The Difference Between Isolated Flux Transfer Events and Flux Transfer Event Cascades

A. Kullen¹, S. Thor¹, and T. Karlsson¹

¹Space and Plasma Physics, School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, Stockholm, Sweden

Abstract This flux transfer event (FTE) study is based on 984 FTEs originally identified by Wang et al. (2005, https://doi:10.1029/2005JA011150) in Cluster data. Due to Cluster’s orbit, the FTE list exclusively contains events detected at the high-latitude dayside magnetopause and low-latitude flanks. The focus of this study is on FTE separation time. The results show that FTEs appearing in cascades are mainly located at the northern dusk and southern dawn magnetopause, while isolated FTEs are equally spread over the region covered by Cluster. This difference may be explained by the different interplanetary magnetic field (IMF) conditions during which the subsets occur. For isolated FTEs, average IMF $B_y$ is close to zero. During such conditions, FTEs are expected to form at arbitrary longitudes along an equatorial merging line. After formation, they propagate northward and southward, causing an equal distribution at higher latitudes. In contrast, FTE cascades typically occur during weakly southward IMF with a negative $B_y$ component. Their asymmetric distribution at higher latitudes is consistent with both the component and the antiparallel merging model for nonzero $B_y$. In both scenarios, newly formed FTEs are expected to move to the northern dusk and southern dawn regions, as observed. Many FTE cascades appearing during northward IMF are located close to the low-latitude flanks, confirming previous reports. We discovered that such FTEs appear during large IMF values. Another new result is that 16% of all isolated FTEs appear during small IMF cone angles, suggesting that these may form as a result of magnetosheath jets impacting on the magnetopause.

1. Introduction

The most important mechanism to transfer energy and mass from the solar wind into the magnetosphere is magnetic reconnection. Often, reconnection appears in the form of localized, transient events, the so-called flux transfer events (FTEs). FTEs appear in the vicinity of the magnetopause, both on the magnetosheath and on the magnetospheric side (Farrugia et al., 1987). It is well known that the location of the reconnection region depends strongly on the direction of the interplanetary magnetic field (IMF). According to the antiparallel merging model (Crooker, 1979; Luhmann et al., 1984), this appears where magnetospheric and solar wind fields have a completely antiparallel direction. This means an (equatorial) merging line occurs only during pure southward IMF, while, for example, for south-dawnward IMF reconnection is expected to take place only at high-latitude dawn and dusk in the Northern (NH) and Southern (SH) Hemispheres, respectively. In the component merging model an antiparallel component of the B-field is considered as sufficient for reconnection to occur. For southward IMF cases that model suggests, a tilted X-line goes through the subsolar point, where the tilt relative to the equatorial plane depends on the ratio between (negative) IMF $B_y$ and IMF $B_z$ (e.g., Cowley & Owen, 1989; Gonzalez & Mozer, 1974; Sonnerup, 1970). Fuselier et al. (2002), showed with help of IMAGE observations that during southward IMF conditions, both reconnection scenarios occur at the magnetopause. Those observations led Trattner et al. (2007) to propose a reconnection model that is basically a combination of the antiparallel reconnection model and a modification of the component reconnection model. Their so-called maximum magnetic shear model assumes that in those Magnetic Local Time (MLT) ranges close to noon where no antiparallel reconnection occurs, reconnection is most likely to take place where the magnetic shear between the magnetosheath and the magnetospheric field is maximal. This results in a reconnection line that connects the high-latitude antiparallel reconnection regions. The reconnection line does not necessarily go through the subsolar point but is displaced toward the winter hemisphere. There exist both observational studies (e.g., Trenchi et al., 2008) and magnetohydrodynamic simulations (Holligkji et al., 2014) confirming such a dipole tilt-dependent shift of the reconnection line toward the winter hemisphere. Comparing the maximum magnetic shear model with reconnection signatures in Polar (Trattner et al., 2007), Time History of Events and Macroscale Interactions during Substorms (THEMIS...
(Trattner et al., 2012), and Magnetic Multiscale Mission (MMS) data (Trattner et al., 2017) showed an excellent agreement with observations for a large majority of cases. Deviations between model and observations occur though for specific IMF conditions. These include, according to Trattner et al. (2012), pure southward IMF and dominant IMF $B_\parallel$ cases (the model predicts in those cases only reconnection along bifurcated antiparallel reconnection regions, which could not be confirmed observationally) and equinox and midwinter cases with IMF clock angles around 140° and 240° (Trattner et al., 2017). As shown in Trattner et al. (2018), the equinox and midwinter deviations disappear when extending the antiparallel reconnection regions to include all field lines that contain antiparallel reconnection somewhere along the field lines. The model deviation from observations for pure southward and dominant $B_\parallel$ with observations still needs to be resolved.

