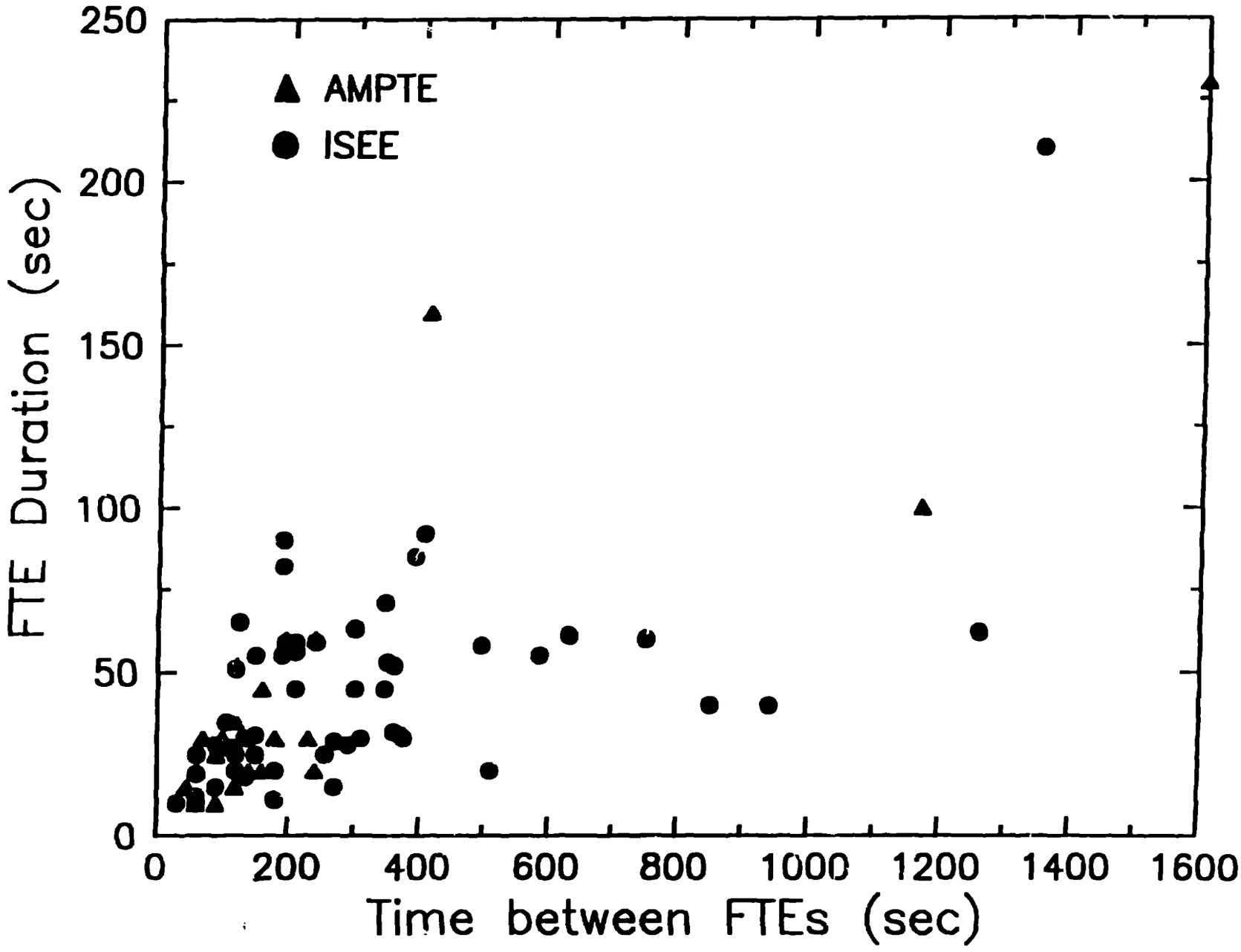

AMPTE
ISEE
FTE Duration (sec)
Time between FTEs (sec)
0
50
100
150
200
250
0
200
400
600
800
1000
1200
1400
1600

Fig. 10.

