The magnetic and plasma structure of flux transfer events

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Abstract. Flux transfer events have been interpreted to be manifestations of transient reconnection of the magnetospheric and magnetosheath magnetic fields at the Earth's magnetopause. In this study we determine the interior structure of flux transfer events by examining high-resolution magnetic field and plasma distribution functions from the ISEE 2 spacecraft. The sampling time and cadence of these data are more than adequate to resolve the rapidly changing plasma regimes and to avoid spatial aliasing. From these data we confirm the existence of two distinct regions within a flux transfer event (FTE), a central core and a field-draping region, and these two regions have been found within FTEs observed both on the magnetosheath side and the magnetospheric side of the magnetopause. The boundaries between the two regions are apparent in both the field and the plasma data. In the field-draping region the plasma distribution functions show little difference from those in the neighboring magnetosheath or magnetosphere, and the magnetic field consistently exhibits signatures expected from field-line draping around a flux tube. Within the central core region, plasma appears to be a mixture of the magnetosheath and magnetospheric components. In FTEs observed in the magnetosphere, we find transmitted magnetosheath plasma and a strong depletion of hot magnetospheric plasma. In FTEs observed in the magnetosheath, we find an outflow of magnetospheric plasma mixed with the magnetosheath plasma. These signatures unambiguously show the reconnection of the interplanetary magnetic field and the Earth's magnetic field. Thus our observations indicate that the magnetic field lines within the central core region are open allowing the inflow of cold magnetosheath plasma and the outflow of hot magnetospheric plasma through the open flux tube. The reconnection picture is further supported by the observation of separate electron and ion edges at the trailing boundary of a northward moving flux tube, expected as time-of-flight effects on newly reconnected field lines. Thus our observations are consistent with the reconnected open flux tube interpretation for FTEs.

1. Introduction

The momentum and energy transfer to the Earth's magnetosphere from the solar wind is generally believed to be controlled primarily by reconnection occurring in the vicinity of the subsolar point and by the amount of southward interplanetary magnetic field (IMF) [see, e.g., Russell and McPherron, 1973]. Some of this reconnection appears to occur in a quasi-continuous fashion, but sometimes reconnection appears to be quite discontinuous. A manifestation of time varying reconnection is believed to be the phenomenon called a flux transfer event [Russell and Elphic, 1978], which is generally most discernible in the magnetic field near the magnetopause. The signature of a flux transfer event (FTE) is a strong component of the magnetic field along the expected normal to the boundary with a bipolar signature outward then inward or vice versa. Other components of the field as well as the field magnitude vary in concert but with a more varied signature. They can be observed both in the magnetosheath and in the magnetosphere near the magnetopause. The original suggestion for their appearance was that they represented the result of a temporary increase in the reconnection rate between magnetospheric and magnetosheath field lines [Russell and Elphic, 1978]. The resulting connected flux tube would go from the solar wind into the magnetosphere and down to the ionosphere. As the flux tube moves tailward, the neighboring magnetic field drapes around it causing the characteristic FTE magnetic bipolar signatures. Early statistical studies revealed that FTEs occur preferentially during nearly horizontal or southward IMF and the polarity of the bipolar signatures is ordered by the geomagnetic equator, in a manner consistent with the global picture of a reconnected flux tube moving away from the equatorial region [Berchem and Russell, 1984; Rijnbeek et al., 1984; Southwood et al., 1986].

To date, the majority of studies of FTEs have focused primarily on their magnetic signatures. Nevertheless, the much studied FTE magnetic signature cannot be regarded as well understood. For example, while the magnetic field component normal to the magnetopause surface consistently exhibits a bipolar signature, the other two components and the field strength are much more variable and do not show consistent patterns. For many FTEs, the magnetic field strength shows a maximum near the center of the FTE. Such maxima can be readily explained by field draping, but some FTEs shows a "crust" signature, or a local minimum [LeBelle et
al., 1987; Hubert et al., 1992), and some show no maximum or minimum. Evidence that the magnetic field inside FTEs sometimes twists about the tube axis has also been reported (Saunders et al., 1984). Such variations in the magnetic field pattern suggest that there is also important structure in the plasma populations within an FTE.

