Initial results of high-latitude magnetopause and low-latitude flank flux transfer events from 3 years of Cluster observations

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[1] We present initial results from a statistical study of Cluster multispacecraft flux transfer event (FTE) observations at the high-latitude magnetopause and low-latitude flanks from February 2001 to June 2003. Cluster FTEs are observed at both the high-latitude magnetopause and low-latitude flanks for both southward and northward IMF. Among the 1222 FTEs, 36%, 30%, 20%, 14%, and 30% are seen by one, two, three, and four Cluster satellites, respectively. There are 73% (27%) of the FTEs observed inside (outside) the magnetopause, which might be caused by the motion of FTEs toward the magnetosheath when they propagate from subauroral magnetopause to the midlatitudinal and high-latitude magnetopause and low-latitude flanks. We obtain an average FTE separation time of 7.09 min, which is at the lower end of the previous results. The mean B0 peak-peak magnitude of Cluster FTEs is significantly larger than that from low-latitude FTE studies. FTE B0 peak-peak magnitude clearly increases with increasing absolute magnetic latitude (MLAT), it has a weaker dependence on magnetic local time (MLT) with a peak near the magnetic local noon, and it has a complex dependence on Earth dipole tilt with a peak at around zero FTE periodic behavior is found to be controlled by MLT with a general increase of FTE separation time with increasing MLT, and by Earth dipole tilt, with a peak FTE separation time at around zero Earth dipole tilt. There is no clear dependence of FTE separation time on MLAT. There is a weak increase of FTE B0 peak-peak magnitude with increasing FTE separation time, and we see no clear dependence of it on FTE B0 peak-peak time. When no FTE identification thresholds are used, more accurate calculations of some FTE statistical parameters, including the mean B0 peak-peak time, can be obtained. Further, comparing results with different thresholds can help obtain useful information about FTEs.


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1. Introduction

[1] Flux transfer events (FTEs) are believed to be the results of temporally and spatially varying, i.e., patchy and impulsive, magnetic reconnection at the magnetopause. It has been shown from observations that FTEs contain a

mixture of magnetospheric and magnetosheath plasmas [e.g., Daly et al., 1981; Paschmann et al., 1982; Sattelkos et al., 1990; Le et al., 1993]. Thus they are important for the coupling of mass, momentum, and energy between the solar wind and the Earth's magnetosphere. Since the discovery of FTEs [Russell and Elphic, 1978, 1979; Haerendel et al., 1978], their statistical properties have been widely studied [e.g., Paschmann et al., 1982; Berchem and Russell, 1984; Rijnbeek et al., 1984, 1986; Southwood et al., 1986; Elphic, 1980; Paschmann et al., 1991; Paschmann et al., 1995; Kawano and Russell, 1996, 1997; Sanzo et al., 1996, 1998]. In addition to the original flux rope model proposed by Rijnbeek and Elphic [1987], several other FTE models have been proposed to explain the FTE formation based on large-scale FTE statistical results [e.g., Lee and Pu, 1985; Scholer, 1988; Silbeck, 1990; Liu et al., 1992].

[1] FTE separation time and B0 peak-peak magnitude provide important information about the generation mechanism and dynamics of FTEs. Rijnbeek et al. [1984] studied ISEE observations and found a mean FTE separation time of 7.8 min. Lockwood and Wild [1993] also studied ISEE

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observations and found a mean time interval between two FTEs of 8 min. Kuo et al. [1995] determined 10.5 min (median: 8 min) FTE separation time from their ISEE 1 FTE study. Neudeck et al. [2000] found from their Equator-5 FTE observations an average FTE separation time of 8.8 min, assuming intervals longer than 20 min are not part of the same reconnection sequence. Kawano and Russell [1986] developed an automatic algorithm to detect 400 magnetopause crossings and surveyed 9 years of ISEE 1 observations. They found a median $B_\parallel$ peak-park magnitude of $14 \text{ nT}$ and a median $B_\perp$ peak-park duration of 36 s. They believed that these values are upper estimates because the automatic algorithm used in their study rejects events with small $B_\parallel$ peak-park magnitude and duration. In contrast, Sonnery et al. [1996] obtained a median $B_\parallel$ peak-park duration time of 3 min, much larger than Kawano and Russell's [1986] result.

