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# THE OCCURRENCE RATE OF FLUX TRANSFER EVENTS

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## ABSTRACT

When the interplanetary magnetic field is southward the component of the magnetic field normal to the magnetopause undergoes a characteristic bipolar oscillation that has been interpreted in terms of spatially and temporally limited reconnection and the subsequent transfer of magnetic flux to the magnetotail. These events have been called flux transfer events or FTEs. They can be detected over about 50% of the magnetopause when the IMF is southward. Bipolar signatures (normal FTEs) that are first outward and then inward are observed to move northward. Bipolar signatures (reverse FTEs) that are first inward and then outward are observed to move southward. Normal FTEs are predominantly, but not exclusively, found north of the magnetic equator; reverse FTEs south of the equator. These disturbances occur both in the magnetosphere and the magnetosheath and can only be interpreted as a "cylindrical" bulge at the current layer that pushes magnetosheath field lines outward and magnetospheric field lines inward. A surface wave model does not reproduce the observed behavior of FTE magnetic and electric fields. FTEs move at close to the solar wind velocity and are about 1 $R_E$ across, thus lasting about 30s. They are separated typically by close to 8 minutes. This separation seems to be nearly independent of solar wind conditions. In particular FTEs are not individually triggered by directional fluctuations in the IMF. A slight decrease in FTE occurrence occurs as the magnetosonic Mach number of the solar wind increases.

## INTRODUCTION

Whereas the size of the magnetosphere is determined principally by the pressure exerted on the magnetosphere by the solar wind, the transfer of energy and momentum is controlled principally by the interplanetary magnetic field (IMF) through the mechanism known as reconnection /1/. Even though the control of geomagnetic activity by the interplanetary magnetic field was known from the earliest days of space exploration /2,3/, and even though the observed dynamics of the magnetosphere could be explained in terms of reconnection at the magnetopause and in the magnetotail /4/, it was not until 1979 that observations of accelerated flow at the magnetopause /5/ led to the general acceptance of this mechanism.

Although reconnection had been initially discussed in terms of the effect of a due southward interplanetary magnetic field and its effects on the magnetosphere in the steady state, it soon became obvious that reconnection occurred for range of southward directions /3/, causing observable asymmetries in magnetospheric processes /6/, and that variations in the reconnection rate had important consequences for geomagnetic activity /4/. On time scales of tens of minute, the magnetosphere seems to be very responsive to variations in the IMF, but on time scales of minutes the reconnection process can be quite unsteady even under steady IMF conditions. This behavior was first discovered at high latitudes /7/ with the HEOS2 spacecraft and at low latitudes /8/ with the ISEE 1 and 2 spacecraft /8/ in 1979. These transient, spatially limited reconnection events became known as flux transfer events (FTEs).

Figure 1 shows the vector magnetic field during a particularly clear example of an FTE /8/. Here the data have been displayed in boundary normal coordinates with the $B_N$ component along the outward directed normal, the $B_L$ component in the direction roughly along the magnetospheric magnetic field and the $B_M$ component perpendicular to $B_N$ and $B_L$ roughly opposite the Earth's rotation. The defining field variation is that of the normal component $B_N$ which moves outward (positive) and then inward (negative) both inside and outside the magnetosphere. This observation alone rules out a surface wave origin of the FTE unless one assumed that the direction of the surface wave motion reversed when the spacecraft crossed the magnetopause at this and every other crossing of the magnetopause. The perturbation of the