Plasma signatures of FTEs are relatively poorly understood. In the plasma moment data (density, flow speed, temperature and heat flux), only a subset of flux transfer events exhibits signatures that distinguish them from adjacent magnetosheath or magnetospheric plasma. For at FTE observed in the magnetosheath (in cases where the FTEs have plasma signatures), the plasma signatures include a decrease in density, an increase in temperature and heat flux, and sometimes an enhancement of flow speed (Daily et al., 1981; Paschmann et al., 1982; Schulz et al., 1982; Daily and Keppler, 1982). Such plasma signatures suggest that the plasma within an FTE is a mixture of magnetosheath and magnetospheric plasma. Thomas et al. (1987) studied the plasma velocity distribution functions within FTEs and confirmed that the plasma within both magnetosheath and magnetospheric FTEs indeed consisted of a mixture of magnetosheath and magnetospheric populations, as suggested from plasma moment data. We know of only one way to obtain such a mixture: reconnection of magnetosheath and magnetospheric field lines at the magnetopause.

Some FTEs have no plasma signature associated with the characteristic bipolar magnetic signature, in particular, no mixture of magnetosheath and magnetospheric plasma. Within the subset for which the plasma mixing signature is found, the mixing signature is present only in a part of the magnetic signature and not in general in the center of the magnetic signature (Epfthic, 1995). Specifically, the bipolar magnetic signature appears to occur over a wider spatial extent than the plasma signature. Often the field lines when a mixture of magnetosheath and magnetospheric plasma is observed occur in the trailing portion of the FTEs (see review by Epficic [1995]). On the basis of various observations of FTEs, Epficic [1995] proposed a taxonomic classification scheme that reflects both the similarities and differences between different classes of FTE signatures.

Many theoretical models based on the original Russell and Epficic [1978] reconnection picture have been proposed to date (see Scholer [1995] for a review). All of them involve the time-dependent reconnection between the IMF and the Earth's magnetic field, although they may differ in how the reconnection is generated. The reconnection forms a localized flux tube that is connected to the tail. However, since observation of FTEs may not be made inside the connected flux tube, plasma properties expected inside the connected flux tube cannot account for all the observations. Variations in both the magnetic field and plasma signatures suggest that there may be two distinct regions within an identified FTE: a core inside the reconnected flux tube and a region with field-line draping around the reconnected flux tube. Our working hypothesis for the variation of plasma signatures within an FTE is that where a mixture of plasma is observed within FTEs, the satellite directly samples reconnected flux tubes, but where this mixture is not observed, the satellite samples field lines that are draped around the reconnected flux tube. Thus most of the field lines in the leading portions of some FTEs may be draped around trailing reconnected field lines. These two distinct regions within an FTE were implicit in the Russell and Epficic [1978] picture.

There have been several studies of the literature concerning the internal structure of FTEs. Southwood [1985] and Farrugia et al. [1987] modeled the field-draping region using incompressible flow around a rigid cylindrical flux tube and found qualitative agreement with observations. Saunders et al. [1984] reported the twisted magnetic field within the central core. Rehbeek et al. [1987] first identified both the central core of the open flux tube and the field-draping region within an FTE using plasma moment data and high-resolution magnetic field data. They estimated that the boundary between these two field regions was of the order of 10 ion gyroradii thick; thus it was essential to use high-resolution data to understand FTE internal structure. Farrugia et al. [1988] found multilayered structure within magnetospheric FTEs using high-resolution data from multiple field and plasma instruments from the IMP-8 (Smith and Owens [1992] observed an increasing perpendicular temperature anisotropy toward the center of an FTE studied by Farrugia et al. [1988] found that the multiple layered structure could be explained as a transient encounter with a series of reconnection layers. Hubert et al. [1992] found in one example that the region around the central core displayed a nonmagnetic feature, a thin sheet structure at the leading edge, and a much larger wake. Wallden et al. [1994] developed a remote-sensing technique to determine the orientation, size, speed, and shape of a bulge on the magnetopause cause by an FTE and found that the overall region affected by the bulge would be many times bigger than the bulge itself.