[1] FTE structures inside and outside of the magnetopause have been found to be the same physical phenomenon [Rijnbeek et al., 1984; Kuo et al., 1995]. Neudeck et al. [2000] found that 75% of their 87 midlatitude FTEs are in the magnetobelt, while the rest are in the magnetospheric or on the magnetopause. In contrast, Rijnbeek et al. [1984], Borochov and Russell [1984], and Kawano and Russell [1996] from their low-latitude ISEE 1 and 2 observations found FTE signatures with nearly equal frequency inside and outside of the magnetopause.

[2] Russell et al. [1997] studied flux transfer events that occurred at times of steady IMF and found that FTE quasi-periodic behavior is controlled by the magnetopause or the magnetosphere and is not driven by the external boundary conditions. However, few dedicated studies so far have been conducted to investigate the relation between FTE periodic behavior and magnetopause/magnetosphere properties. Although these previous FTE statistical studies have provided considerable information about FTEs, most of them concentrated on low-latitude and midlatitude magnetopause observations and ground observations. There has been a scarcity of studies on the detailed magnetic properties of high-latitude FTEs, possibly due to the complication of the vicinity of the cusp. Cluster observations provide a great opportunity to advance the understanding of FTEs in this region, not only because Cluster has a trajectory which encounters the high-latitude region, but also because the Cluster spacecraft are four spacecraft allowing detailed study of FTE structure and motion. Cluster FTE-related event studies have already been conducted by some authors [e.g., Hild et al., 2001; Zhou et al., 2001; Boogaard et al., 2001; Zhang et al., 2003; Vourlidas et al., 2003; Sonnery-Cottet et al., 2004; Thompson et al., 2004]. It is important to extend our knowledge of Cluster data to the Earth's magnetopause because there is a lack of information on magnetic properties of high-latitude FTEs in this region. Herein we refer to as Wang et al., submitted manuscript, 2005) reported Cluster FTE dependence on geophysical parameters, such as IMF and Earth dipole tilt.

Cluster FTEs were observed from dawn to dusk from -9 to -17 MLT. Also, they found that FTE occurrence is reduced when the dipole tilt is close to zero. Also, when dipole tilt is positive (negative), Cluster observes more FTEs in the southern (northern) hemisphere. This Cluster FTE Earth dipole tilt dependence is consistent with the Cluster global simulation results by Runov [2005].

[1] The purpose of this paper is to extend the study by Wang et al. [submitted manuscript, 2005] and make use of the large Cluster FTE data set to have a detailed study of some important properties of Cluster high-latitudinal magnetopause and low-latitudinal flank FTEs. In the paper we first have a detailed discussion of the stretched Shue et al. [1998] magnetopause model for Cluster magnetic field LMIN coordinate transformation. Then, we prove a brief introduction and the instrumentation and data used in this study, including our criteria for FTE identification. In section 4 we show the results of this FTE statistical study. Finally, we discuss and summarize our findings.

2. Stretched Shue et al. [1998] Magnetopause Model

[1] FTE signatures have proven to show best in the LMIN boundary coordinate system [Russell and Elphic, 1978]. In this system the magnetic field can be decomposed as $B_\parallel$ along the outward normal to the magnetopause, $B_\perp$ along the projection of the Earth dipole axis onto the magnetopause (positive northward), and $B_\perp$ directed downward. A convenient way to construct an LMIN coordinate system is through a magnetopause model. The empirical magnetopause model of Shue et al. [1998] has been shown to be one of the magnetopause models with smallest errors [Sidorova et al., 1999]. In this model, an analytical form of the magnetopause location is used to best fit magnetopause location observations:

