JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. A8, PAGES 7397–7404, AUGUST 1, 1985

Flux Transfer Events at the Jovian Magnetopause

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Recent evidence indicates that magnetic reconnection at the earth's magnetopause may not be a steady process, but rather it is frequently impulsive and limited in spatial extent. These limited reconnection events are called flux transfer events (FTE's). We have searched the magnetic field observations at Jupiter from Pioneer 10 and 11 and Voyager 1 and 2 for evidence of FTE's and have found 14 possible events. The FTE's at Jupiter are associated with northward magnetosheath fields. The electric fields generated by Jovian FTE's are small in comparison with the corotation E field throughout much of the magnetosphere. Thus FTE's are probably not an important source of flow within the Jovian magnetosphere.

1. INTRODUCTION

Magnetic reconnection at the magnetopause is thought to control much of the dynamics of the earth's magnetosphere. Evidence for quasi-steady reconnection which lasts on time scales longer than that required to set up a flow of open flux tubes over the dayside magnetosphere (~ 10 min) has been found on occasion in the ISEE particle and fields records [*Paschmann et al.*, 1979; *Sonnerup et al.*, 1981*b*; *Gosling et al.*, 1982; *Paschmann*, 1984]. However, quasi-steady reconnection is not the most frequently observed form of reconnection. The ISEE observations indicate that temporarily and spatially limited reconnection is the most commonly observed form of reconnection. These localized reconnection events are now called flux transfer events (FTE's).

The first report of localized reconnection events was by *Haerendel et al.* [1978], who examined field and plasma measurements in the high-latitude boundary layer from HEOS 2. They observed spikes in the magnetospheric field and interpreted them in terms of reconnection in the polar cusp. *Russell and Elphic* [1978] and *Elphic and Russell* [1979] examined low-latitude data from ISEE and found localized reconnection events which they called flux transfer events. A recent study has demonstrated that the HEOS 2 flux erosion events are the same as the flux transfer events [*Rijnbeek and Cowley*, 1984].

Sonnerup et al. [1981*a*] have looked for evidence of reconnection in the magnetic record at the Jovian magnetopause. They searched for a normal component of **B** which would be indicative of quasi-steady reconnection. Although they found two examples of rotational discontinuities suggestive of reconnection, they concluded that the Jovian magnetopause is less likely to develop a measurable normal field component than is the earth's magnetopause. Earlier, *Brice and Ioannidis* [1970] estimated the convective electric field at Jupiter which would result from steady state reconnection. They concluded that the corotational electric field will dominate the convective electric field almost everywhere in the Jovian magnetosphere.

Figure 1 shows what a flux transfer event might look like at the Jovian magnetopause. The figure shows a front (magnetosheath) view (Figure 1*a*), a back (Jupiter) view (Figure 1*b*), and cross sections (Figures 1*c* and 1*d*) of an FTE, one end of which is attached to the northern hemisphere and which is moving northward. The magnetosheath field has a negative B_y (dawnward pointing) component. A major effect of the reconnection is that the magnetic tension will cause the flux tube to contract in the direction of the large, open arrow. The magnetosheath end of the open flux tube will be pulled toward the direction of Jupiter's field (a southward tilt), while the magnetospheric end will be pulled toward the direction of the magnetosheath field (a $-Y$ direction tilt). This contraction will lead to differential motion between the reconnected flux tube and its unreconnected neighbors. The resultant motion of the open flux tube along the magnetopause will displace the surrounding plasma and magnetic flux which has not been reconnected. This contributes to the characteristic magnetic signature of flux transfer events. As the reconnected flux tube passes over a satellite, the component of the magnetic field normal to the magnetopause (B_N) will have a bipolar change (positive then negative or vice versa). In addition, *Saunders et al.* [1984*a*, *b*] have provided evidence of field twisting associated with field-aligned currents within the events at earth. The exact pattern of the bipolar change is determined, in part, by the motion of the reconnected flux tube with respect to the surrounding field and, in part, by the internal twist of the flux tube. If the reconnected flux tube has northerly motion, the perturbation in B_N in the draped field due to the motion of the FTE will be first inward (toward Jupiter) as the flux tube approaches and then outward as the flux tube leaves. For a southward moving FTE the perturbation will be outward and then inward as the flux tube sweeps past the spacecraft (see *Cowley* [1982] for a description at the earth). The same perturbation is seen in both the magnetosheath and the magnetosphere segments of the FTE.

There will be changes in the magnetic field in the plane tangent to the boundary as well. The field tension on open field lines will tilt the FTE magnetic field in the direction of the field on the opposite side of the magnetopause [*Cowley*, 1982]. In addition, the twisting due to field-aligned currents within the events causes a further deflection of **B** within the FTE, so that sometimes the field in the event will be tilted toward the field on the other side of the magnetopause, while sometimes it will be tilted away.

The displacement of the surrounding field around the open flux tube will result in additional normal forces on the open tube which will tend to compress the magnetic field and plasma within the FTE (dark arrows in Figures 1*c* and 1*d*). Thus most FTE's are accompanied by an increase in the field magnitude, although at earth cases in which there is no change or even a decrease have been reported [*Russell and Elphic*, 1978; *Saunders et al.*, 1984*b*; *Rijnbeek et al.*, 1984*a*].