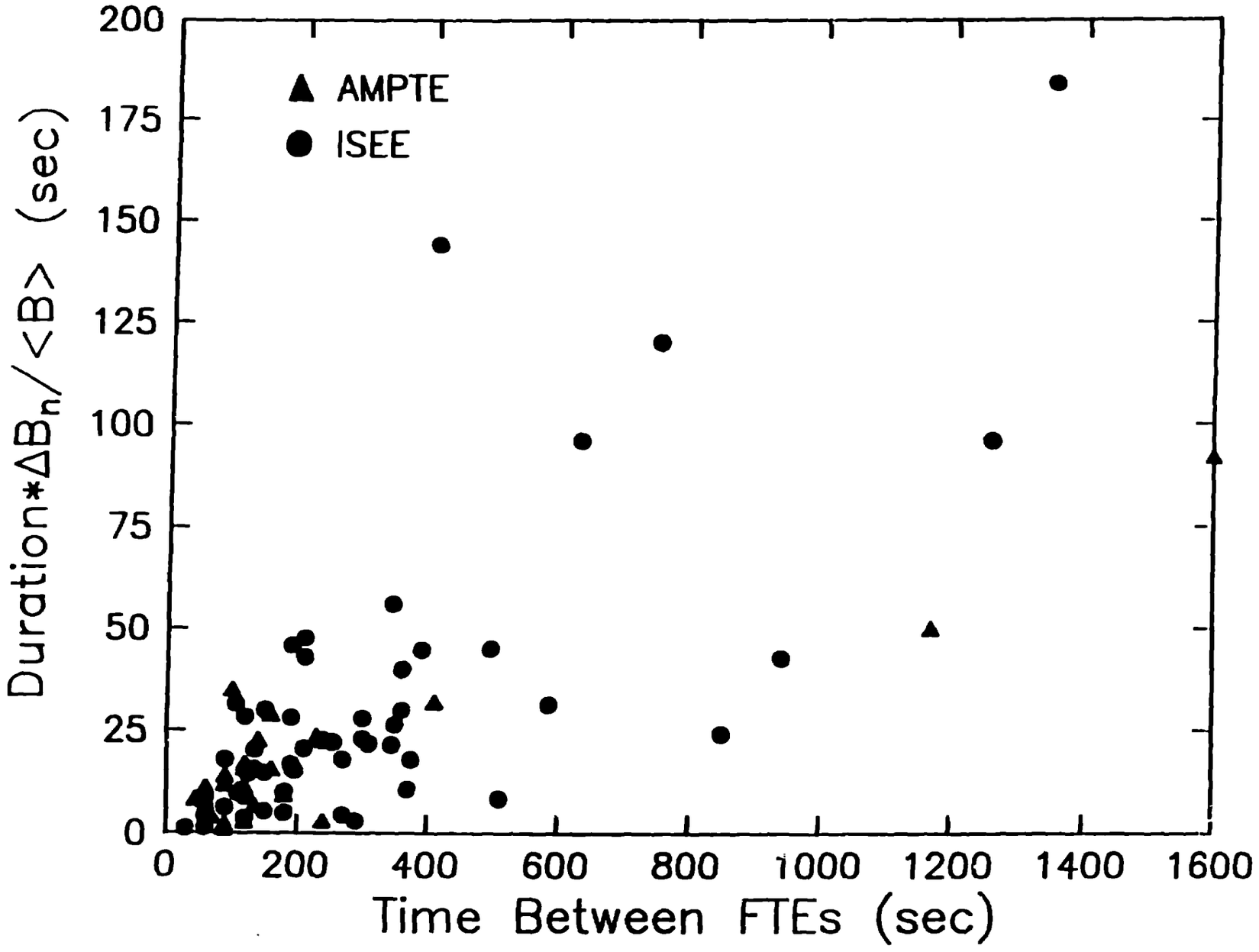

AMPTE
ISEE
Duration*ΔB_n/<B> (sec)
Time Between FTEs (sec)
0
25
50
75
100
125
150
175
200
0
200
400
600
800
1000
1200
1400
1600

Fig. 11.