$$r_0 = n_0 r_0 \left( 1 + \cos \theta \right)^{-\alpha},$$

$$r_0 = (10.22 + 1.29 \tan \theta \cdot \sin \phi) \left( 1 + 8.14 \right)^{-0.06},$$

$$\alpha = (0.54 - 0.007 \theta) \left( 1 + 0.24 \right) [\text{F}_0].$$

Here, $B_\parallel$ is the IMF z component in nT in GSM coordinates, $P_{min}$ is the solar wind dynamic pressure in nPa, and $\theta$ is the angle between the Earth-Sun line and magnetopause location vector $r$.

In practice, the spacecraft magnetopause crossing location, $(r', \theta')$, is very likely to be away from the model magnetopause surface. Such an inconsistency may lead to errors in the LMIN transformation. To solve this problem, we stretch the Shue et al. [1998] magnetopause model radially, with the same ratio for each Cluster magnetopause crossing, to fit each spacecraft crossing location. This leads to:

$$r' = r \left( 1 + \cos \phi \right)^{-\alpha}(1 + \cos \theta \phi),$$

$$\phi = \frac{\pi}{2} \left( 1 + \cos \theta \phi \right)^{-\alpha}(1 + \cos \theta \phi).$$

In this study we use this method for each magnetopause crossing to perform the LMIN transformation.

3. Instrumentation and Data

[1] The Cluster mission was launched in 2000, and it consists of four identical satellites. Cluster's orbit has a 90° inclination with a perigee of 4 RE and an apogee of 19.6 RE. The plane of Cluster's orbit precesses clockwise looking down from the north, and it extends outside of the magnetopause from the near end of one year to the next.
around July of the next year, during which FTEs can be observed. In this study, we surveyed the first 3 years of Cluster FTE observations from February 2001 to June 2003. Cluster magnetic field observations from the Fluxgate Magnetometer (FGM) [Balogh et al., 1997] and plasma observations from the Cluster Ion Spectrometry (CIS) instrument [Roemer et al., 2001] were used to identify Cluster magnetopause crossings, and FGM observations were used for FTE identifications. We use ACE Solar Wind Electron Proton Alpha Monitor (SWEPAM) [McComas et al., 1998] and Magnetic Field Instrument (MFI) [Smith et al., 1998] observations for the stretched [Shue et al., 1998] magnetopause model calculations and IMF sorting of the FTEs. The time shift of the ACE observations for each FTE is visually determined by matching Cluster magnetosheath magnetic field clock angles and ACE Bz clock angles close to the Cluster magnetopause crossing related to this FTE.

[1] Previous studies have used numerous criteria to identify FTEs, most commonly adopted in a Bz bipolar signature and [B] enhancement [Russell and Birn, 1978]. Rijnbeek et al. [1984] used a much more refined version of the above pattern criteria which does not negate obvious [B] enhancement. Berchem and Russell [1984] used Bz bipolar signature and [B] enhancement, but they also included the tangential field increase and rotation toward a direction that lies neither along the magnetosheath nor along the magnetospheric field orientations. However, Paschmann et al. [1982] found from INSE 1 and 2 observations that the Bz and Bx components showed considerable variation from event to event. In addition, Kawan 1996] and Russell [1996] showed that there were only 933 out of their 1246 FTEs showing rotational polarity in the MN plane. In our present study we inspect Cluster magnetic field time-series data to isolate FTEs such that they clearly show Bz bipolar signature and [B] enhancement. We also require that an FTE clearly isolates itself from its surroundings, which avoids identifying FTEs in highly oscillating field structures. A sample Cluster FTE fitting such criteria was observed at ~0420 UT on 19 February 2001 at (5.8, 0.8, 10.2) R_E in GSM coordinates and its magnetic field observations are shown in Figure 1.