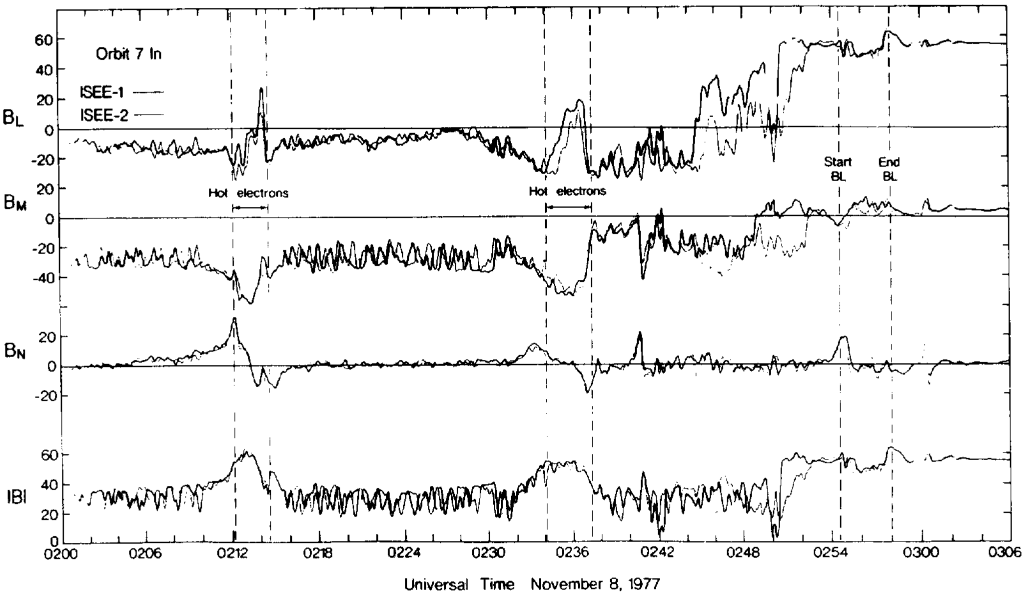

Fig. 1 The magnetic field observed by ISEE (thick line and ISEE 2 (thin line) as the two spacecraft cross the magnetopause inbound on November 8, 1977. The magnetic field measurements are expressed in boundary normal coordinates with $B_N$ outward along the boundary normal, $B_L$ along the projection of the field in the magnetosphere and $B_M$ completing a righthanded set. Twelve second averages every 4 seconds are displayed /8/.

boundary must be a bulge that pushes both inward and outward as it moves along the magnetopause. These data illustrate several properties of FTEs that are seen repeatedly. First the magnetic field strength inside an FTE is stronger than that outside the FTE especially in the magnetosheath. Secondly the magnetic field in the $B_M$ component is amplified in FTEs (in the magnetosheath) whereas the $B_M$ component tends to zero (by definition) in the magnetosphere. The field variation in the $B_L$ component in the magnetosheath resembles that crossing the magnetopause but in the magnetosphere there is little $B_L$ variation. Another important feature is that the $B_N$ component is almost identical at the two spacecraft whereas the $B_L$ component has a nested signature. This observation indicates a structure with a significant extent of the radial magnetic field but a significant shear in the field perpendicular to the normal direction over the separation of the spacecraft, roughly 400 km along the normal.

A model that reproduces qualitatively the behavior of the normal component on the two sides of the boundary and has significant shear in the field component along the magnetopause is shown in Figure 2, which illustrates a connected bent magnetic flux tube moving across the surface of the magnetopause pushing magnetospheric lines inward and magnetosheath field lines outward. Variants of this picture have been presented by several authors. Some have postulated that flux transfer events are indeed transient events but that they arise along an extended distance along the "magnetic equator" /9/. Others have postulated that the reconnection occurs due to multiple x-line formation on the magnetopause /10/. We believe that the reason these authors have developed these alternative models is that they have been guided by two-dimensional thinking associated with their two dimensional models. In the three dimensional magnetosheath, time and space are inextricably linked by the streamlines of the magnetosheath flow. If a phenomenon is temporally limited it becomes spatially limited and vice versa.

The right hand panel in Figure 2 suggests that the distortion in the magnetospheric magnetic field is less than that in the magnetosheath. Since we observe FTE events inside the magnetosphere whenever they occur outside, we can measure the relative sizes of FTEs by examining the occurrence rates of FTEs of different sizes both inside and outside the magnetopause. Figure 3 shows these two rates as a function of the size of the perturbation in the normal component /11/. The curves are very similar in shape and would overlie each other if the magnetospheric FTEs were only 30% larger. Thus the sketch in Figure