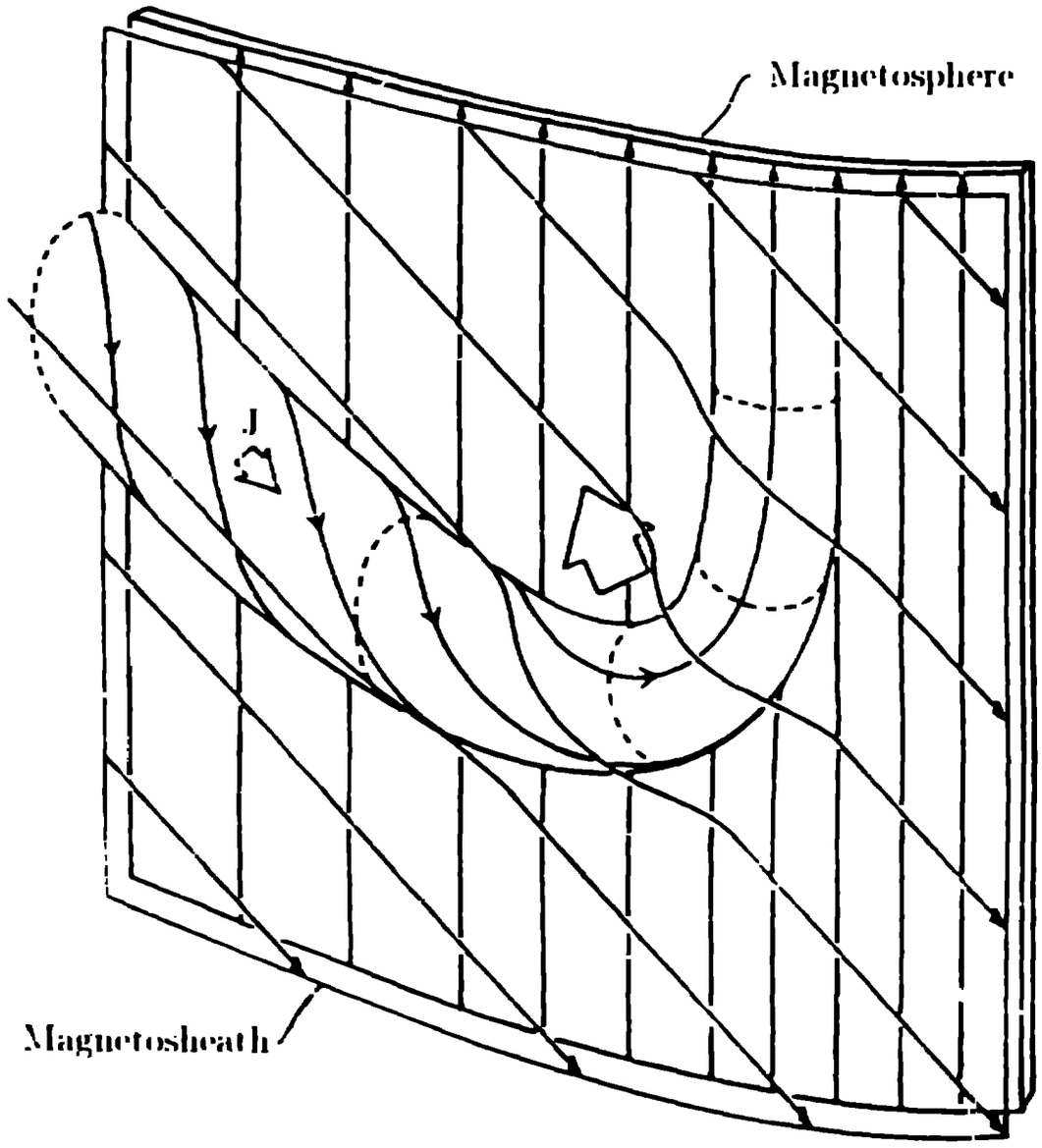



Fig. 12

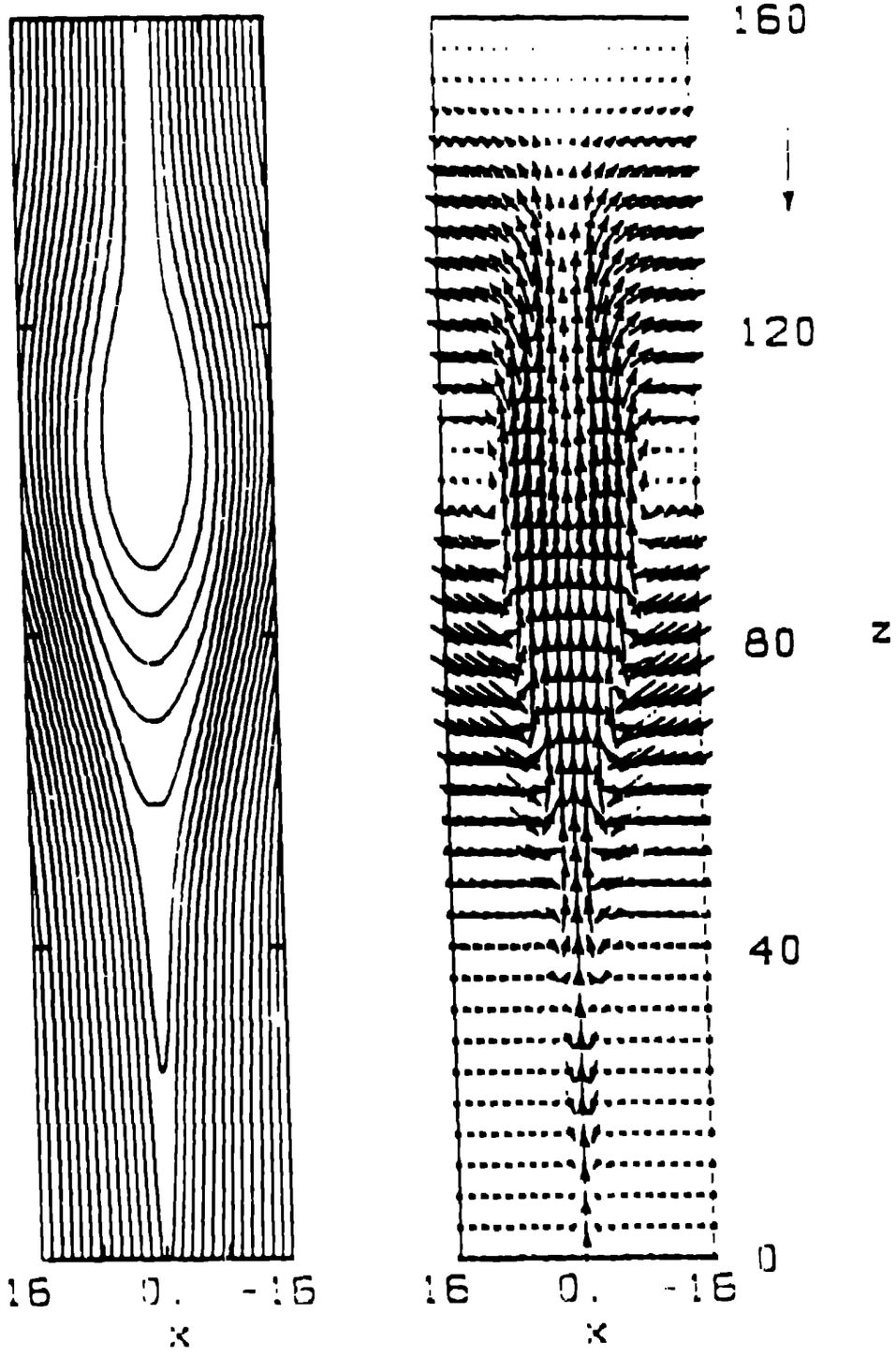