[2] Many quantitative FTE identification thresholds have also been used in previous studies, for example, minimum Bz peak magnitude and minimum FTE duration [e.g., Rijnbeek et al., 1984; Southwood et al., 1996; Kao et al., 1995; Kawan 1996]. During our visual identification of Cluster FTEs, we did not apply any such thresholds because some clear FTE signatures do not fall in the arbitrary thresholds used by some previous studies. Note here that there is still an actual lower limit of Bz peak-time peak of 4 s in this study because of the Cluster data sampling rate. Here, Bz peak-time peak time is defined as the time between Bz positive and negative peaks in each FTE. In this way, we can keep as many events with as large spatial and temporal scales as possible. Southwood et al. [1986] pointed out in their UK spacecraft FTE study that their use of an amplitude threshold criterion in event selection was solely for operational purposes, and it is entirely possible that there is a continuous graduation in scale of events. Also, they believed that the different criteria used in the FTE studies should not influence the results in a significant way. Wang et al. submitted manuscript, 2005] found from their Cluster FTE study that different FTE selection thresholds change some, but not all, statistical results in a significant way. They believed that the case that different thresholds caused big differences was the result of Cluster orbital bias. To obtain more profound understanding about the influence of FTE criteria on FTE statistical results, we make more investigations using the same criteria as used by Wang et al. [submitted manuscript, 2005]. Bz peak in T > 10 nT and Bz peak - creasing > 10 nT (Threshold 1), [Bz peak - creasing > 17 nT and Bz peak - decreasing > 17 nT (Threshold 2). For convenience, we define Threshold 0 as the case without thresholds.
without quantitative FTE identification thresholds (Threshold 0). The left panel of Figure 2 shows the percentages of the number of Cluster spacecraft seeing the same FTEs without thresholds. Because FTEs have limited sizes in space and Cluster satellites are separated from each other, sometimes only a few, but not all, Cluster satellites see the same FTEs. In 36%, 20%, 14%, and 10% of the 1222 FTEs, one, two, three, and four Cluster satellites see the same FTEs, respectively. If an FTE is seen by multiple Cluster satellites, we choose the FTE observations from the Cluster satellite with the best FTE signatures for the statistic later in the paper. Why some FTEs are observed by all the four satellites, while some are observed by only one, should be related to the relative distance of the four satellites, which is a topic of future research. The right panel of Figure 2 shows the percentages of the FTEs inside and outside of the magnetoopause for the case without thresholds. There are 73% (27%) of the FTEs observed outside (inside) the magnetoopause. Note here that the FTEs inside the magnetopause crossings are not necessarily in the magnetosheath. Instead, they may also be in the cusp region. Further study shows that the percentages of FTEs inside/outside of the magnetoopause do not change much for low-latitude and high-latitude FTEs: for low-latitude FTEs $|B_{z|FTE}| < 7.5 \text{ nT}$, 69% (11%) FTEs are observed outside (inside) the magnetopause; for high-latitude FTEs $|B_{z|FTE}| > 7.5 \text{ nT}$, 76% (24%) FTEs are observed outside (inside) the magnetopause.

Figure 3, from top to bottom, shows the locations of the FTEs without thresholds in the GSM xz, yz, and xz planes, respectively; from left to right, shows the FTEs during all, southward, and northward IMF orientations, respectively. Tsyganenko 1996 magnetic field model [Tsyganenko, 1996] and the cusp boundaries are shown as the basis ground in each panel for reference. From the figure, we see that many of the FTEs are observed at the high-latitude magnetopause near the cusp boundaries. However, there are also a considerable number of low-latitude FTEs near the magnetopause flanks. In the middle and right panels of Figure 3, FTEs are observed at both the high-latitude magnetopause and low-latitude flanks for both southward and northward IMF conditions.