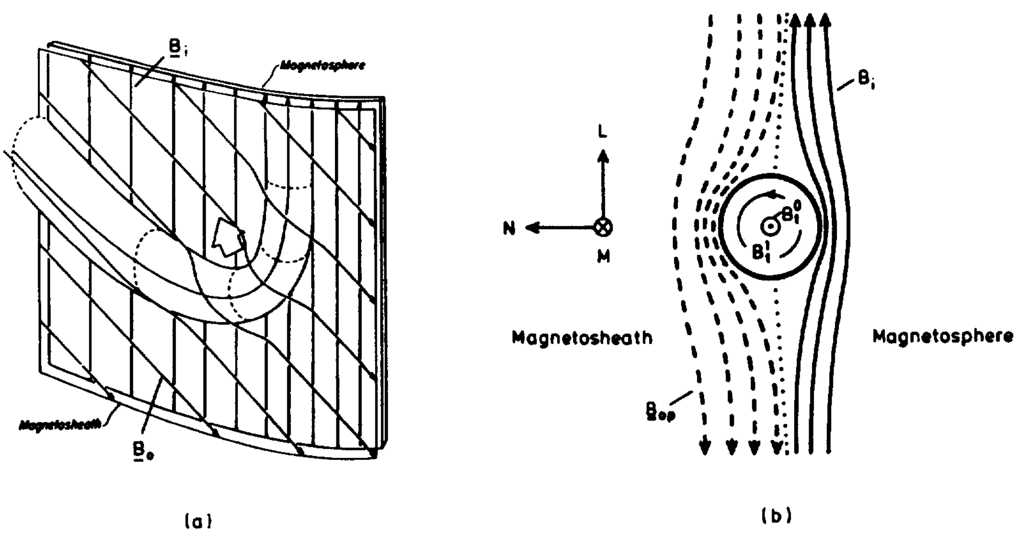

Fig. 2 Schematic diagram of the structure of an FTE. On the left a bundle of flux tubes is shown having become connected between the magnetosheath (foreground) and magnetosphere (background). On the right the bulge in the magnetosheath and magnetospheric fields is illustrated.

2 is qualitatively correct but exaggerates the difference between magnetosphere and magnetosheath perturbations.

The purpose of this review is to examine the occurrence of FTEs at the Earth's magnetopause. Three aspects of occurrence will interest us: where the FTEs are found on the magnetopause; their repetition rate when they are present; and what factors affect their appearance rate. We review each of these in turn.

## SPATIAL DISTRIBUTION

FTEs are found with two different polarities: a normal component that is outward and then inward called normal or standard FTEs and a normal component that is inward and then outward called reverse FTEs. The former are interpreted as bulges moving northward on the magnetopause and the latter as

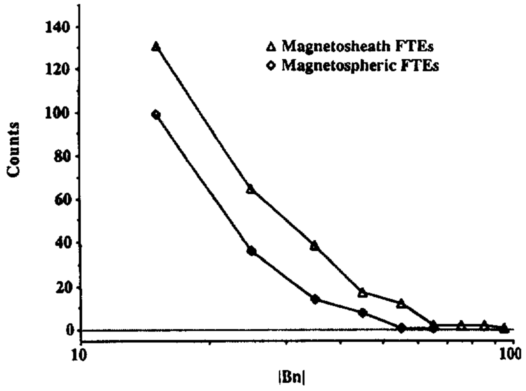

Fig. 3 Number of magnetospheric and magnetosheath FTEs observed by the ISEE 1 and 2 spacecraft as a function of the size of the variation in the normal component of the magnetic field /11/.

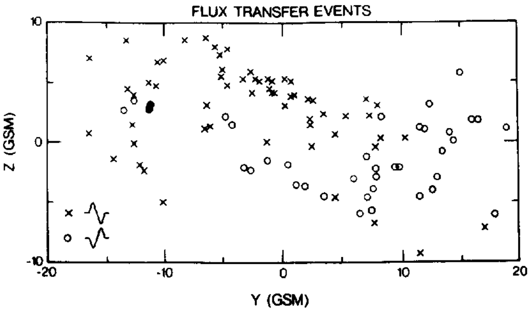

Fig. 4 The location of flux transfer events seen by ISEE 1 and 2 projected on the Y-Z GSM plane. Crosses and circles denote the two types of FTEs, standard and reverse /12/.