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Paper number 4A8331.
0148-0227/85/004A-8331$05.00

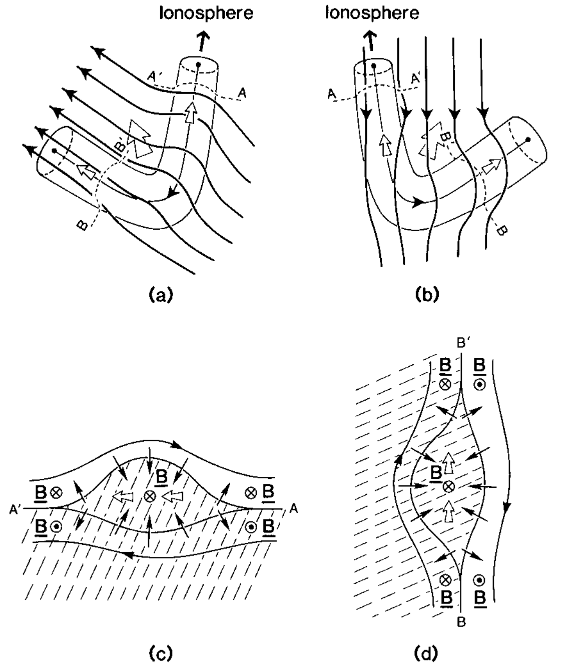

Fig. 1. (*a*) Front (solar) and (*b*) back (Jupiter) views and (*c*, *d*) cross sections of a northward moving flux transfer event at Jupiter [after *Cowley*, 1982]. Since Jupiter's intrinsic field points southward, the IMF was assumed to have a northward component. The IMF, also, was assumed to have an east-west component pointing toward dawn. In Figures 1*a* and 1*b* the large open arrows indicate the direction in which the tube is contracting, while the small open arrows indicate that plasma will flow away from the bend. The field lines in Figure 1*a* are magnetosheath field lines which overlay the reconnected flux tube, while the field lines in Figure 1*b* are underlying magnetospheric field lines. The Figure 1*c* cross section is along the line A'A, and the Figure 1*c* cross section is along B'B. The open arrows give the directions of flow, and the solid arrows show the force due to the tension of overlying field lines.

The interpretation that the magnetic field changes were the result of reconnection has been confirmed at earth by studies of energetic particles and plasma observations. Energetic magnetospheric ions streaming out of the magnetosphere are found within the FTE's, but the low-energy plasma is of magnetosheath origin [*Daly et al.*, 1981, 1984; *Paschmann et al.*, 1982].

Recent statistical studies of flux transfer events at earth show them to be very common [*Berchem and Russell*, 1984; *Rijnbeek et al.*, 1984*a*]. Berchem and Russell used a very conservative definition of FTE's. They required the magnetic field change for each event to show all three signatures (bipolar B_N change, twisting in the tangential plane and compression) and still found FTE's on 25% of the ISEE passes through the magnetopause. Berchem and Russell found that FTE's are associated with southward interplanetary magnetic field (IMF) and used their statistical distribution with latitude to argue that they are generated near the equator. *Rijnbeek et al.* [1984*a*] used a more liberal definition for FTE's, allowing cases with a nonsymmetrical B_N signature and cases which did not show an increase in field strength. They also included cases in which there were large oscillatory changes in the tangential component during the FTE. Their statistical results were similar to those of Berchem and Russell.

Rijnbeek et al. [1984*a*, *b*] used the frequency of occurrence of FTE's and an estimate of their size to determine the voltage generated by the reconnection. They estimated that the cross-magnetospheric voltage generated by FTE's is at least 10 kV. Since in the earth's magnetosphere the typical cross-magnetospheric voltage is only about 50 kV, FTE's are significant for driving magnetospheric flows.

In this paper we expand the *Sonnerup et al.* [1981*a*] study by looking for evidence of localized reconnection at Jupiter. In particular, we have searched the magnetic field observations from the Pioneer and Voyager flybys for evidence of flux transfer events. In the last section we compare the Jovian observations with those at the earth.

2. OBSERVATIONS

The search for flux transfer events is greatly facilitated if the magnetic field observations are first transformed into boundary-normal coordinates [*Russell and Elphic*, 1978]. In boundary-normal coordinates at earth, the $\hat{N}$ component is directed outward along the magnetopause normal and the $\hat{L}$ direction is along the projection of the solar magnetospheric $\hat{Z}$ direction into the plane perpendicular to $\hat{N}$. The $\hat{M}$ direction completes a right-handed system ($\hat{M} = \hat{N} \times \hat{L}$) and points roughly in the eastward or morning direction. At the earth, Russell and Elphic determined the boundary normal in three ways. They used either a model of the magnetopause to determine $\hat{N}$, the tangential discontinuity method, or the minimum variance method. Since no empirical models exist for Jupiter, we used only the tangential discontinuity and minimum variance methods. For both methods we first determined the time of the magnetic field change associated with the boundary from published times determined from plasma observations [*Sonnerup et al.*, 1981*a*; *Bridge et al.*, 1979*a*, *b*] and an inspection of the magnetic field data. For the tangential discontinuity method we found the normal by taking the cross product of an average magnetospheric field vector with an average magnetosheath vector. In the minimum variance case we found $\hat{N}$ as the direction of minimum variance [*Sonnerup and Cahill*, 1967]. The observations in Figures 2, 4, and 5 were organized by using the minimum variance method. $\hat{L}$ is the direction of maximum variance. Its sign was chosen by requiring that $\hat{L}$ had a northward component in the coordinate system of the measurement. $\hat{M}$ is the direction of intermediate variance. Its sign was chosen so that LMN formed a right-