This paper presents results of a study of the combined magnetic and plasma structure within FTEs using high-time-resolution magnetic field data and plasma distribution functions. The data sets are from the joint database of UCLA magnetometer (Russel, 1978) and Los Alamos/Max-Planck-basin fast plasma experiment (FPE) (Barge et al., 1978) from the ISEE mission. In this paper, we examine detailed magnetic field signatures and plasma distribution functions within several FTEs observed both in the magnetosheath and in the magnetosphere that exhibit plasma signatures.

2. Observations

In this section we present and discuss three examples of flux transfer events observed near ISEE magnetopause crossings. The examples presented here were chosen from the subset of FTEs that exhibit clear plasma signatures in the ISEE 2 data. The FPE instrument provides two-dimensional (2-D) ion and electron velocity distribution functions centered on the spacecraft spin plane (basically the ecliptic plane). In one spacecraft spin period of 3 s, the FPE instrument completes a measurement of ion and electron velocity distributions at 16 energies at each of 16 azimuths, integrated over 55° elevation angle relative to the ecliptic. The FPE data were transmitted to the ground every spacecraft spin in high data rate and every fourth spin in low data rate, and thus the FPE provides 2-D distributions of the function data with temporal resolution of 3 s at high data rate or 12 s at low data rate. The highest temporal resolution of magnetic field data is 1/16 s at high data rate and 1/4 s at low data rate.

2.1. Plasma within the September 11, 1979 Magnetospheric FTE

Figure 1 shows magnetic field data and FPE ion moment data around the ISEE outbound magnetopause crossing on September 11, 1979. For this interval the data are available at low data rate. Figure 1 (top) shows the magnetic field components in boundary normal coordinates [Russell and Epficic, 1978] as well as the field magnitude. The magnetic field data have 4 s temporal resolution. They were obtained by averaging the high-resolution data (1/4 s) over a
12 s overlap window: Figure 1 (bottom) shows PPE ion moment data, including the density, the velocity, the flow azimuthal angle, and the temperature. The magnetopause crossing occurs around 0410 UT. The spacecraft was located at 1148 LT and 21°N latitude (solar ecliptic) with a radial distance of 11.6 R_E at the magnetopause. This magnetopause crossing is distinguished by a strong accelerated flow at the magnetopause and a large flux transfer event in the magnetosheath. The properties of this crossing have already been documented in the literature as evidence for magnetic reconstruction at the magnetopause [Sousens et al., 1981; Scarry et al., 1994]. The structure of the magnetopause was found to agree with that of a rotational discontinuity. The ion distribution function within the accelerated flow was found to consist of a warm dense magnetosheath component which had been accelerated up from the adjacent magnetosheath flow, as well as a hotter magnetospheric component. The accelerated flow velocity was found to be in approximate agreement with the prediction of the reconstruction model.

There are a number of PTEs occurring on both sides of the magnetopause with the most dramatic one being in the magnetosheath around 0432 UT. This large flux transfer event has been studied previously but none provided detailed high-resolution magnetic field and plasma distribution functions [Paschmann et al., 1982; Berchem and Russell, 1984; Le et al., 1993; Scarry et al., 1994]. It has a plasma signature associated with the magnetic field signature and in general fits a type B magnetosheath PTE as given by Elphic (1995) taxonomic classifications. It is evident in Figure 1 (top) that the characteristic PTE bipolar signature occurs from ~0428 UT to 0434 UT (the shaded interval). However, the ion moment data in Figure 1 (bottom) do not show a distinct change from adjacent magnetosheath values until ~0430.30 UT, ~2 min after the start time in the field signature. The plasma signature ends at ~0432:40, about ~1 min before the end of bipolar magnetic field signature. This observation is confirmed by examining plasma distribution functions within the PTE and comparing with those in the magnetosheath and magnetosphere. Figure 2 shows 3 s snapshots of plasma velocity distribution functions obtained within the magnetosphere (0405:28-0405:31 UT) (Figure 2a), the magnetosheath (0424:04-0424:07 UT) (Figure 2b), and the PTE (0429:04-0429:07 and 0432:16-0432:19 UT) (Figures 2c and 2d), with these times indicated by arrows in Figure 1. The distribution functions are shown as contours of constant phase-space density separated logarithmically. Numbers on the slashed circles show the velocity in kilometers per second. The arrows show the elliptic projection of the magnetic field. The plasma in the magnetosphere and magnetosheath have very distinct velocity distributions, as