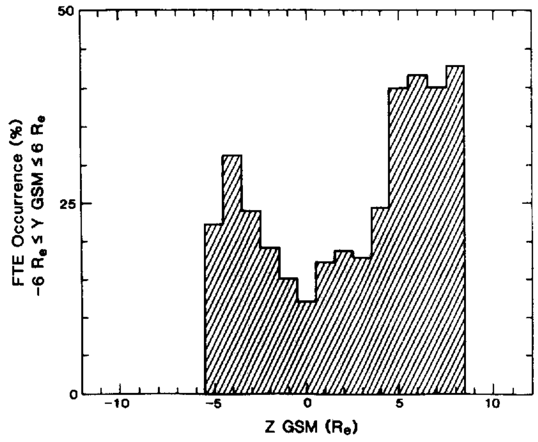

Fig. 5 Occurrence rate of FTEs as a function of Z GSM position on the magnetopause /12/.

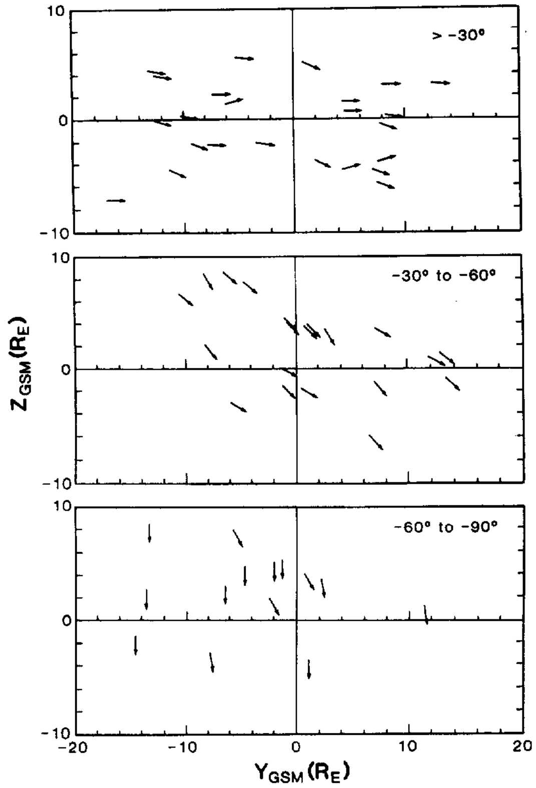

Fig. 6 Location of FTEs for varying orientation of the IMF. The projection of the IMF on the YZ GSM plane is shown /14/.

bulges moving southward. Figure 4 shows the distribution of standard and reverse FTEs on the magnetopause /12/. This diagram shows that standard FTEs are principally but not exclusively a northern hemisphere phenomenon and that reverse FTEs are principally but not exclusively a southern hemisphere phenomenon. If our interpretation of moving bulges is correct then this asymmetry indicates that most, but not all, of the FTEs arise in the equatorial regions and move away from the equator. Similar distributions have been obtained by other researchers /13/. The notion of an equatorial source is reinforced by the occurrence rate as a function of latitude shown in Figure 5 /12/. The rate is a minimum at the equator and increases to the north and the south.

The distribution of FTEs across the magnetopause is also influenced by the direction of the IMF. Figure 6 shows the location of FTE observations and the direction of the IMF projected on the magnetospheric Y-Z plane in each of 3 angular ranges. When the IMF is horizontal FTEs are seen almost everywhere across the magnetopause. When the IMF is inclined at roughly 45° to the GSM equator (and southward) the FTEs are found in a band crossing the subsolar point. When the IMF is almost due southward but directed slightly toward dusk FTEs occur principally on the morning side /14/.

A most important observation because it confirms our primary assumption of FTEs is shown in Figure 7/15/. This diagram shows the flow directions of FTEs as derived from the electric field measurements of the UCB instrument on the ISEE-1 spacecraft. The FTEs move northward for standard FTEs and southward for reverse FTEs.

In summary, FTEs occur everywhere across the dayside magnetopause, in a pattern that is controlled by the direction of the IMF. FTEs have two polarities: out/in and in/out which indicate the direction of motion of the FTE. The normal components that point out and then in correspond to FTEs moving northward and those that point in and then out correspond to FTEs moving southward. Principally FTEs move away from the equator but some FTEs appear to be moving toward the equator.