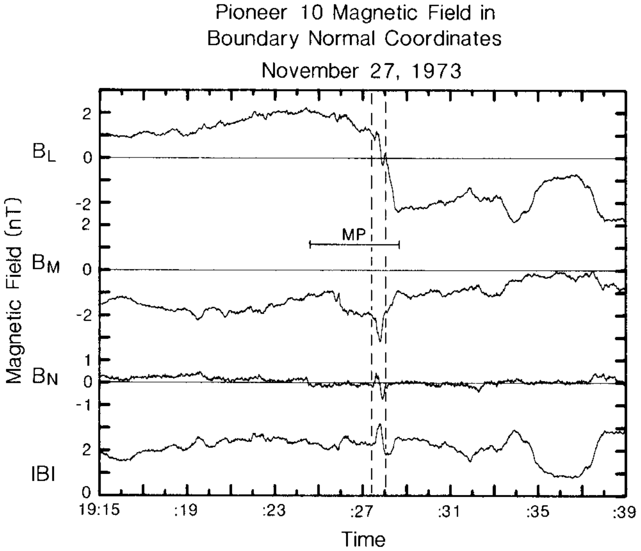

Fig. 2. Pioneer 10 magnetic field observations in boundary-normal coordinates. The horizontal bar labeled MP is the interval used for the minimum variance calculation. The dashed lines indicate an interval containing a possible flux transfer event.

handed system. The resulting coordinate system is very similar to the system used at earth. For instance, for the magnetopause crossing in Figure 2, $\hat{L}$ is mainly northward and $\hat{M}$ is toward the east. The coordinates of $\hat{L}$ in solar-Jovian (SJ) coordinates are (0.36, 0.10, 0.93). SJ coordinates are similar to geocentric solar ecliptic coordinates at earth (see *Smith et al.* [1976] for a description of SJ coordinates). The transformation matrix from SJ coordinates to *LMN* coordinates which we determined was essentially the same as that found by *Sonnerup et al.* [1981*a*].

The magnetic field observations plotted in Figure 2 are from the first Pioneer 10 inbound magnetopause crossing when the spacecraft was 96 R_J (R_J is the radius of Jupiter, 71,398 km) from Jupiter. The data are 1.5-s averages. The horizontal bar labeled MP indicates the time interval over which the minimum variance procedure was applied. The observations are very well organized in this coordinate system, with eigenvalues of (1.205, 0.281, 0.021). Changes in the exact interval used to define this boundary did not alter the three components significantly, provided the interval was within a few minutes of the magnetopause crossing. Prior to the magnetopause crossing the magnetosheath field was northward. There is a clear bipolar change in B_N of the type associated with an FTE starting at about 1927 earth received time. The change in B_N is first away from and then toward Jupiter. This is consistent with southward motion of an open flux tube with its ionospheric end in the south polar region. Pioneer 10 was 4° south of the Jovigraphic equator at this time and at about 0900 LT.

There is a clear compression of the magnetic field within the region of the bipolar B_N change. In addition, the field in the plane tangent to the boundary changes orientation during the event. Because the FTE is so close to the boundary, it is difficult to separate a field rotation toward the magnetospheric field direction associated with the FTE from that associated with the boundary. However, there is a rotation toward the magnetosheath direction in the second half of the event (~1927:50). This can be seen most clearly in Figure 3, where we have plotted B_N along with α, the angle of the field in the *LM* plane ($\alpha = \tan^{-1}(B_M/B_L)$); α is about $-45°$ in the magnetosheath and about $-155°$ in the magnetosphere. *Sonnerup et al.* [1981*a*] have presented a hodogram for this magnetopause crossing (their Figure 5). This too shows the rotation toward the magnetosheath direction. This rotation toward the magnetosheath is opposite to the direction of rotation which we would expect because of the magnetic tension on open field lines. *Saunders et al.* [1984*a*, *b*] have attributed this sort of field twisting to field-aligned currents within reconnected flux tubes. The field twisting in this event is consistent with a current flowing along the field (i.e., in the southward direction).