Figure 4 shows the FTE separation time distribution, FTE $B_{z|FTE,max}$ distribution, FTE $t_{m|FTE,max}$ distribution, and FTE $B_{z|FTE,max}$ peak-peak magnitude distribution, all with no thresholds. Note here that each FTE separation time in the upper left panel is calculated between two contiguous FTEs without neglecting that they correspond to the same Cluster magnetopause crossing. From the figure, we see that all these distributions show more of a bell-shaped profile. The mean FTE separation time is 37.15 min (median: 12.12 min), the mean FTE $B_{z|FTE,max}$ is 13.13 nT (median: 11.67 nT), the mean $B_{z|FTE,max}$ peak-peak time is 28.89 s (median: 20.87 s), and the mean $B_{z|FTE,max}$ peak-peak magnitude is 25.36 nT (median: 22.09 nT).

Table 1 shows some FTE statistical parameters for Thresholds 0, 1, and 2. As pointed out by Wang et al. (submitted manuscript, 2005), with tighter thresholds, a larger proportion of FTEs are seen during southward IMF (57% for Threshold 0, 63% for Threshold 1, and 65% for Threshold 2). Although the proportion of northward IMF FTEs decreases with increasing threshold, the occurrence rate stays relatively high even for very tight threshold conditions. It is unlikely that such constraints result in the selection of phenomena other than FTEs. Therefore the large occurrence rate during northward IMF FTEs is realistic. Also seen in the table is that the mean $B_{z|FTE,max}$ peak-peak time has little dependence on thresholds, similar to the portion of the FTEs seen inside and outside of the magnetopause. Because of the increasing $B_{FTE,max}$ with $B_{z}|FTE,max|$ and $B_{z|FTE,max}$ with $B_{z}|FTE,max|$ as expected.

In Figure 5, from left to right, shows the FTE $B_{z|FTE,max}$ peak-peak magnitude dependence on MLT, MLAT, and Earth dipole tilt, all without quantitative FTE identification thresholds. The thick horizontal bars are the medians of FTE $B_{z|FTE,max}$ peak-peak magnitude for MLT with a peak near 0 MLT and the magnitude generally decreases further away from the magnetic noon local time. In contrast, FTE $B_{z|FTE,max}$ peak-peak magnitude...
magnitude shows a strong dependence on MLAT. The larger the absolute FTE magnitude, the larger the FTE tilt. The $B_n$ peak-peak magnitude dependence on Earth dipole tilt is more complex, with no major variation for negative Earth dipole tilt, a peak where Earth dipole tilt is close to zero, and decreasing $B_n$ peak-peak magnitude with increasing positive Earth dipole tilt.

Figure 6, from left to right, shows the FTE separation time dependence on MLT, MLAT, and Earth dipole tilt, all without thresholds. Only FTE separation times less than $20\text{ min}$ are used in this plot, assuming that intervals larger than $20\text{ min}$ are not part of the same reconnection sequence [Newell et al., 2000]. The MLT, MLAT, and Earth dipole tilt values for each FTE separation time are the averages of their corresponding values for the two FTEs concerned. The thick horizontal bars are the medians of FTE separation time for the MLT, MLAT, and Earth dipole tilt ranges that they span. The thin horizontal bars are the standard errors of the median values that they correspond. From the figure, we see a general increase of FTE separation time with increasing MLT. FTE separation time peaks at around zero Earth dipole tilt and it generally decreases with increasing absolute Earth dipole tilt. There is no clear dependence of FTE separation time on MLAT.

Figure 7 shows the $B_n$ peak-peak magnitude dependence on FTE separation time. The $B_n$ peak-peak magnitude for each FTE separation time is...
the average of the corresponding values of the two FTEs for the separation time. The right panel of the figure shows the FTE \( B_z \) peak-peak magnitude dependence on FTE \( B_z \) peak-peak time. In both panels, the thick horizontal bars are the medians of FTE \( B_z \) peak-peak magnitude in the horizontal range that they span, the thin horizontal bars are the standard errors of the median values that they correspond. In the figure, FTE \( B_z \) peak-peak magnitude generally increases with increasing FTE separation time. We see no strong dependence of \( B_z \) peak-peak magnitude on FTE \( B_z \) peak-peak time.