Fig. 13

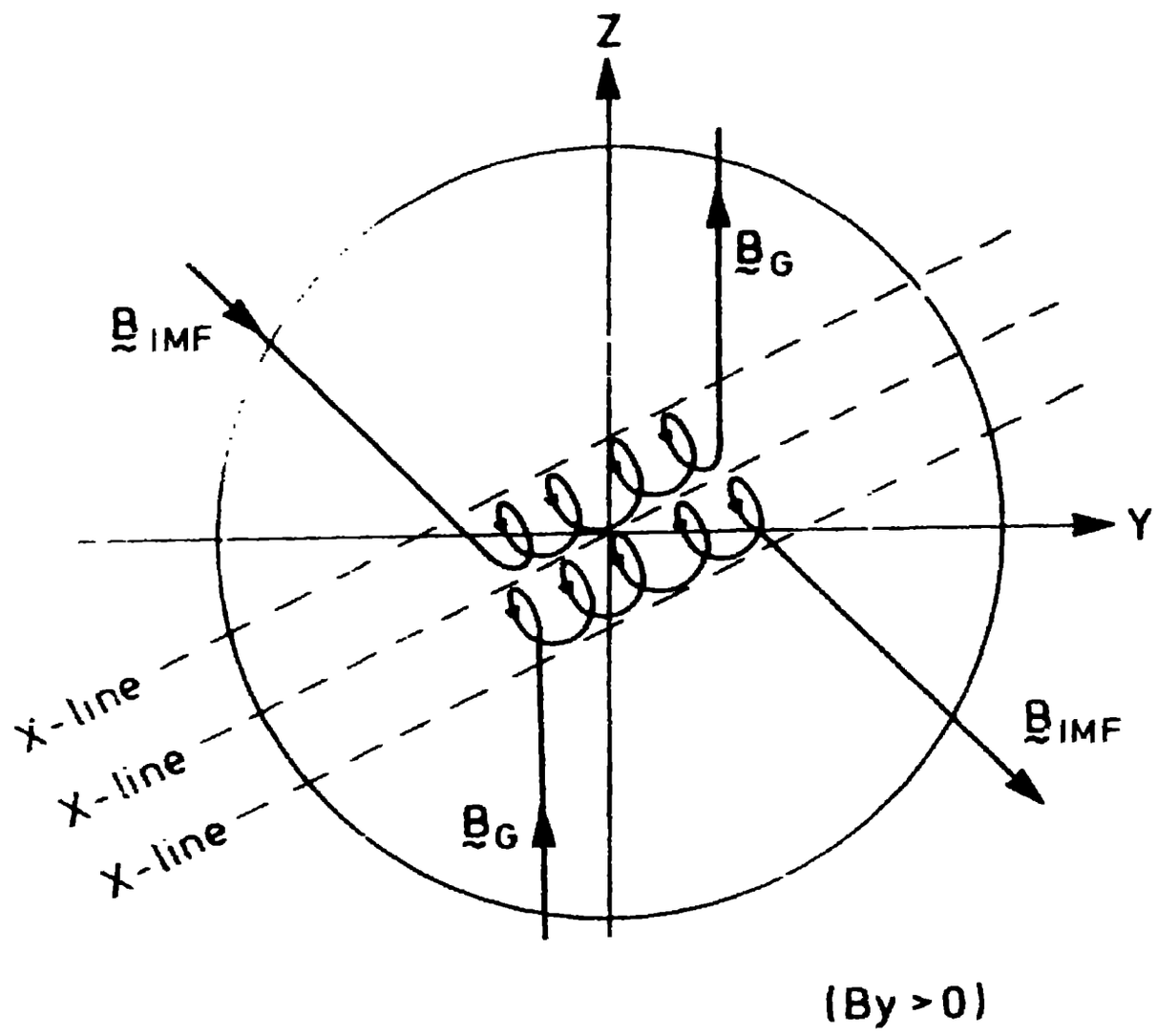

Z
Y
$\underset{\sim}{B}_G$
$\underset{\sim}{B}_{IMF}$
$\underset{\sim}{B}_{IMF}$
$\underset{\sim}{B}_G$
X-line
X-line
X-line
(By > 0)