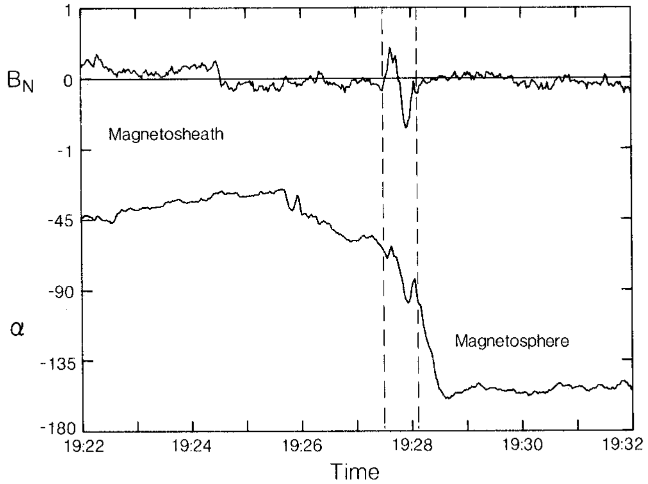

Fig. 3. The normal component of **B** and the angle of the field in the *LM* plane. The field in the magnetosheath is about −45°, while that in the magnetosphere is about −155°. The FTE interval is indicated by vertical dashed lines.

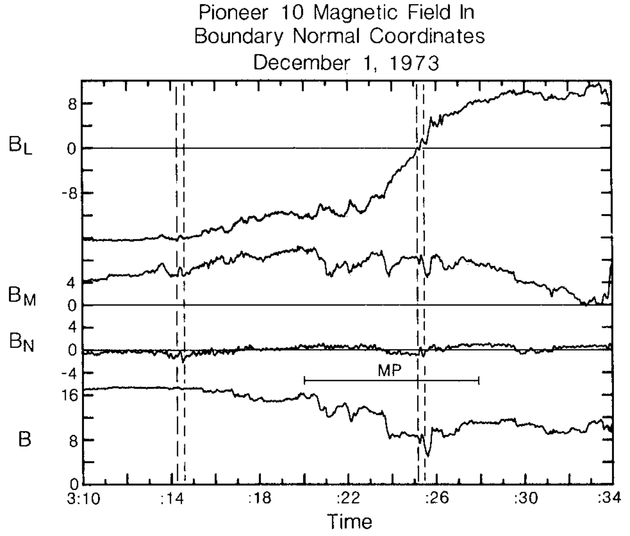
Pioneer 10 Magnetic Field In
Boundary Normal Coordinates
December 1, 1973

Fig. 4. Same as Figure 2. The dashed lines indicate possible flux transfer events.

This small FTE lasts about 30 s. Since the magnetosheath flow velocity was about 200 km/s just prior to the magnetopause crossing [*Intriligator and Wolfe*, 1976], the FTE has a scale size of about 6000 km tangential to the magnetopause if we assume the flux tube is convecting past the spacecraft with the plasma velocity. At earth the scale size of an FTE is about the same in the normal direction as in the tangential direction [*Saunders et al.*, 1984*a*, *b*]. If we assume that the reconnected flux tube has the same size in both directions at Jupiter as well, then the flux in this FTE is about 6×10^4 Wb.

The magnetic field data when Pioneer 10 left the magnetosphere temporarily at 53 R_J is plotted in Figure 4. Again, Pioneer was about 4° below the Jovigraphic equator at about 0900 LT. This is a relatively noisier interval and is more typical of the Jovian magnetopause observations than are the data of Figure 2. (Note the scale change to 4 nT per division in this plot.) There are two possible FTE's during this crossing. The clearest event occurred at about 0325 in which the sign of the change in the normal field is the same as in Figure 2. Again, this is consistent with a southward moving flux tube connected to the southern ionosphere. The field in the tangential (*LM*) plane rotates within this event. The rotation is toward the magnetosheath field direction. The event is accompanied by a clear compression of the field. Since this possible FTE lasts only about 20 s, the reconnected flux is about 1×10^5 Wb. The other possible FTE was observed at about 0314. It is characterized by a bipolar B_N perturbation with the same sense as in the previous two examples. There is a twisting of the field in the *LM* plane in the direction of the magnetosheath field; however, there is little or no compression in the field during this event. As noted in the introduction, FTE's without compression have been observed at the earth. Thus

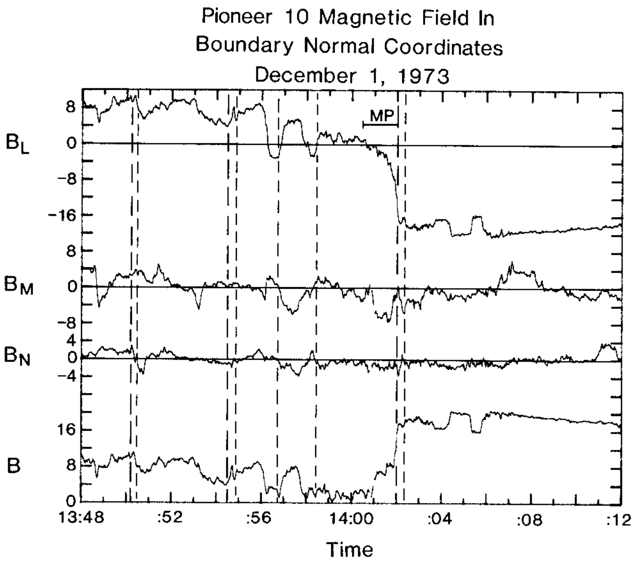

Fig. 5. Same as Figure 4.

this may be an example of an FTE within the magnetosphere. Since the change in B_N is the same on either side of the magnetopause, this, too, is consistent with a southward moving flux tube connected to the southern ionosphere.