![Figure 1. ISEE 2 magnetic field data (4 s resolution) in boundary normal coordinates and PPE plasma moment data (12 s resolution) around the outbound magnetopause crossing on September 11, 1979.](image-url)
Figure 2: Four 3 s snapshots of plasma velocity distribution functions taken at times corresponding to arrows in Figure 1. (a) the magnetosphere, (b) the magnetosheath, and (c) and (d) the magnetosheath flux transfer event (shaded interval in Figure 1). The arrows show the ambient projection of the magnetic field.

shown in Figures 2a and 2b. The snapshots in Figure 2c are taken within the FTE before the plasma moment data show any change. At this moment both the ion and electron distribution functions are nearly identical to those in the magnetosphere shown in Figure 2b. We do not see any trace of hot magnetospheric plasma in the distribution functions, indicating that the magnetosheath field is not connected to the magnetosphere in this region of the FTE. However, the distribution functions in Figure 2d, taken in the latter stage of the FTE, clearly show a mixture of warm magnetosheath and hot magnetospheric components, although both components in electron distribution are individually present at lower densities than either the magnetosheath or the magnetosphere proper. The warm magnetosheath component is somewhat broad relative to the magnetospheric component since the spacing of contour levels becomes wider. The existence of hot magnetospheric plasma indicates that the magnetic field in this region of FTE is connected to the magnetosphere and so allowing the hot magnetospheric plasma to flow outward along the field lines. Thus, on the basis of the observations above, we can identify two regions within this magnetosheath-FTE: a larger region with field lines unconnected to the magnetosphere and a smaller connected core region with connected magnetic field lines. In the region where the magnetic field is not connected to the magnetosphere, the magnetic field exhibits a draping signature, i.e., a perturbation in the magnetic field normal component which is opposite in sign on either side of the connected core region, although the plasma shows little change from the magnetosheath plasma. This observation is consistent with most FTE models, i.e., magnetic field lines draping around a moving reconnect flux tube. Within the core region of the reconnect flux tube, the plasma consists of a mixture of magnetosheath and magnetospheric populations. This feature is shown consistently throughout the core region.

The low-resolution data in Figure 1 do not reveal clearly the magnetic structure near the boundary of the two regions within the FTE. In Figure 3, we show high-resolution magnetic field data along with FTE ion moment data for the time interval 0428-0436 UT. The format is the same as Figure 1 except that the temporal resolution of the magnetic field data is 34 s. The dots in Figure 3 (bottom) mark the center of 3 s FTE distribution function snapshots, which are available every 12 s. The two solid lines enclose the entire region identified as the FTE based on the perturbation of magnetic field normal component. The two dashed lines enclose the central core region identified as the reconnect flux tube based on the FTE plasma data. The region outside the core and between the solid and dashed lines is the identified field-draping region. The high-resolution magnetic field data reveal distinct magnetic boundaries at the interfaces between the draping (unconnected) and the core (connected) regions. As expected, these magnetic boundaries coincide with the plasma boundaries. In this example, the boundaries are visible in all three magnetic field components,
however, the transition is sharper at the trailing edge of the core region. Within the identified draping region, the magnitude of both the total field and the perturbations of the normal component increases as the spacecraft gets closer to the central core. The perturbation in the normal component is bipolar, i.e., opposite in sign on the leading and trailing sides of the draping region. The draping region is wider on the leading side than on the trailing side. Such asymmetry was reported in an example of a magnetospheric FTE by Hubert et al. [1992], in which the leading draping region was thinner than the trailing draping region. Within the central core of the reconnecting flux tube, the magnetic signature exhibits considerable variation. In this example, the field magnitude maximizes within the central core. The magnetic field parallel to the magnetopause boundary is unipolar, and the normal component is strongly bipolar. It shows that the magnetic field within the reconnecting flux tube is twisted. Such a feature has been reported previously by Paschmann et al. [1982] and Saunders et al. [1984].