For northward IMF, reconnection is expected to appear poleward of the cusps in the high-latitude lobes where open tail field lines reconnect with the IMF resulting in reoriented open field lines that are draped over the dayside magnetopause before moving tailward, while a new, strongly kinked IMF field line is created above the lobe (e.g., Dungey, 1963; Crooker & Rich, 1993; Maezawa, 1976).

The magnetic field structure of an FTE consists of a tube with a helical magnetic field and a local magnetic field maximum in its center (Haerendel et al., 1978), resulting in the known bipolar signature of the $B$-field normal toward the magnetopause. Russell and Elphic (1978, 1979) suggested that such a magnetic structure forms as a result of a localized reconnection burst, resulting in the reconnection of only a few flux tubes, forcing surrounding not-reconnected magnetic field to drape around these. Recently, reconnected field lines are strongly kinked; thus, both the southern and northern open field lines will be straightened out by the $j \times B$ force in poleward direction while being dragged by the solar wind around the dayside magnetopause and further in tailward direction. Also FTEs move in the same direction after having formed. They form in pairs, where one branch moves to higher northern latitude and the other moves to higher southern latitude, before propagating further tailward, as reported by, for example, Rijnbeek et al. (1984). The FTE motion of about 200 km/s is much faster than an Earth-orbiting satellite passing through the dayside magnetopause (Fear et al., 2007). Thus, the FTE will pass the satellite in poleward direction, which results in the bipolar structure of $B_N$ (magnetic field component perpendicular to the magnetopause) in the magnetic field measurements. This $B_N$ signature is easily detected in the satellite’s $B$-field measurement.

How FTEs form is still an open question. Instead of appearing as an elbow-shaped bundle of newly reconnected flux tubes, resulting from a local reconnection burst (Russell & Elphic, 1978, 1979), Lee and Fu (1985) proposed that FTEs may form between multiple X-lines during nonzero IMF $B_\parallel$ conditions. Simulation results by Raeder (2006) show that FTE-like structures form indeed between two X-lines as long as the Earth dipole tilt is strong. In their magnetohydrodynamic simulation for southward IMF and a large Earth dipole tilt, an X-line appears in the winter hemisphere close to the subsolar point and convects poleward and flankward where it becomes less active, while a second X-line appears at the original reconnection location. Between the two reconnection lines a magnetic loop forms, which resembles an FTE that moves poleward/flankward as well. Interestingly, for zero dipole tilt, only one equatorial X-line appears in their simulation, and no FTE forms. That multiple X-lines during large dipole tilts may lead to the formation of an FTE that was later on confirmed by observations (Hasegawa et al., 2010). Raeder’s (2006) results may also explain why FTEs often appear in cascades, as the sequentially activated X-lines in their simulation lead to repeated creation of new FTEs.