Observations from the magnetopause entry nearest (47 R_J) Jupiter are presented in Figure 5. In this case, too, Pioneer was at about 0900 LT and just below the Jovigraphic equator (~7°). This is the noisiest of the Jovian magnetopause crossings. There are several relatively large fluctuations in the normal **B** component. These fluctuations in B_N which are associated with rotation of the field in the direction toward the magnetosphere and compression in |**B**| were only found immediately adjacent to the magnetopause. This structure suggests multiple flux transfer events. Indeed, four of these fluctuations have signatures suggestive of flux transfer events. They are marked with dashed lines. The clearest event occurred at about 1357. Here B_N decreases and then increases. This suggests northward motion of the FTE. There is both compression and a rotation of the field in the tangential plane during this event. This has the longest duration of any of the Jovian events, 90 s, and had the largest reconnected flux, $\sim 3 \times 10^6$ Wb. There are three other possible FTE's associated with this magnetopause crossing at 1402, 1354, and 1350. Of these the one at 1402 is the clearest. It occurs just within the magnetopause and is associated with a twisting in the *LM* plane toward the magnetosheath direction as well as a bipolar B_N change. There appears to be only a small amount of compression during this event but the signature may have been obscured by the field increase associated with the entry into the magnetosphere. The possible event at 1354 is about the smallest event we can identify during this magnetopause crossing, since the B_N change (~2 nT) is comparable with the noise.

The normal component of **B** has been plotted for 17 dayside magnetopause crossings in Figure 6. The data are 1.5-s averages for Pioneer and 1.92-s averages for Voyager. The abbreviations MSH and MSP indicate when the spacecraft was in the magnetosheath or magnetosphere, respectively. The information on the right-hand side gives the spacecraft, date, time of the start of the magnetopause crossing, the radial distance, the angle between the magnetosheath field and the magnetosphere field, and the average magnetosheath north-south component for 1 hour prior to the magnetopause crossing. The times are earth received time for Pioneer and spacecraft event time for Voyager. As before, MP with a horizontal bar indicates the interval used for the magnetopause in the minimum variance calculation. The magnetopause crossings have been plotted in order of decreasing angle between the magnetosheath field and the magnetosphere field.

As noted above, for each of the Jovian magnetopause crossings, we calculated the magnetopause normal by using both the minimum variance technique and the tangential discontinuity method. In general, the minimum variance method did a significantly better job in organizing the data. However, in three cases the tangential discontinuity method worked better.

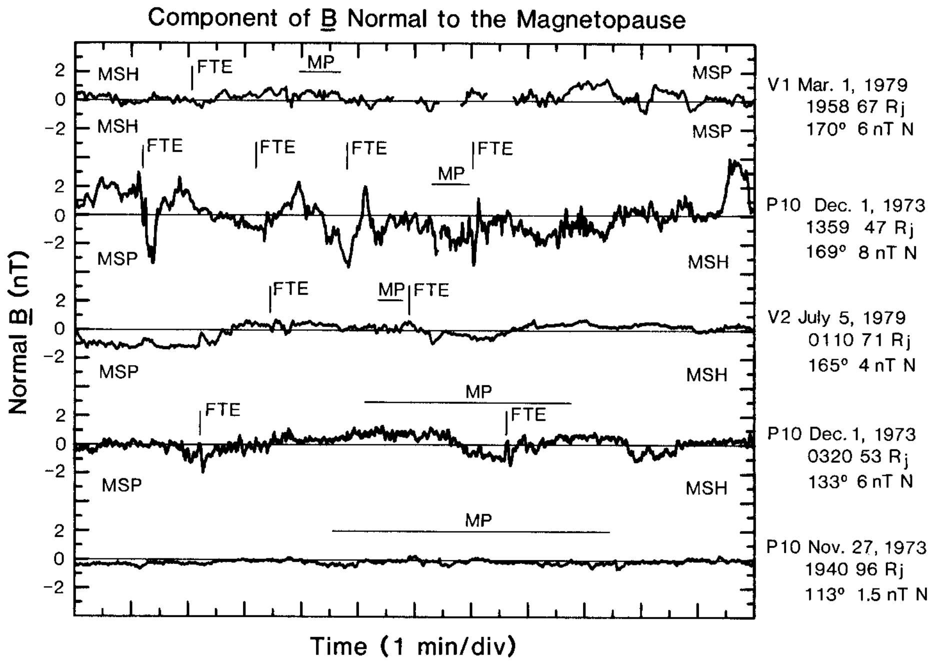

Fig. 6*a*. The component of **B** normal to the magnetopause for each of the Jovian magnetopause crossings. See the text for a description of the notation.