Fig 11

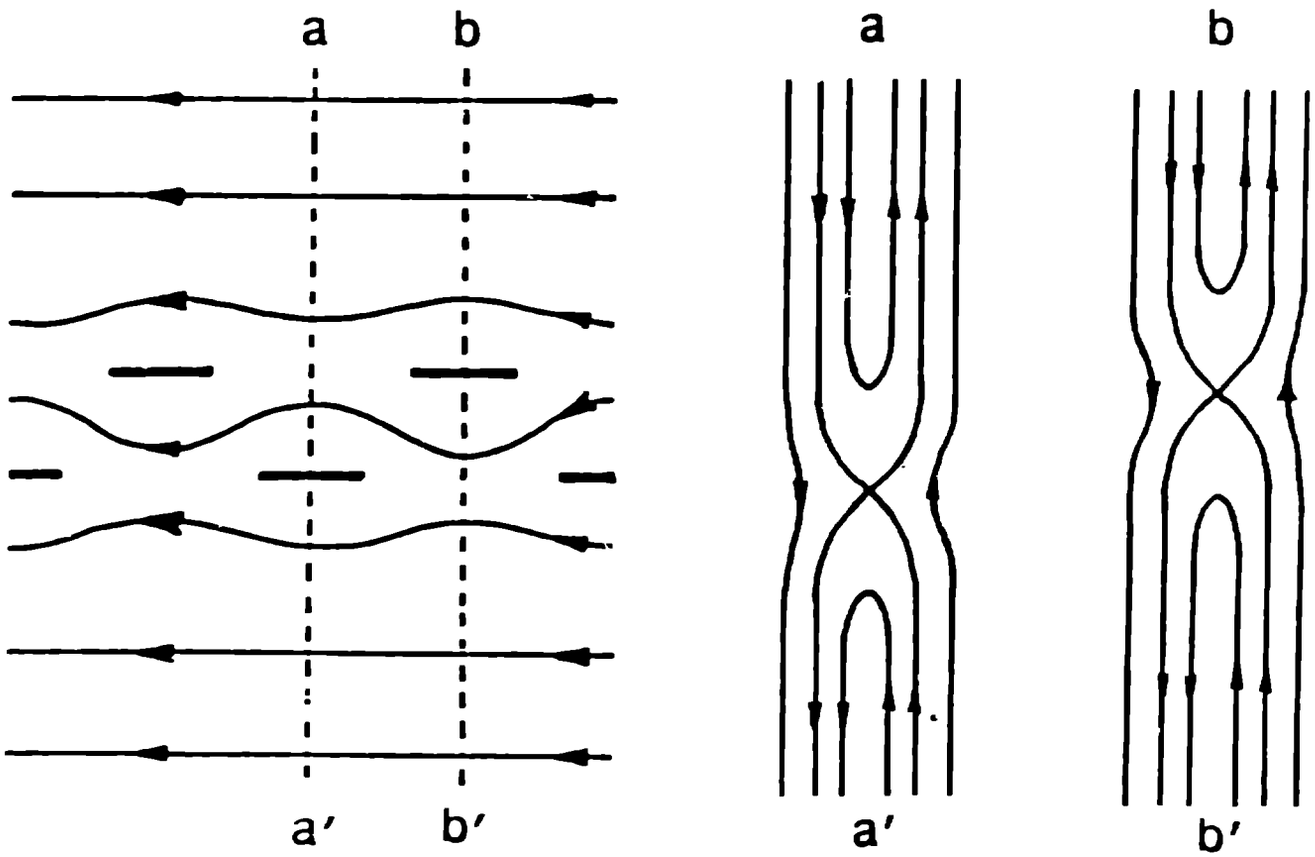