5. Discussion

As pointed out by Wang et al. (submitted manuscript, 2005), among the 1222 Cluster FTEs in this study without quantitative FTE identification thresholds, 57% correspond to southward IMF and 43% correspond to northward IMF.

### Table 1. Some FTE Statistical Parameters for Different Thresholds

<table>
<thead>
<tr>
<th>Threshold</th>
<th>( B_x &lt; 0 )</th>
<th>( B_x &gt; 0 )</th>
<th>( T_{peak_time} )</th>
<th>( [B_{peak_peak}] )</th>
<th>( [B_{peak_surrounding}] )</th>
<th>Mean</th>
<th>Mean</th>
<th>Mean</th>
<th>Mean</th>
<th>Inside</th>
<th>Outside</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>57%</td>
<td>43%</td>
<td>25.4 ( \pm ) 13.1 ( \pm )</td>
<td>8.9%</td>
<td>72%</td>
<td>28%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1°</td>
<td>61%</td>
<td>39%</td>
<td>26.4 ( \pm ) 19.5 ( \pm )</td>
<td>9.3%</td>
<td>74%</td>
<td>26%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2°</td>
<td>60%</td>
<td>40%</td>
<td>26.3 ( \pm ) 25.4 ( \pm )</td>
<td>11.3%</td>
<td>73%</td>
<td>27%</td>
<td></td>
<td></td>
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</tbody>
</table>

\( ^{a} \) No thresholds.

\( ^{b} \) \([B_{peak\_peak}] \geq 10 \text{ nT} \) and \([B_{peak\_surrounding}] \geq 10 \text{ nT} \).

\( ^{c} \) \([B_{peak\_peak}] \geq 17 \text{ nT} \) and \([B_{peak\_surrounding}] \geq 17 \text{ nT} \).
and such a large proportion of northward IMF FTEs is possibly caused by high-latitude reconnection [Wild et al., 2001; Vourlidas et al., 2003]. Supporting evidence for the above conclusion is shown in the right panels of Figure 3 where there is a significant number of high-latitude FTEs during northward IMF. Also in the right panels of the same figure there are a large number of low-latitude flank FTEs during northward IMF. Kawano and Russell [1997a] provided four possible explanations for similar cases during northward IMF in their ISEE FTE study: (1) a possible negative B8 component at the postterminator magnetopause causing local reconnection; (2) tilted equatorial reconnection at the postterminator magnetopause; (3) polar cap reconnection; and (4) random reconnection around the subsolar magnetopause (please refer to their paper for more detailed discussion). Kawano and Russell [1997b] further evaluated these possible explanations and found that explanations 2 and 3 were supported by ISEE FTE observations.

The FTE separation times from all our Cluster FTEs without quantitative identification thresholds have an average of 37.15 min (median: 12.12 min), which is significantly larger than the previous results. If we follow Neudreg et al.'s [2000] assumption to remove larger than 20 min intervals, an average FTE separation time of 7.09 min (median: 5.62 min) is obtained. These mean and median FTE separation times are at the lower end of the previous results. A possible explanation for our smaller FTE separation times is that there is an additional source of FTEs from high-latitude reconnection than the low-latitude observations. Kawano and Russell [1996] found from their ISEE
FTE study that the occurrence rate of FTEs tends to increase with decreasing distance from the magnetopause. Thus it is also possible that Cluster skims along the magnetopause much longer near the low-latitude magnetopause flanks than those low-latitude satellites used in previous FTE studies, thus allowing Cluster to see more subsequent FTEs, which leads to shorter FTE separation time. 