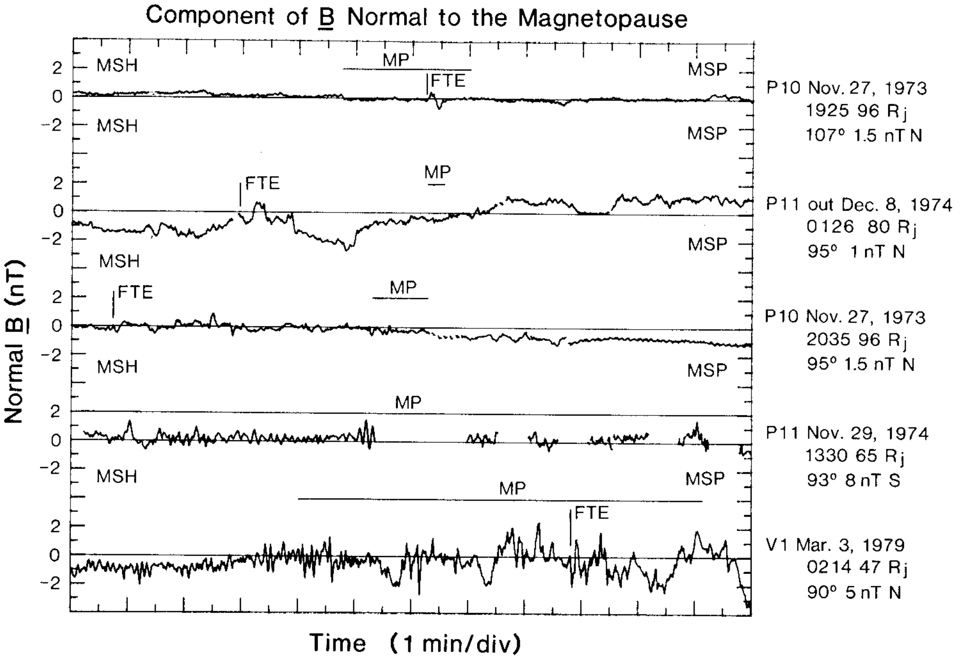

Fig. 6b. Same as Figure 6a.

In these cases (Voyager 2 on July 5, 1979, at 1836 and Pioneer 11 on December 6, 1974, at 0847 and 1907) we have plotted the normal component obtained by using the tangential discontinuity method.

Each possible FTE in Figure 6 has been labeled FTE. We have used a liberal definition of an FTE in order to include all possible events. In particular, we used a definition similar to that used by *Rijnbeek et al.* [1984*a*, *b*] at earth. We required each FTE candidate to have both a bipolar B_N signature and a twisting or tilting of the field in the tangential plane. However, we have included events which did not have a clear increase in $|\mathbf{B}|$. Those FTE's in which $|\mathbf{B}|$ did not increase are noted in Table 1. By using this definition we may have included some events which are not FTE's. However, we used it

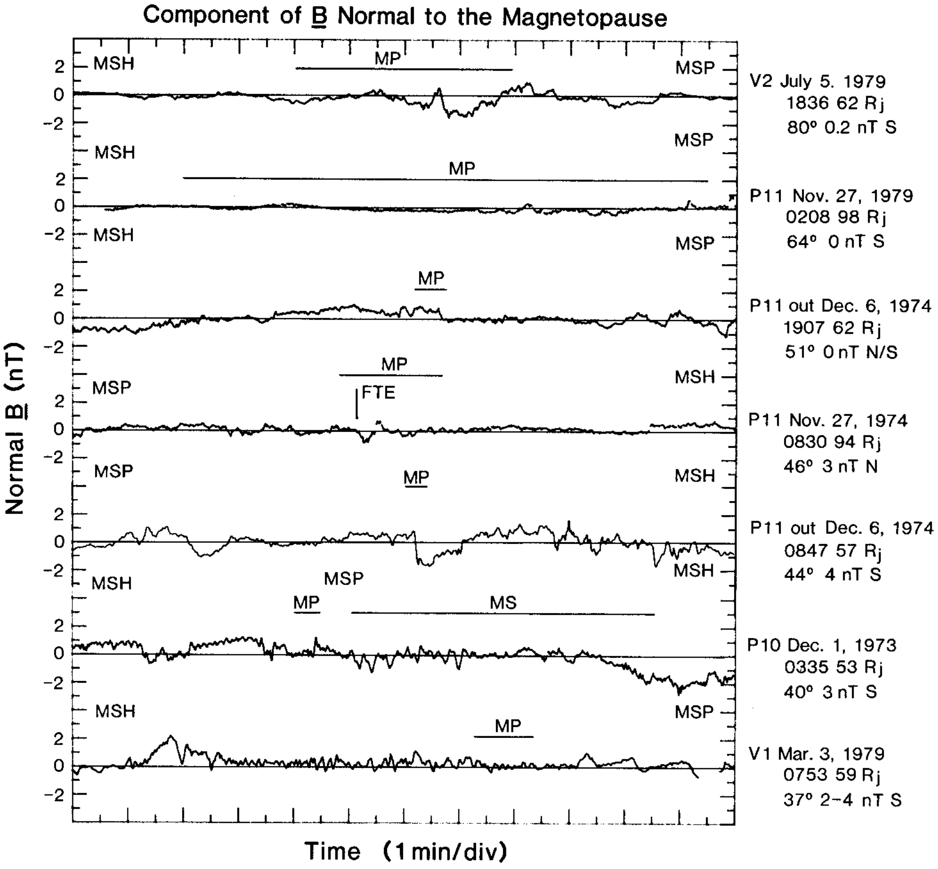

Fig. 6c. Same as Figure 6a.