## FTE SPACING

As evident from Figure 1, FTEs occur with a nearly periodic rate but not precisely periodic. The average or median spacing is about 8 minutes /13/. The distribution of FTE spacings is shown in Figure 8/11/. This figure illustrates that the spacing of FTEs covers a very wide range. It is not evident what controls that spacing. We have looked at solar wind dynamic pressure and Mach number and found no correlation with the FTE spacing. R. C. Elphic /16/ found weak correlations between FTE duration and FTE spacing and FTE "size" and FTE spacing but there was much scatter. These correlations suggest that the FTE is growing between FTE observations.

A very different model for FTE spacing is that FTEs are directly driven by variations in the direction of the IMF /17/. This model was inspired by the similarity in the distribution of the spacing of IMF directional changes and the spacing of FTEs. However, the IMF is usually steady in the minutes prior to the occurrence of an FTE /18/. Figure 9 shows a sample of FTE occurrences during a period of steady southward IMF. Neither the magnetospheric FTE or the three magnetosheath FTEs appear to be driven by IMF changes. We note that the particularly large FTE occurring at 0433, large as measured by the variation in the normal component and in duration, occurred after a pause in FTE occurrence. A small FTE may have occurred at the magnetopause crossing but it is difficult to identify FTEs as the field direction undergoes a major change.

In summary, FTEs occur in an irregular but quasi-periodic sequence with a typical spacing of 8 minutes. This sequence does not appear to be due to external forcing but rather due to processes acting at the magnetopause.

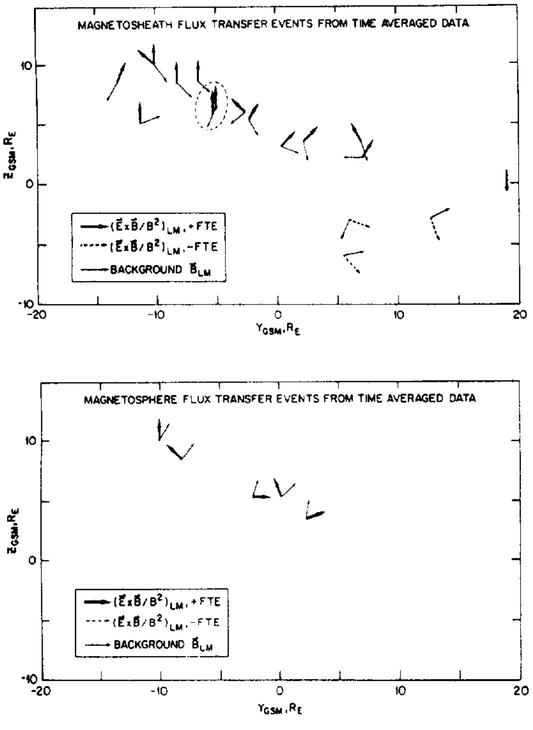

Fig. 7 Velocity of FTEs from electric field measurements. Dashed lines show the velocity of reverse FTEs; heavy lines show the velocity of standard FTEs and light solid lines show the direction of the background IMF. The top panel shows the location of magnetosheath FTEs and the bottom panel the position of magnetospheric FTEs.