The plasma distribution functions in both the draping region and the central core are very consistent and steady throughout each region. We have examined the change of plasma distribution functions at the boundaries of the central core or reconnecting flux tube within the FTE. In Figure 3, the arrows labeled a, b, and c near the leading edge and d and e near the trailing edge indicate times for consecutive snapshots of plasma distribution functions upon entry of ISEE 2 into and exit from the core region, respectively. The 3 s snapshots of 2-D ion and electron distribution functions for these times are shown in Figure 4. The distribution functions in Figure 4a are taken inside the leading draping region but near its inner edge, both the ion and electron distribution functions are similar to those observed in other parts of draping region (Figure 2c) and in the magnetosphere (Figure 2b). The distribution functions in Figure 4c are taken near the outer edge of the reconnecting flux tube. At this time, a hot magnetospheric population is clearly present, similar to those taken near the center of the reconnecting flux tube (Figure 3d). The distribution functions in Figure 4b are taken at the boundary. The magnetic boundary crossing overlaps partially with the second half of 3 s time span in Figure 4b. The distribution functions are intermediate between those found on either side of the boundary. The magnetic field boundary at the trailing edge occurs near the end of the 3 s time span in Figure 4d. The distribution functions in Figure 4d are similar to those taken in the core region, showing a mixture of magnetospheric and magnetospheric populations,
although they also are somewhat time alised because of the proximity of the boundary. The distribution functions in Figure 4
take inside the tailing draping region but near in inner edge. They are the same as those in the magnetosheath.

2.2. Plasma within the December 16, 1979 Magnetospheric FTB

Figure 5 shows the magnetic field data and the FPE ion moment data around the ISEE outbound magnetopause crossing on
December 16, 1979. The data resolution and the display format are the same as in Figure 1. The magnetopause crossing occurs around
03:03 UT. The spacecraft was located near the dawn flank 0652 LT and 127 latitude (solar ecliptic) with a radial distance of 17.6 R_E at
the magnetopause. The ion velocity data in Figure 5 (bottom) show accelerated flow at the magnetopause, indicating the occurrence of
magnetic reconnection at the magnetopause. We can identify three FTBs in the magnetosphere and one FTE in the magnetosheath, and
all of them have distinct plasma signatures embedded in the bipolar magnetic signature, as shown in the example in shaded oval
(centered at 0243:30) in Figure 5. Thus both the field-draping region and the core region, or reconnected flux tube, can be identified
from these data. To illustrate plasma features within the two distinct regions, we present high-resolution magnetic field data and
plasma distribution functions for the magnetospheric FTB centered at 0243:30 UT.

Figure 6 shows high-resolution (114 s) magnetic field data and plasma moment data from 0244 to 0244 UT. The dots indicate the
center of 35 snapshots of FTE plasma distribution function measurements (available every 11 s). The region between the two
solid lines is the FTB identified from the magnetic signature. Within the FTE is embedded a subregion with enhanced ion density and
lower ion temperature. A magnetic field boundary can be identified in the high-resolution data, as denoted by dashed lines, which appear
to coincide with the boundary of the distinct plasma signatures. Figure 7 shows several snapshots of ion and electron distribution functions within the FTE at the times indicated by arrows in Figure 6. The distribution functions in Figures 7a and 7d are taken in the field-draping region and show that plasma in this region is purely hot magnetospheric plasma with no trace of
magnetosheath plasma. The distribution functions in Figures 7b and 7c are taken near the edge and well into the central core region,
respectively. Both show the existence of transmitted magnetosheath plasma in addition to the magnetospheric plasma. (The lack of
correlations at the lowest energies in proton distribution functions is an instrumental effect because the counts are below the instrumental
threshold). Meanwhile a strong depletion of magnetospheric plasma, especially the electrons, is very evident in these data. These observations support the idea that the field lines in the central core region are open to the magnetosheath, thus allowing the escape of hot magnetospheric plasma and the entry of
magnetosheath plasma into the FTE. In this example, we do not see significant difference between the distribution functions taken near
the edge and deep into the central core region (Figures 7b and 7c). However, Thomsen et al. [1987] found that the depletion of both
hot magnetospheric ions and electrons was more pronounced near the central than near the edge of FTE, suggesting that the field lines
depth within the FTE have been reconnected for the longest time.