TABLE 1. Magnetopause Crossings With Possible Flux Transfer Events

Start Time of Boundary Crossing	Spacecraft	R, R_J	Jovigraphic Latitude, deg	Jovigraphic Longitude,* deg	FTE Time	$\lvert\mathbf{B}\rvert$ Increase	Reconnected Flux, Wb
Nov. 27, 1973; 1925†	P10	96	−4	70	1927†	yes	6×10^4
Nov. 27, 1973; 2035†	P10	96	−4	27	2025†	no	7×10^4
Dec. 1, 1973; 0320†	P10	53	−4	56	0314†	yes	3×10^5
					0324†	yes	1.3×10^5
Dec. 1, 1973; 1359†	P10	47	−7	30	1350†	no	1×10^6
					1354†	yes	5×10^5
					1357†	yes	3×10^6
					1402†	no	5×10^5
Nov. 27, 1974; 0830†	P11	94	−7	259	0830†	no	3×10^5
Dec. 8, 1974; 0126†	P11	80	33	336	0119†	yes	9×10^5
March 1, 1979; 1958‡	V1	67	4	285	1952‡	yes	1×10^6
March 3, 1979; 0214‡	V1	47	2	225	0223‡	yes	6×10^5
July 5, 1979; 0110‡	V2	71	6	4	0106‡	yes	1×10^6
					0110‡	yes	1.3×10^6

*Pioneer 10, 11 and Voyager 1, 2 were inbound between 0900 and 1000 LT; Pioneer 11 outbound was at 1200 LT. Longitudes are in −System III.

†Earth received time.

‡Spacecraft event time.

because we want to know the maximum number of FTE's in order to determine how important they are for driving magnetospheric flows at Jupiter and because we wanted to produce as complete a list as possible so that data from other experiments can be compared with the magnetic field observations. Our search for FTE's was not limited to the intervals plotted here. We examined high-resolution magnetic data for approximately 30 min on either side of the plotted intervals but did not find any additional FTE-like signatures. We also examined 12-s Pioneer data and 9.6-s Voyager data in order to determine if there were FTE's on a larger scale (i.e., several minutes), such as those initially observed by *Russell and Elphic* [1978] at earth, but did not find any. Thus we are confident that any events in the Pioneer and Voyager records of longer duration than 10–20 s which have magnetic signatures similar to those identified as FTE's at earth are included in Figure 6 and Table 1.

For those magnetopause crossings during which the magnetosheath field was northward, we found evidence for several FTE's (Figure 6*a*). They were typically less than 1 minute in duration. The change in the normal component is typically about 1 nT, with the largest change being about 2 nT.

Pioneer 11 outbound was the only spacecraft to cross the magnetopause near local noon and at high latitudes (Figure 6*b*). All of the outbound trajectories except Pioneer 11 were on the nightside of Jupiter. Pioneer 11 outbound encountered the magnetopause at about 33° Jovigraphic latitude. Despite a very rapid magnetopause crossing, the data were not as well organized by boundary-normal coordinates as most of the other magnetopause crossings. The normal component is nonzero throughout much of the interval plotted. However, we found evidence for at least one FTE on this crossing. The other two Pioneer 11 outbound boundary crossings occurred when the magnetosheath field was southward and were not accompanied by FTE's.

Several magnetopause crossings are accompanied by many oscillations in B_N. Examples of this can be found in the Pioneer 11 crossing on November 29, 1974, at 1330 (Figure 6*b*), the Voyager 1 crossing on March 3, 1979, at 0214 (Figure 6*b*), the Pioneer 10 crossing on December 1, 1973, at 0335 (Figure 6*c*), and the Voyager 1 crossing on March 3, 1979, at 0753 (Figure 6*c*). These events are not accompanied by any of the other **B** changes associated with an FTE and therefore are probably not flux transfer events. The normal magnetic field component during the November 29 event tends to be slightly positive (<0.5 nT) throughout the entire magnetopause crossing. Sonnerup et al. have suggested that this may be a rotational discontinuity and is consistent with steady state reconnection (see Figure 12 of *Sonnerup et al.* [1981*a*]). The Voyager magnetopause crossing on March 3, 1979, at 0214 also was very noisy. One interval satisfied all three of the criteria for an FTE and has been noted in Figure 6*b*; however, because of the noise, care must be exercised in interpreting this event.

When the angle between the magnetosheath field and the magnetopause field was small (<90°), we found only one possible FTE (Figure 6*c*), and that event from Pioneer 11 on November 27, 1974, at 0830 was associated with a northward magnetosheath field. We did not find any FTE candidates when the magnetosheath field was southward.

3. FLUX TRANSFER EVENTS AT JUPITER AND THE EARTH

The events we have identified as possible flux transfer events at Jupiter are similar to FTE's observed at earth in several respects. FTE's at both planets are observed on both sides of the magnetopause [*Daly and Keppler*, 1982]. At the earth, FTE's occur almost exclusively when the interplanetary magnetic field is southward [*Berchem and Russell*, 1984; *Rijnbeek et al.*, 1984*a*]. While we do not have simultaneous IMF data at Jupiter, the Jovian events occurred when the magnetosheath field was northward. Nine of the 10 magnetopause crossings when the magnetosheath field was northward have evidence of FTE's.