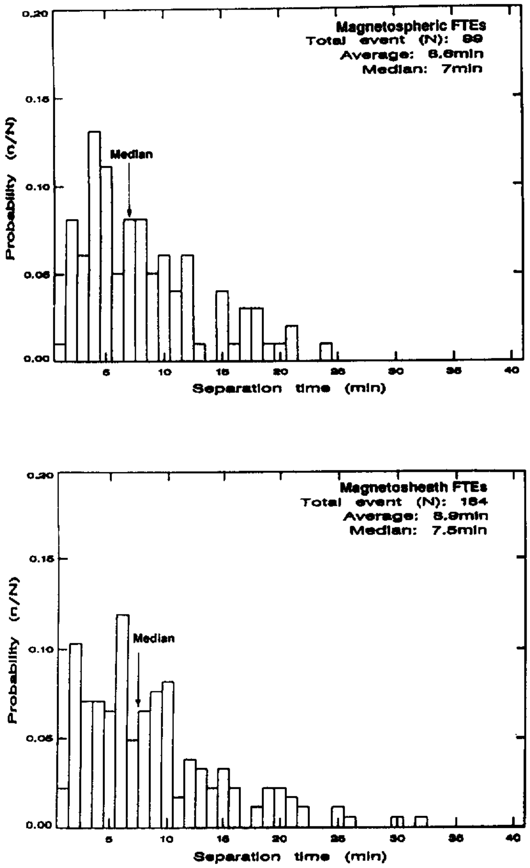

Fig. 8 Number of FTEs observed by ISEE 1 and 2 as a function of spacing between successive FTEs /11/.

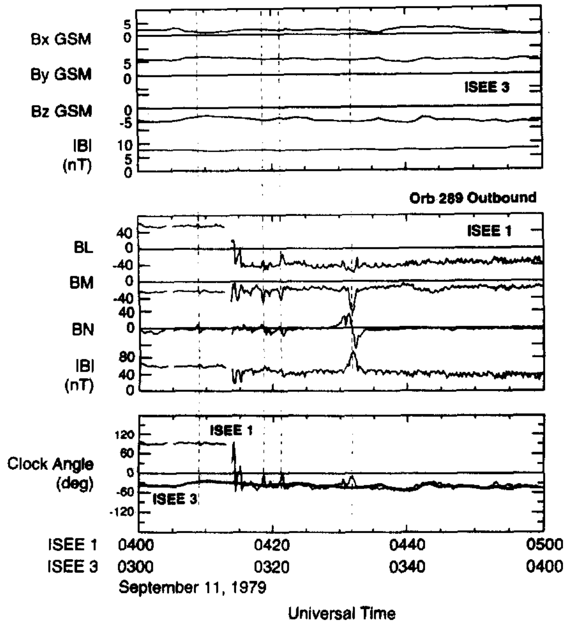

Fig. 9 ISEE measurements of FTEs surrounding a magnetopause crossing at a time of steady IMF. The top panel shows the magnetic field measured by the ISEE-3 spacecraft in GSM coordinates. The middle panel shows the ISEE-1 measurements of the magnetic field at the magnetopause in GSM. The bottom panel shows the clock angle of the magnetic field as measured by ISEE 1 and ISEE 3 /18/.

## FACTORS CONTROLLING FTE OCCURRENCE

As evident from the discussion thus far FTEs are clearly phenomena associated with a southward component of the IMF and thus are most certainly reconnection phenomena. Figures 10 and 11 show the rates of occurrence of FTEs in the magnetosheath and the magnetosphere as a function of the clock angle of the IMF /11/. These rates are dependent on the threshold used to define an FTE. We have used a 10 nT variation in the normal component. As Figure 3 indicates the rate would be greater if the threshold were less. However, a smaller threshold would also result in more ambiguity in FTE identification.

It is clear from these two figures that the FTE phenomenon disappears for northward IMF but occurs almost uniformly with angle once the IMF is southward. This is true for both magnetospheric and magnetosheath FTEs. The difference in rates between the magnetosphere and magnetosheath can be attributed to the smaller magnetospheric effect of FTEs discussed above.

Since all indications point to a magnetic reconnection origin of FTEs we might expect that other factors that affect the reconnection rate might also affect FTE occurrence. Since the IMF direction has such a strong controlling influence on the occurrence of FTEs, it is difficult to identify secondary influences. Figure 12 shows the one secondary influence we have been able to identify /11/. The magnetosonic Mach number of the solar wind flow past the Earth which controls the strength of the bow shock and the beta in the magnetosheath plasma has a weak effect on FTE occurrence so that fewer FTEs occur at higher Mach numbers. This effect could be the result of a weakening of the size of FTEs' effects on the normal component at high beta conditions in the sheath. The solar wind Mach number has been found to affect the rate of reconnection in previous studies.

In summary, the north-south component of the IMF is the principal controlling factor in the occurrence of FTEs. However, increasing solar wind Mach number reduces slightly the occurrence rate. Both these correlations are consistent with a reconnection source for FTEs.