2.3 Plasma Boundary within the October 1, 1978 Magnetospheric FTE

During the time interval around the magnetopause crossing on October 1, 1978, both the magnetic field data and the FPE plasma
data are available at high data rate, 4 times higher than those in the
Figure 5. ISEE 2 magnetic field data (4 s resolution) in boundary normal coordinates and PFE plasma moment data (12 s resolution) around the outbound magnetopause crossing on December 16, 1979.

Figure 6. High-resolution magnetic field data (1 s resolution) and plasma moment data for the magnetospheric flux transfer event on December 16, 1979. The dots mark the center of 3 x PFE distribution function snapshots, which are available every 12 s. The two solid lines enclose the whole region identified PFE, and the two dashed lines enclose its central core region.
previously examples in 2.1 and 2.2. This enables us to examine the FTE internal structure in even greater detail. Figure 8 shows magnetic field data (averaged to 4 s resolution) and FPE ion moment data (3 s resolution) around the X point outbound magnetoopause crossing from 2330 UT, October 1 to 0010 UT on October 2. The data display format in Figure 8 is the same as in Figure 1. The magnetoopause crossing occurred around 2330 UT on October 1. The spacecraft was located near the subsolar region at 1016 UT and 237N latitude (solar ecliptic) with a radial distance of 11.1 Xp, the magnetopause. The ion velocity data in Figure 8 show a strong accelerated flow with speed well above the magnetosheath value at the magnetopause, indicating the occurrence of magnetic reconnection at the magnetopause. We can identify several FTEs in the magnetosphere that have distinct plasma signatures occurring within the magnetic bipolar signatures. In Figure 9, we show the high-resolution magnetic field data (1/16 s) and plasma moment data (3 s) for the FTE centered near 2342-40 UT on October 1 (stabilized interval in Figure 8). The ripples indicate the center of 3 s snapshots of FTE plasma distribution function measurements (available every 3 s). The region between the two solid lines are the FTE identified from the magnetic bipolar signature. Within the FTE, distinct magnetic field boundaries can be identified in the high-resolution data, as denoted by dashed lines. Thus again, both the field-draping region and the core region, or reconnected flux tube, can be identified from these data. Figure 10 shows two snapshots of ion and electron distribution functions taken well into the field-draping region (2342-01-2342-04 UT) (Figure 10A) and the central core region (2342-40-2342-43 UT) (Figure 10B). In Figure 10A, the region in which the magnetic field exhibits a draped geometry, the distribution functions are basically identical to the magnetosheath case. However, in the central core region of the FTE (Figure 10B), transmitted magnetosheath plasma is detected. Similar to the magnetosheath FTE on December 16, 1979, presented in Section 2.2, a strong depletion of hot magnetosheath plasma is detected throughout the central core region, indicating an open magnetic field configuration.

By examining continuous plasma measurements across the boundary between the two distinct regions within the FTE, we have found additional evidence that supports the reconnecteFTE Lorentz force effects on recently reconnecteFTE, which cause separate electron and ion flows. As the boundary of the FTE-central core region, similar to what has been observed at the magnetopause during accelerated flow events (Gosling et al., 1990a). Since the merging of most FTEs is near the equator (Daly et al., 1984) and the spacecraft is located north of the equator during the time interval studied, the FTEs in Figure 8 should be reconnecteFTE flux tubes moving northward from the equator, that is also consistent with the polarity of the bipolar magnetic normal component observed in this example. Thus, most recently reconnecteFTE, within the central core region should be found at the trailing boundary (Southwood et al., 1988). Figure 11 shows eight consecutive 3 s snapshots of distribution functions across the trailing boundary of the central core region for the FTE in Figure 9. The center times for
Figure 8. ISEE 2 magnetic field data (3 s resolution) boundary normal projections and PFE plasma moment data (5 s resolution) around the outbound magnetopause crossing on October 1, 1978.