It is not surprising that the field changes associated with the Jovian FTE's are smaller than those at earth. The field at the magnetopause is smaller at Jupiter. However, it is interesting to note that the FTE candidates which we have identified are of shorter duration at Jupiter. FTE's reported at earth last from 1 or 2 min to 4 or 5 min. While shorter ones probably exist, they have not been reported. Most of the possible FTE's which we found in the Jovian record are less than 1 min in duration. We did not find any of the long-duration events reported at earth. As a result of the smaller field magnitude and shorter duration events, the reconnected flux is less at Jupiter. The reconnected flux in our events is typically ∼5

TABLE 2. Magnetotail Electric Field Generated by Flux Transfer Events

Magnetopause Location	B, nT	Interval Between FTE's, min	Duration of FTE, min	Φ_{tail}, kV	E_{tail}, mV/m
100 R_J	2	4	1	2.2×10^3	0.06
100 R_J	2	1	1	8.4×10^3	0.24
50 R_J	12	4	1	6.3×10^3	0.18
50 R_J	12	1	1	2.6×10^4	0.72

$\times 10^5$ Wb. The reconnected flux varies from 6×10^4 to 3×10^6 Wb (Table 1). This large variability in the reconnected flux occurs because of the large variability in the magnetopause positions and hence **B**. At the earth the reconnected flux is typically 4×10^6 Wb [*Saunders et al.*, 1984*a*, *b*], although values as large as 3×10^7 Wb have been reported [*Russell and Elphic*, 1978].

Flux transfer events at the earth tend to occur in groups. Magnetopause crossings with several FTE's are commonly observed on the ISEE 1 and 2 spacecraft [*Berchem and Russell*, 1984]. At Jupiter, three of the eight magnetopause crossings which have possible FTE's have more than one and only one of these has more than two. FTE's are observed with a separation of about 8 min at the earth [*Rijnbeek et al.*, 1984*a*, *b*], while during the one Jovian event with four FTE's, the separation was about 4 min. Flux transfer events are very important for driving flows at the earth, since the ISEE observations indicate that a large fraction of the cross-magnetospheric electric field can be generated by these limited reconnection events [*Cowley*, 1982; *Saunders et al.*, 1984*b*; *Rijnbeek et al.*, 1984*a*, *b*]. In Table 2 we have used the results of our survey to estimate the electric field at Jupiter generated by FTE's. Although our statistics are poor, we can obtain an upper limit on the electric field. The weakest feature of the survey is the information on the frequency of occurrence of the events. For this reason we have used two values for the mean separation times between events. We used 4 min, which was the separation observed during the December 1, 1973, magnetopause crossing at 1359, and 1 min, which is the separation if the events are occurring one right after another without pause. For example, if the magnetopause is at 100 R_J, $B \sim 2$ nT and the flux in an FTE is about 3×10^5 Wb. If we divide this by the recurrence frequency of 4 min, we obtain a voltage of about 1200 V. Since the observations are limited to only one longitude, we cannot tell whether there are FTE's occurring simultaneously at other longitudes. As an upper limit we have assumed that FTE's are occurring simultaneously at all longitudes across the dayside magnetopause, which was taken to be a hemisphere. Thus in our example, we obtain 2.2×10^3 kV or 0.06 mV/m if the magnetotail is 500 R_J across. The electric fields are similar to those inferred in the earth's magnetosphere, a few tenths of a millivolt per meter. However, these electric fields are much smaller than those associated with corotation in the Jovian magnetosphere. For example, at 50 R_J the corotation **E** field is 7.5 mV/m, while at 100 R_J it is 2.5 mV/m. Thus FTE's are probably not important for driving flows throughout much of the Jovian magnetosphere.

4. SUMMARY

We have searched the magnetic field record from the Jovian flybys of Pioneer 10 and 11 and Voyager 1 and 2 for evidence of the spatially and temporally limited reconnection events called flux transfer events. We found 14 examples which had the bipolar change in the component of **B** normal to the magnetopause and a tilting or twisting of the magnetic field in the plane tangential to the boundary which are characteristic of FTE's at earth. Most of these (9 of 14) were associated with an increase in the field magnitude. All of the Jovian FTE candidates occurred when the magnetosheath field was northward, and 9 of 10 magnetopause crossings in which the magnetosheath field was northward had evidence for flux transfer events. The reconnected flux in the typical event at Jupiter was about an order of magnitude less than that typically reported for FTE's at the earth. The electric field generated by FTE's at Jupiter is small in comparison with the corotation **E** field throughout much of the magnetosphere. This indicates that FTE's are not an important source of flow at Jupiter.

Acknowledgments. We wish to thank M. A. Saunders for critically reading an earlier version of this manuscript and for his helpful comments. This research was supported by NASA Jupiter Data Analysis Program grant NAGW 162 and NASA Planetary Atmospheres grant NSG-7295. The Pioneer magnetometer data were provided courtesy of E. J. Smith. The Voyager data were obtained from the National Space Science Data Center. Institute of Geophysics and Planetary Physics publication 2583.

The Editor thanks E. J. Smith and another referee for their assistance in evaluating this paper.

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(Received September 17, 1984;
revised April 15, 1985;
accepted April 16, 1985.)