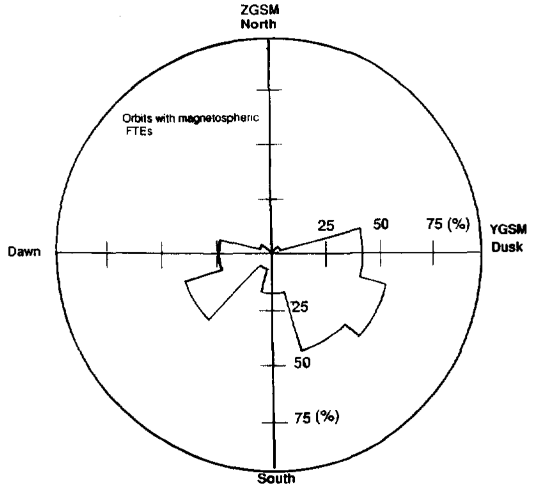

Fig. 11 The occurrence rate of FTEs in the magnetosphere as a function of the direction of the IMF in the plane orthogonal to the solar direction /11/.

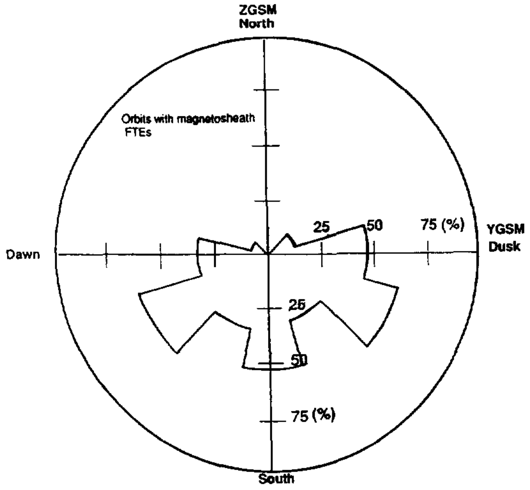

Fig. 10 The occurrence rate of FTEs in the magnetosheath as a function of the direction of the IMF in the plane perpendicular to the solar direction. The rate of occurrence has been normalized by the occurrence rate of IMF directions for times when FTEs were and were not observed /11/.

## CONCLUSIONS

Flux transfer events are found in both the magnetosheath and the magnetosphere. Since they have the same effect on the magnetosheath field and the magnetospheric field they must be due to moving bulges on the magnetopause and not surface waves. The early interpretation of the signature of the normal component in terms of motion north or south has been confirmed by measurements of the velocity of FTEs using the electric field. FTEs occur over about 50% of the magnetopause when the IMF is horizontal or southward. The signature of FTEs in the normal component of the magnetic field is about 30% smaller in the magnetosphere than in the magnetosheath. Thus FTEs are found somewhat less often in the magnetosphere than in the magnetosheath when the same threshold is used. FTEs are not triggered

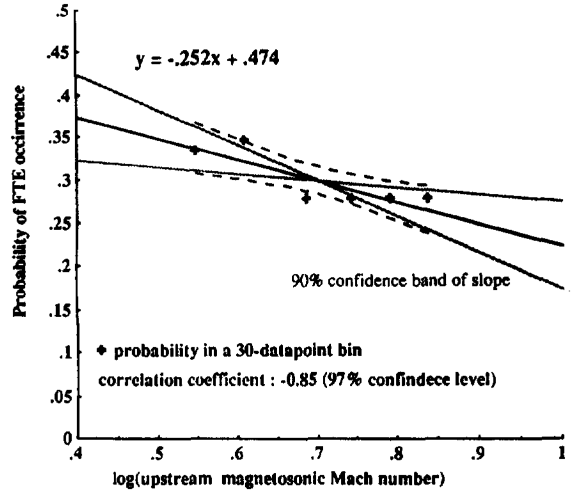

Fig. 12 The probability of occurrence of FTEs as a function of the Mach number of the solar wind flow past the Earth /11/.

by IMF directional changes. While the interval between FTEs does vary, this spacing appears to be independent of external conditions but perhaps controlled by factors at the magnetopause so that FTE spacing and size are coupled. While a detailed understanding of the FTE formation mechanism remains elusive, these dependences clearly point to transient reconnection as the principal cause.

## ACKNOWLEDGMENT

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