That FTEs often occur in sequences of up to 10 FTEs after each other with typical separation times of 8–10 min is known since a long time (e.g., Lockwood & Wild, 1993). Kuo et al. (1995), using ISEE1 and ISEE2 satellites which cross the dayside magnetopause mainly in the equatorial plane, reported of an average separation time of 8.6 min. The vast majority of those events appeared with separation times of 1 to 12 min (median 8 min), while hardly any FTEs with separation times over 25 min were observed in their data set. A more recent statistical FTE study by Wang et al. (2005), which is based on Cluster satellite passages through the high-latitude dayside and low-latitude flank magnetopause, observed much larger separation times of in average 37.15 min, with a vast spread of separation times of up to many tens of minutes. Still, about half of the events appeared for separation times between 1 and 12 min (median value 12.12 min). Note that Wang et al. (2005) themselves reported a much shorter average separation time of 7.09 min, arguing that FTE separation times of over 20 min would indicate a new sequence of FTEs, thus excluding the latter from the separation time analysis.
It is known since a long time that the direction and strength of the IMF influences FTE occurrence frequency as well as the FTE separation time. FTEs have been shown to appear mainly during southward IMF (Kuo et al., 1995). However FTEs at the magnetopause flanks (Fear et al., 2005; Kawano & Russell, 1997) and at high latitudes (Wang et al., 2005) also appear in significant numbers during northward IMF (Wang et al., 2005, reported 43% FTEs during northward IMF). Wang et al. (2006) showed for FTEs with separation times up to 20 min that the time distance between subsequent FTEs depends mainly on IMF $B_z$ and IMF magnitude. The separation times (between 0 and 20 min) increase for increasingly more northward IMF as well as with decreasing IMF magnitude.

The reason for the large spread of FTE separation times is to date unknown. Studying the FTE separation time may allow us to get a better idea of how FTEs are formed. It may also result in a better understanding of how and why certain types of dayside auroral arcs form and decay, which have been suggested to be the auroral signatures of FTEs. This concerns both poleward-moving auroral forms (Lockwood et al., 1989) and bending arcs (Carter et al., 2015). Poleward-moving auroral forms are transient dayside auroral features that form and move within 8–10 min into the polar cap (the typical recurrence rate of FTE cascades) before they fade (Sandholt & Farrugia, 2007). Bending arcs are faint, isolated polar cap arcs that split from the dayside oval and move into the polar cap within a few tens of minutes (Kullen et al., 2015), suggesting isolated FTEs as a possible source (Carter et al., 2015).

The scope of this study is to investigate FTE separation times in more detail to find out what possibly controls the temporal distance between individual FTEs. For this, the FTE data set of Wang et al. (2005) is reevaluated, taking into account also those FTEs with separation times of several tens of minutes and isolated events. Possible correlations between FTE separation time, FTE distribution along the magnetopause, and IMF direction are analyzed.

2. Instruments

This study is mainly based on data from the Cluster satellites. The Cluster satellites are four identical satellites launched by the European Space Agency in the year 2000 to monitor the near-Earth space environment (Escoubet et al., 2001). Scientific measurements are available from January 2001 onward. The present FTE study is based on events identified by Wang et al. (2005) in Cluster’s magnetic field data from the fluxgate magnetometer (Balogh et al., 2001) from February 2001 to June 2003. During the first 3 years of the mission, Cluster was in a 4 x 19.6 Re polar orbit with an orbital period of about 56 hr. The satellites were placed in a tetrahedron formation with a distance between the satellites that was altered approximately every 6 months. It varied during that time period from 100 (Jan–March 2002) to 6,000 km (June 2002 to March 2003). The orbital plane was fixed in inertial space, and so the plane of the orbit precessed through local time through the year such that Cluster has a nearly identical orbit at the same calendar day each year during 2001–2003. This is illustrated in Figure 1, which contains the satellite orbit of Cluster 1 during the first day of each month projected to the xy-plane in geocentric solar ecliptic system (GSE) coordinates. Cluster moves through the NH during the duskward part of the orbit and through the SH during the dawnward part of each orbit.

Figure 1 shows only orbits for those months with Cluster magnetopause crossings between February 2001 and June 2003. The straight, dashed, and dotted lines correspond to Cluster’s orbit in 2001, 2002, and 2003, respectively. As Figure 1 shows, Cluster crosses the magnetopause during approximately 8 months each year in 2001–2003, starting in November at the dusk flank and ending early July at the dawn flank. Due to Cluster’s polar orbit, the magnetopause is crossed twice each orbit at high latitudes (January-April) and low-latitude flanks (November–December at dusk and May–July at dawn). It takes the satellites at least 6 hr until they have passed through the dayside magnatosheath. FTEs appearing within 6 hr will therefore still belong to the same magnetopause crossing of the satellites (Taylor et al., 2010).
Solar wind data used for the analysis of FTEs were taken from the OMNI data set, which can be found at http://omniweb.gsfc.nasa.gov. This data set consists of measurements from the nearest solar wind monitor. The data are adjusted for an estimated propagation time to the Earth bow shock (King & Papitashvili, 2005). For this study, 1-min resolution of the solar wind data was used.