[2] We obtain a mean $B_0$ peak-peak magnitude of 25.36 nT (median: 22.09 nT) and an average FTE $B_0$ peak-peak time of 25.79 s (median: 20.07 s). Our median $B_0$ peak-peak time falls within 3 s obtained by Kawano and Russell [1996] and 3 min obtained by Sonney et al. [1996]. The low $B_0$ peak-peak duration identification criteria used in these two previous studies definitely contribute to their larger $B_0$ peak-peak duration. Our median $B_0$ peak-peak magnitude is significantly larger than that from Kawano and Russell [1996], which is surprising, especially since we did not use a lower threshold for $B_0$ peak-peak magnitude during FTE identification. Since Kawano and Russell’s [1996] ISEE database also includes low-latitude magnetopause flank FTEs, this large difference may imply that high-latitude FTEs have systematically larger magnitude than low-latitude FTEs. In support of this, the middle panel of Figure 5 shows that FTE $B_0$ peak-peak magnitude increases with increasing absolute MLAT. It is also indirectly supported by FTE $B_0$ peak-peak magnitude dependence on MLT in the left panel of the same figure. There is a weak $B_0$ peak-peak magnitude peak close to the magnetic local noon (MLT = 12) where FTEs are observed at the high-latitude magnetopause (see Figure 3). While FTE $B_0$ peak-peak magnitude is smaller farther away from the magnetic local noon at the magnetopause flanks where there are many low-latitude FTEs. This systematic trend of increased FTE $B_0$ peak-peak magnitude with increasing MLAT might be caused by the stronger shear fields draped over the FTEs when the FTEs propagate from low-latitude magnetopause to the high-latitude magnetopause.

[2] In Table 1, ~72% of the Cluster FTEs are observed outside of the magnetopause crossings for different thresholds, and this percentage does not change much for both low- and high-latitude FTEs. This is consistent with the midlatitude FTE study results of Newell et al. [2000]. The greater number of FTEs observed outside than inside of the magnetopause at the midlatitude and high-latitude magnetopause, as well as the low-latitude flanks, than the low-latitude subauroral magnetopause [Krimik et al., 1984; Berchem and Russell, 1984; Kawano and Russell, 1996] might imply that there is a significant motion of the FTEs, originated at the low-latitude dayside magnetopause, from inside the magnetopause to the magnetosheath when they propagate away from their origin. If this is true, such motion should be caused by the interaction between the FTEs and surrounding plasma and field in the complex magnetopause and magnetosheath environment. More studies, especially numerical studies, are needed to explain what processes cause such FTE evolution. On the other hand, it is also possible that FTEs generated on the magnetopause away from the low-latitude dayside magnetopause are more likely to extend more outside of the magnetopause than FTEs generated at low-latitude dayside magnetopause.

[2] Wang et al. (submitted manuscript, 2005) found from their Cluster FTE study that the normalized FTE MLAT dependence without thresholds has a peak near the magnetic equator and it decreases farther away from it. They believed that this result is likely caused by the orbital bias of Cluster because, for a given high-latitude magnetopause crossing at the magnetopause flank, Cluster spends a significant amount of time close to the low-latitude magnetopause which allows more chance to see FTEs. For the case with Threshold 2, a much more flattened normalized FTE MLAT dependence is obtained. They believed that it is likely the result of the strong
constraints which remove low latitude flank FTEs. Supporting evidence for the above assertion is shown in the middle panel of Figure 5 which shows that FTE B, peak peak magnitude increases with increasing absolute MLAT. Thus when we use thresholds with larger B[peak-peak] than lower thresholds, we are more likely to remove low latitude FTEs, which helps cancel the Cluster orbital bias for FTE MLAT dependence.  

[17] We show in Figure 6 that FTE separation time is dependent on MLT, MLAT, and Earth dipole tilt, also neglecting separation times larger than 20 min. From the figure, we see a slight increase in FTE separation time with increasing MLT. FTE separation time peaks at around zero Earth dipole tilt and it generally decreases with increasing absolute Earth dipole tilt. These results confirm Russell et al.'s [1997] conclusion that FTE generation rate can be controlled by some geophysical parameters. In contrast, there is no clear dependence of FTE separation time on MLAT. We leave the possibility of solar wind control of FTE generation and periodicity for a later study.