Figure 9. High resolution magnetic field data (3/16 s) and plasma moment data (3 s) for the magnetopause flux tube event on October 1, 1978. The arrow on the right of Figure 9 shows the relative location of the magnetopause crossing on the right of Figure 8. The two solid lines are the outer boundary identified from the magnetopause crossing on the right of Figure 8.
Figure 18. Two 3-s snapshots of 2-D ion and electron distribution functions taken at times corresponding to arrows A (in the field-draping region) and B (in the central core) within the magnetospheric flux transfer event in Figure 9. The arrows show the ecliptic projection of the magnetic field. Each 3-s time interval are denoted by arrows a-b in Figure 9. As the spacecraft crosses the trailing boundary, both the ion and electron distribution functions change characteristics from those inside the central core region (similar to Figure 10B for reconnected open field lines) to those in the field-draping region (similar to Figure 10A for closed magnetospheric field lines). However, a short transition region is revealed in the high-resolution distribution function data. In the snapshot in Figure 11a, taken near but inside the boundary of the core region, both ion and electron distribution functions show a mixture of transmitted magnetospheric plasma and hot magnetospheric plasma. The strong depletion of the magnetospheric plasma indicates that the spacecraft is on an open magnetic field lines. The change of plasma characteristics start with the next snapshot in Figure 11b, coinciding with the trailing boundary identified in the magnetic field data. The ion distribution function is mainly magnetospheric; there is only a trace of magnetospheric ions occurring in a small phase range of the instrument azimuthal angle. This feature is seen in four successive snapshots of ion distribution functions (from Figures 11b to 11e, totaling ~12 s). Starting with Figure 11f, the ions appear to be completely magnetospheric in origin. Despite the near absence of transmitted magnetospheric ions, the magnetospheric electrons continue to be present from Figures 11b to 11g (totaling ~18 s). The magnetospheric electrons in Figures 11b to 11g do not show any significant difference in density from those in Figure 11a. This is more evident in Figure 12 when we compare the cuts through the electron distribution functions along the magnetic field for Figures 11a and 11b. Thus the transmitted electrons are found earthward from the transmitted ions. In this transition region, the magnetic field lines appear to be newly reconnected since there is very little loss of hot magnetospheric plasma evident in either the ion or the electron data. At the time shown in Figure 11b, the transmitted warm magnetospheric electrons are seen and cold electrons at low energies are mostly photoelectrons. Thus, starting with Figure 11b, both the electrons and the ion distribution functions become consistent with magnetospheric, indicating that the field lines are closed and the spacecraft is in the field-draping region. Despite the high-rate data for this example, the separation of electron and ion edges are seen only at the trailing boundary where the field lines are recently reconnected. They are not apparent in the plasma data near the leading boundary of the central core, probably because the field lines there were reconnected some time in the past. Thus the boundaries identified in the magnetic field data (two dashed lines in Figure 9) bracket the region of a well-defined reconnected flux tube with field lines that can have been open for a longer time than those at the trailing edge. Finally, we note that this short transition region may not be resolved when plasma data are available only at the lower data rate of every 12 s.

3. Discussion

In section 2 we presented observations of plasma velocity distribution functions within three flux transfer events selected from the subset of events that exhibit plasma mixing signatures. Our hypothesis is that the plasma mixing signatures arise when the spacecraft passes through the actual reconnected flux tube. We associate the absence of a mixing signature with field line draping around the reconnect flux tube. Using high-resolution data in our observations, we were able to confirm this hypothesis by identifying the two distinct regions (a central core and a field-draping region) and their interfaces in both the magnetic field and the plasma data. The plasma observations within the central core region indicate that the magnetic field lines within the central core region are open, allowing the inflow of warm magnetospheric plasma and outflow of hot magnetospheric plasma through the open flux tube. These signatures are unique to the reconnection in the interplanetary magnetic field and the Earth’s magnetic field. Thus our observations are consistent with the reconnected open flux tube interpretation for FTEs, although it is still not well established how the reconnection is generated for FTEs.