The figures in this study are partly shown in GSE and partly in geocentric solar magnetospheric system (GSM) coordinates. The GSE is a coordinate system that has its $x$-axis pointed toward the Sun, and its $y$-axis lies in the orbital plane, with the positive direction toward dusk. The $z$-axis is pointed toward the ecliptic pole with north as the positive direction. Similarly, in the GSM coordinate system, the $x$-axis points from the Earth toward the Sun. However, the $z$-axis in GSM is the projection of the Earth's magnetic dipole axis on the plane perpendicular to the $x$-axis (north is positive $z$). The $y$-axis is determined as the direction perpendicular to both the $z$-axis and the $x$-axis. (Kivelson & Russell, 1995).

3. FTE Data Set

Our investigation of FTE separation times is based on the FTE list that has been made publicly available as auxiliary material S3 of the article by Karimabadi et al. (2009). It contains 984 unique FTEs. These events were originally identified by Wang et al. (2005) in Cluster fluxgate magnetometer magnetic field data from February 2001 to June 2003. Karimabadi et al. (2009) used this FTE list as a training list for automatic FTE detection routines. Wang et al. (2005) selected the events by visual inspection of magnetic field data after a coordinate transformation to boundary normal (LMN) coordinates, as FTE signatures are easiest detected in that coordinate system (Russell & Elphic, 1978). For the coordinate transformation, a stretched version of the Shue et al. (1998) magnetopause model was used by Wang et al. (2005). To be classified as an FTE, Wang et al. (2005) required a clear bipolar signature in the $B$-field direction normal to the magnetopause and a simultaneous enhancement of the magnetic field magnitude. No lower limit on $B$-field magnitude enhancement, width or height of the bipolar signature, was required to qualify as an event. However, due to limitations in data resolution, the minimum extension of an FTE identified in this data set is 4 s. Only those events where the bipolar $B$-field variation appeared as an isolated signature were included in the list. The FTEs identified in this way by Wang et al. (2005) have a mean peak-peak magnitude of 25.36 nT, a mean peak-peak time of 25.8 s, and a mean separation time of 37.15 min (median 12.25 s). With these criteria, Wang et al. (2005) identified 1,222 individual FTEs; 36% of the FTEs were detected by one satellite, 20% of the events by two, 14% by three, and 30% of the FTE signatures appeared in data from four satellites. Wang et al. (2005) showed the results change only slightly when introducing a minimum threshold for the peak-peak magnitude of $B_N$, peak-peak $\geq 17$ nT. When this threshold is introduced, a slightly lower number of northward IMF FTEs are discovered (35%, instead of 43%) and the mean peak-peak value increases from 25.4 to 38.8 nT, as could be expected.

4. Results

4.1. Dependence of FTE Distribution on Separation Time

Figure 2 shows the location of all 984 unique FTEs from Karimabadi et al.’s (2009) list at the point of time when the FTEs appear in Cluster data. The location of each FTE is marked with a red dot, projected on the $xy$, $yz$, and $xz$-planes in the GSE coordinate system. Where an FTE was observed by several satellites, the detection time and location of the satellite with the lowest satellite number is used. The FTE distribution in GSM coordinates, overlaid over a model magnetosphere, can be found in Wang et al. (2005), their Figure 3. Here we show the FTE distribution in GSE coordinates (Figure 2), which illustrates better where the Cluster satellites crossed the magnetopause between 2001 and 2003: Only the high-latitude regions of the dayside magnetopause and the low-latitude flanks up to 10 Re downtail are covered by Cluster data. Figure 2 shows one of Wang et al.’s (2005) main results: FTEs are found in the entire area covered by Cluster magnetopause crossings, but with a clear occurrence frequency maximum in the northern dusk region and a less pronounced maximum in the southern dawn region of the magnetopause. As shown in Figure 1, the Cluster satellites sweep uniformly from dusk to dawn through the dayside magnetopause during each year between 2001 and 2003 (Taylor et al., 2010); thus, there is no dawn-dusk bias in Cluster magnetopause crossings, and the asymmetric FTE distribution is a real effect.
Figure 2. Location of the 984 flux transfer events (FTEs) listed in Karimabadi et al. (2009) in geocentric solar ecliptic system (GSE) coordinates. Each red point corresponds to one FTE. The FTEs were originally identified by Wang et al. (2005) in Cluster magnetopause crossings from February 2001 to June 2003.