[18] Table 1 shows several key statistical parameters, including mean B, peak peak time, and the percentage of FTEs inside/outside of the magnetopause, only change slightly for different thresholds. This is consistent with the assertion by Southwood et al. [1986] that the results reported by Wang et al. [submitted manuscript, 2000] that different criteria used in the FTE studies should not influence the results in a significant way. On the other hand, by not using quantitative FTE identification thresholds, we can avoid numerical errors introduced by arbitrary thresholds during FTE identification, thus allowing more accurate calculations of some FTE statistical parameters, for example, FTE B, peak peak time. As shown in Figure 6, the peak peak time generally decreases with increasing B, peak peak magnitude. Statistical results with different thresholds can help obtain useful information about FTEs. For example, Table 1 shows that the separation time between northward IMF for different thresholds, by increasing the threshold, large proportion of FTEs are seen during southward IMF. This is directly confirmed by the mean B, peak peak magnitude for FTEs during southward IMF (0.04 nT) and northward IMF (0.24 nT). Also, the mean B, peak peak time in Table 1 changes very little for Thresholds 0, 1, and 2, from which we can infer that there should be no strong correlation between B, peak peak magnitude and B, peak peak time in Figure 7.

6. Summary

[19] Figure 5 shows large-scale Cluster high latitude magnetopause and low latitude flank FTE statistical study, we reach the following conclusions:

[20] Cluster FTEs are observed at both the high latitude magnetopause and low latitude flanks for both northward and southward IMF.

[21] Among the 1222 Cluster FTEs, 36%, 70%, 14%, and 30% are seen by one, two, three, and four Cluster satellites, respectively.

[22] There are 73% (27%) of the Cluster FTEs observed outside inside of the magnetopause, which is significantly different from the results from low latitude FTE studies. This might imply that there is a significant motion of the FTEs, originating at the low latitude dayside magnetopause, from inside the magnetopause to the magnetospheric when they propagate to the midlatitude and high-latitude magnetosphere.

[23] We obtain an average FTE separation time of 7.09 min, which is at lower end of the previous results. This might be caused by additional source of FTEs at the high-latitude magnetopause or the Cluster orbital effect of swimming along the magnetopause flanks.

[24] The mean B, peak peak magnitude of Cluster FTEs is significantly larger than that from low latitude FTE studies. Further, B, peak peak magnitude clearly increases with increasing absolute MLAT. This systematic trend might be caused by the stronger shear fields draped over the FTEs when the FTEs propagate from low-latitude magnetopause to the high-latitude magnetopause. There is a weaker dependence of FTE B, peak peak magnitude on MLAT with a peak near 12 MLT and the magnitude generally decreases farther away from the magnetic equator. The B, peak peak magnitude dependence on Earth dipole tilt is more complex with a peak at around zero Earth dipole tilt.

[25] FTE periodic behavior is found to be controlled by MLT, with a slight increase of FTE separation time for increasing MLT, and by Earth dipole tilt, with a peak FTE separation time at around zero Earth dipole tilt. There is no clear dependence of FTE separation time on MLAT.

[26] There is a weak increase of FTE B, peak peak with decreasing IMF, but no clear dependence of B, peak peak magnitude on FTE B, peak peak time.

[27] We further confirm that FTE statistical results do not change in a significant way by using different FTE criteria. When no thresholds are used, more accurate calculations of some FTE statistical parameters, including mean B, peak peak time, can be obtained. Further, comparing results with different thresholds can help obtain useful information about FTEs, e.g., southward IMF should correspond to FTEs with larger peak peak magnitude, and there should be no strong correlation between B, peak peak magnitude and B, peak peak time when we use thresholds.

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