Much evidence for quasi steady state reconnection at the magnetopause has been reported, where the interplanetary magnetic field and plasma data have become available [Paschmann et al., 1979, 1985, 1986; Sonnerup et al., 1981; Gosling et al., 1982, 1986, 1990a,b, 1991]. The primary evidence is the observation of accelerated flow with velocities predicted by the reconnection model and boundary layers populated by plasma from both the magnetosphere and magnetosheath. If FTEs are a transient reconnection phenomenon, the plasma inside the reconnect flux tube will exhibit similar reconnection-related properties. Not all FTEs are associated with accelerated flow. Paschmann et al. [1982] found that only the FTEs close to the magnetopause show plasma flow speed enhancement, and those enhanced flow velocities are restricted to the trailing portion of the events (all the FTEs in Paschmann et al.’s study were northward moving FTEs observed in the northern hemisphere). It is possible that the observed accelerated flow is associated with ongoing reconnection near the subsolar region or newly reconnected field lines. Our observations inside the FTE core central are very similar to those in the accelerated flow at the magnetopause [e.g., Gosling et al., 1990a,b; Swartz et al., 1994] in the sense that in both cases the magnetic field
Figure 11. Eight consecutive 3 s snapshots of 2-D ion and electron distribution functions taken near the trailing boundary of the central core within the magnetospheric flux transfer event in Figure 9. The arrows show the ecliptic projection of the magnetic field. The times for each snapshot correspond to arrows a-h in Figure 9.
lines appear to be open and plasma consists of a mixture of magnetostatic and magnetospheric components. Furthermore, our observations at the trailing edge of a northward moving flux tube reveal a transition region where a mixture of magnetostatic and magnetospheric electrons are present but the ions are mainly magnetospheric. We attribute this transition region to be associated with time-of-flight effects that cause separate electron and ion edges on newly reconnected field lines, first reported during accelerated flow events by Gosling et al. (1990a).

The high-resolution magnetic field data show that the magnetic field signature are not continuous throughout the PTE; rather they reveal clearly the magnetic field boundary at the edge of core. Outside the central core region, the magnetic field consistently shows a draping signature, i.e., the strength of both the normal component and the total field increase as the spacecraft gets closer to the reconnected flux tube and the normal component has opposite signs in the leading and trailing draping region. The plasma distribution functions in the draping region are essentially the same as those found in the neighboring magnetostatic or magnetospheric region.

Inside the central core region, the magnetic field signature is often complicated. If the flux tube were tangent to the magnetopause surface, the magnetic normal components within the core would be zero. However, some PTEs exhibit much stronger bipolar signatures in the central core than in the field-draping region (e.g., Figures 3 and 9), indicating that the magnetic field in some PTEs is twisted (Punchmos et al., 1982; Saunders et al., 1984). Some PTEs do not have well defined Bz signatures (e.g., Figure 6). The magnetic field strength inside the central core is also variable, as evident in Figures 3, 6, and 9. The variability of magnetic field signatures within the central core region may be partially related to different spacecraft trajectories relative to the reconnected flux tube.

4. Conclusions

In this study, we examined high-resolution magnetic field and plasma distribution function data observed through flux transfer events observed near the dayside magnetopause. From these data, we have identified two distinct regions within PTEs observed both in the magnetosheath side and magnetospheric side: a central core and a field-draping region with clear boundaries at the interfaces. In the field-draping region, the plasma distribution functions show little difference from those in the neighboring magnetosheath or magnetosphere, and the magnetic field consistently exhibit signatures expected from field lines draping around a flux tube. Within the central core region, we confirmed previous observations that plasma appears to be a mixture of the magnetosheath and magnetospheric components (Thomas et al., 1987). In PTEs observed in the magnetosphere, we find transmitted magnetosheath plasma and a strong depletion of hot magnetospheric plasma. In PTEs observed in the magnetosheath, we find an outflow of magnetospheric plasma to mix with the magnetosheath plasma. These signatures are unique to the reconnection between the interplanetary magnetic field and the Earth’s magnetic field, and our observations indicate that the magnetic field lines within the central core region are open allowing the inflow of warm magnetosheath plasma and outflow of hot magnetospheric plasma through the open flux tube. The reconnection picture is further supported by the observation of separate electron and ion edges at the trailing boundary of a northward moving flux tube, expected as time-of-flight effects on newly reconnected field lines. Thus our observations are consistent with the reconnected open flux tube interpretation for PTEs.

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