In this paper, we show that the FTE distribution depends strongly on FTE separation time. Figure 3 illustrates this. The first plot is the same as Figure 2 (middle) and shows all FTEs from the Karimabadi et al. (2009) list projected on the yz-plane in GSE coordinates. The next plot in Figure 3 shows in red only those

Figure 3. Flux transfer event (FTE) distribution for different FTE separation times projected to the yz-plane in geocentric solar ecliptic system (GSE) coordinates. The first plot shows all FTEs from the Karimabadi et al. (2009) list. The subsequent five plots mark in red only those FTEs with separation times of at least ±10, ±20, ±30, ±60, and ±90 min. The remaining FTEs are marked as light gray dots in the background of each plot.
FTEs that have a separation time larger than ±10 min; that is, no other FTE appears in Cluster data during the last 10 min before and after the plotted FTE. In the remaining plots of Figure 3, the minimum separation times are set to ±20, ±30, ±60, and ±90 min. These plots clearly show that with increasing separation time the dawn-dusk asymmetry of the FTE distribution disappears gradually. This means that FTEs with a short separation time appear preferably in the northern dawn and southern dusk section, while FTEs with very long separation times are equally distributed over the entire magnetopause region, covered by Cluster measurements.

For a more detailed examination of FTE separation times and their dependence on IMF, we sort the FTEs into three different subgroups. The subgroup “FTE cascades with short separation times” contains all individual FTEs that have a separation time of ≤10 min to the previous and following FTEs. The subgroup “FTE cascades with long separation times” contains all individual FTEs that have a separation time of 10–70 min to the previous and following FTEs. The subgroup “isolated FTEs” contains all FTEs where no other FTE appears up to 70 min before and after the FTE.

Applying this definition to the data set of 984 FTEs, we get 151 individual FTEs that belong to the subgroup “FTE cascades with small separation times,” 98 individual FTEs that belong to “FTE cascades with long separation times,” and 171 isolated FTEs. For the remaining 563 FTEs, the separation times to the nearest FTE before and after differ too much to belong to the above-defined FTE subgroups. They are not further investigated in this study.

Note that sorting the FTEs only after the time span to the next FTE (thus allowing an arbitrary separation time to the previous FTE) results in much larger subgroups (329 short separation time, 313 long separation time, and 329 isolated FTEs) but slightly less clear results than with our definition. The reason is that when only taking into account the time span to the next FTE, the last FTE in a cascade of FTEs will erroneously be treated as an isolated FTE. Furthermore, it cannot be ruled out that the first FTE in a cascade appears during IMF conditions typical for isolated FTEs (in case such conditions exist), while the following FTEs appear after the IMF has changed to conditions favorable for cascades; thus, even the first FTE in a cascade should not always be sorted into the group of FTE cascades. More importantly, as we do not know how much time has passed between the actual FTE formation and the identification in Cluster, any possible IMF dependence will show up more clearly when focusing only on those FTEs that have similar separation times to the previous and next FTEs.

The division into only three groups with 0- to 10-, 10- to 70-, and >70-min separation times has been done to have enough events in each group for statistically relevant results even for subsets of these three main groups. The time limits have been chosen such that FTE cascades with short separation times, FTE cascades with long separation times, and isolated FTEs have a similar number of events for easier comparison of the results. Changing the separation time limit between the subgroup “FTE cascades with short” and the subgroup “FTE cascades with long separation times” to 5 or 15 min (instead of 10 min) changes the results only marginally. The same holds for changing the separation time limit between FTE cascades with long separation times and isolated FTEs to 50 min (instead of 70 min).