Fig. 15.

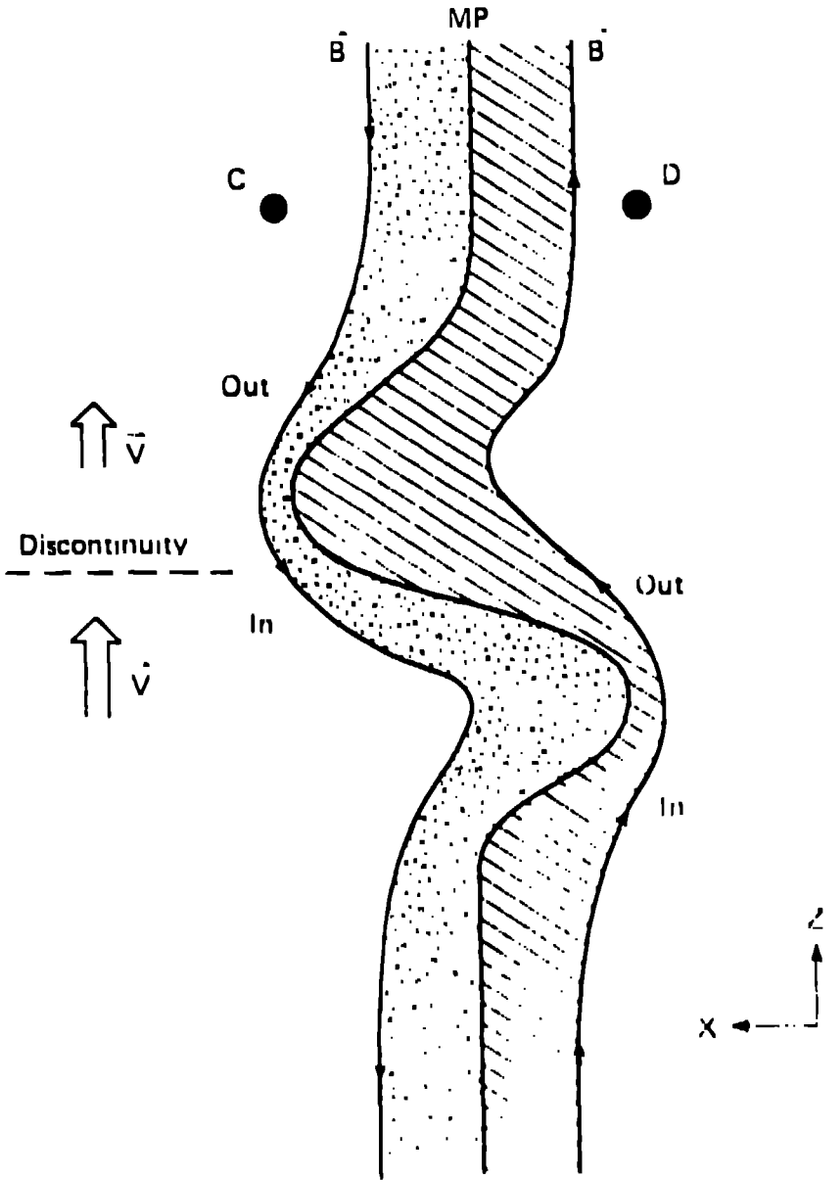



Fig. 16