It is self-evident that with the help of Cluster measurements only a lower limit of FTEs within one FTE subgroup can be identified, as the magnetopause crossings of Cluster are both temporally and spatially limited. Thus, not all events in the group “isolated FTEs” will be truly isolated events as further (in time or space) nearby FTEs may have been missed by Cluster. The same holds for events in the subgroup “FTE cascades with long separation times.” Some of these might belong to the subgroup “FTE cascades with short separation times” due to missed FTEs.

Another problem is a possible bias for the distribution of FTE cascades with long separation time due to Cluster’s orbit. Overlaying Cluster’s orbit on the Shue model magnetopause reveals that Cluster will be close to the magnetopause (±1 Re) for about 1,000–1,500 min on the flanks (June-July and November-December each year; see Figure 1), while this time interval shrinks to 100–120 min on the high-latitude dayside passages (January-April each year; see Figure 1). This would mean that some of the isolated FTEs on the highest latitudes may in fact belong to the group of FTEs with long separation times, as the long separation time group is defined such that it includes even events with a 70-min gap from the last FTE to the current one and a 70-min gap to the next one. To be able to identify such a case as FTEs with long separation times, a magnetopause crossing must be at least 140 min long; that is, such
an extreme “FTE with a long separation time” event would be missed on Cluster crossings that last only 100–120 min.

However, the above-described estimate is based on the assumption that the magnetopause does not move during the Cluster passage through it. In reality, the magnetopause crossings are most of the time much longer, probably due to magnetopause oscillations forth and back over the (in comparison) extremely slowly moving Cluster satellites. To get an estimate for the typical time span during which Cluster may detect FTEs on one magnetosheath crossing, we calculated the time span between the first and last (of, e.g., 10 consecutive) detected FTEs in each magnetosheath passage. Figure 4 shows the maximal time span of subsequent FTEs found for each month in 2001–2003. As the Cluster orbits are nearly identical on the same day of 2001–2003 (see Figure 1), we summarize the results for each month in Figure 4. As could be expect from Figure 1, the shortest FTE sequences appear between January and April when Cluster crosses the high-latitude dayside magnetopause. The longest time periods with subsequent FTEs during over 10 hr appear in June and July, when Cluster is at the dawn flank, followed by December, when Cluster crosses the dusk flank. The shortest time period of subsequent FTEs in one Cluster magnetopause passage occurs in February (Cluster orbits close to noon; see Figure 1) and is nearly 200 min long, which is well above the necessary 140-min time span (horizontal red line) that separates isolated FTEs from FTEs with long separation times in our study. We thus conclude that a possible effect of this bias should be small.

As will be shown in the following sections, each FTE group shows a characteristic FTE distribution and IMF dependence, which strongly suggests that only a negligible number of events has been wrongly categorized. Thus, although the results of this study do not necessarily apply for each event, they are statistically relevant.

Figure 5 shows the distribution of the three FTE subgroups projected on the yz-plane in GSE coordinates. The red dots represent only those FTEs that belong to the shown FTE subgroup. The gray dots mark all other FTEs from the Karimabadi et al. (2009) FTE list for easier comparison. The plots reveal a striking difference between isolated events (Figure 5, right) and both types of FTE cascades. FTE cascades with short separation times appear mainly in the northern dusk and southern dawn regions of the magnetopause. FTE cascades with long separation times have a similar distribution; however, the occurrence density maxima are slightly

Figure 4. The longest time sequence of subsequent flux transfer events (FTEs) occurring in one Cluster magnetopause crossing for each month between February 2001 and June 2003. Note that Cluster has nearly identical orbits for the same calendar day between 2001 and 2003. The horizontal dotted line at 140 min marks the separation between FTEs with long separation times and isolated events according to our selection criteria.

Figure 5. The flux transfer event (FTE) distribution in the geocentric solar ecliptic system (GSE) yz-plane of (a) FTE cascades with short separation times (Δt ≤ 10 min), (b) FTE cascades with long separation times (10 min < Δt ≤ 70 min), and (c) isolated FTEs (Δt > 70 min). The red dots mark the FTEs of the respective subgroup. FTEs not belonging to the FTE subgroup are marked as light gray dots in the background.
less pronounced. In contrast, isolated events are uniformly spread over the entire region that is covered by Cluster’s magnetopause crossings.

4.2. FTE Dependence on IMF

To evaluate a possible effect of IMF direction and magnitude on the distribution of FTEs with different separation times, we investigate the influence of the different IMF components for each FTE subgroup separately.

4.2.1. IMF $B_y$ Dependence

Figure 6a shows superposed epoch analysis plots of average IMF $B_y$ for FTE cascades with short separation times (left), FTE cascades with long separation times (middle), and isolated FTEs (right) up to 3 hr before and after FTE detection time. The blue curve shows average IMF $B_y$, and the black dotted curves show the 2-sigma deviation from the mean value (this corresponds to a 95% confidence interval of the mean value). The results differ strongly between the three FTE groups. Average IMF $B_y$ is clearly negative in the hours around FTEs with short separation times, weakly negative around FTEs with long separation times, and close to zero during isolated FTEs.

To be able to interpret the results accurately, we attempt to separate between FTEs that form as a result of dayside reconnection and those that form as a result of high-latitude lobe reconnection. It is well known that dayside reconnection does not only occur during southward but also occurs even during weakly northward
IMF as long as \( B_y \geq B_z \). According to Freeman et al. (1993) and Senior et al. (2002), the separator between the high-latitude lobe and dayside reconnection lies at an IMF clock angle of 70°. The IMF clock angle is here defined as \( \arctan(|B_y|/B_z) \) (0° means purely northward IMF, 90° pure dawnward or duskward IMF, and 180° purely southward IMF).

In Figure 6b we show the results for average IMF \( B_y \) only for those FTEs for which dayside reconnection is assumed to occur by excluding all FTEs where the IMF clock angle (averaged over the last 10 min before detection time) is lower than 70°. The resulting plots look very similar to the plots in Figure 6a. Apparently, the IMF \( B_y \) conditions during which dayside and high-latitude lobe FTEs form are the same.

To see where FTEs associated with positive and negative IMF \( B_y \) are located, Figure 7 shows the FTE location in the \( yz \)-plane color coded according to the sign of \( B_y \). The figure is shown in the GSM coordinate system instead of GSE, as the directions of the GSM \( z \)-axis and \( y \)-axis depend on the Earth dipole tilt, which makes it easier to localize the reconnection (and FTE source) region. An FTE is marked in red in case IMF \( B_y \) averaged over the last 10 min before detection time is negative and in black in case the sign of IMF \( B_y \) is positive. Blue dots mark those FTEs where no IMF data were available. For comparison, the light gray dots mark the positions of all other FTEs of the data set (i.e., FTEs that did not fall into the separation category for that plot).

The distribution of FTEs during negative and positive IMF \( B_y \) in Figure 7 is in agreement with the results of Figure 6. A large majority of FTEs with short separation times (78%) and a small majority of FTEs with long separation times (56%) appear during negative IMF \( B_y \) conditions, while equally many isolated FTEs appear during positive and negative IMF \( B_y \) (50%).

To test how much the results in Figure 7 depend on the time span over which the IMF values are averaged, we reproduce this figure for 1- and 20-min averaged IMF \( B_y \) as well (not shown here). The resulting plots give nearly identical results as Figure 7: Using 1-, 10-, and 20-min averaged IMF \( B_y \) values, FTE cascades with short separation times consist of 78%, 78%, and 78% negative \( B_y \) sign cases; FTE cascades with long separation times have 55%, 56%, and 57% FTEs with negative \( B_y \); and isolated FTEs have 50%, 50%, and 49% FTEs with negative \( B_y \), respectively. This shows that the statistical results in Figure 7 do not depend on the length of the time averaging period up to (at least) 20 min. This is already indicated in the only small variations in average IMF \( B_y \) in Figure 6 several tens of minutes before FTE detection. The same procedure has been repeated for the other IMF components as well—with the same result: The statistical results about the IMF distribution during FTEs are not affected by the time span (up to at least 20 min) over which IMF is averaged.

4.2.2. IMF \( B_x \) Dependence

In Figure 8, superposed epoch analysis plots for the IMF \( B_x \) component are shown for all three FTE subgroups. The figure has the same format as Figure 6a. The results of Figure 8 are very similar to Figure 6a;
however, average $B_x$ has an opposite sign and a lower average magnitude than has $B_y$. The opposite sign of average $B_x$ is expected from the typical Parker spiral configuration where $B_x$ and $B_y$ have opposite signs (e.g., Kivelson & Russell, 1995). FTE cascades with short separation times appear for clearly positive IMF $B_x$, cascades with long separation times for weakly positive IMF $B_x$, and isolated FTEs for $B_x$ close to 0.

Superposed epoch analysis plots for the IMF magnitude are not shown here. They reveal, although the difference is not as significant as for IMF $B_y$ and $B_x$, a similar trend. FTE cascades with short separation times appear during highest (8.02 nT at FTE detection time), FTE cascades with long separation times during medium (7.57 nT), and isolated FTEs during lowest IMF magnitudes (6.91 nT). Removing all FTEs with dominant northward IMF results in IMF magnitude plots with slightly lower values, but the decrease in magnitude between the subgroups still exists (average $|\text{IMF}|$ at detection time = 7.58 nT for short cascades, 7.13 nT for long cascades, and 6.84 nT for isolated FTEs).

### 4.2.3. IMF $B_z$ Dependence

Figure 9a shows IMF $B_z$ superposed epoch analysis plots centered around FTE detection time. As could be expected, FTEs with short separation times as well as isolated FTEs form in average during southward IMF conditions. Surprisingly, IMF $B_z$ is in average northward for FTE cascades with long separation times.

As already reported by Wang et al. (2006), 43% of all FTEs in the Cluster data set occur during northward IMF. As could be expected, for our three subgroups we get similar numbers; the percentage of northward FTEs is 41%, 51%, and 42% for FTE cascades with short separation times and long separation times and isolated FTEs, respectively. An examination of IMF conditions for each FTE that appears during northward IMF in FTE cascades with short and long separation times reveals that most of these occur during IMF conditions with hours of large IMF magnitude, including high values of northward IMF (see also Fear et al., 2005). These strongly northward IMF $B_z$ FTEs are the cause for average IMF $B_z$ becoming only weakly southward around the detection time of short separation time FTEs, and clearly northward around the detection time of long separation time FTEs in Figure 9a. To show this statistically, two more figures with IMF $B_z$ superposed analysis plots have been produced (Figures 9b and 9c).

Figure 9b contains IMF $B_z$ superposed epoch analysis plots where FTEs with dominant northward IMF are excluded. The plot is done in the same way as Figure 6b; that is, all cases are removed where the IMF clock angle (averaged over the last 10 min before FTE detection) is less than 70°.

Figure 9c shows superposed epoch analysis plots of average IMF $B_z$ only for FTEs where the average IMF magnitude is smaller or equal to 10 nT the last 10 min before FTE detection.

About one quarter of all FTEs in each FTE subgroup occur during dominantly northward IMF conditions with clock angles <70°: 24% FTEs during short time separation cascades, 27% FTEs during long time separation cascades, and 27% isolated FTEs. A similar number of events appear during large IMF magnitudes in the

![Figure 8](image-url)  
**Figure 8.** Interplanetary magnetic field (IMF) $B_x$ superposed epoch analysis plots centered at flux transfer event (FTE) detection time for the three different FTE subgroups introduced in Figure 5. The plots are done in the same way as Figure 6a. GSM = geocentric solar magnetospheric system.
two FTE subgroups with cascades (24% short time separation and 21% long time separation cascade FTEs), while much less isolated FTEs appear for large IMF magnitudes (9%).

As is expected by excluding FTEs for small IMF clock angles in Figure 9b, average IMF $B_z$ now becomes clearly southward around FTE detection time for all three FTE subgroups. FTE cascades with short
separation times have the longest period of clearly southward IMF $B_z$ values. More interesting are the results of Figure 9c: By excluding the high-IMF magnitude cases, even FTE cascades with long separation times now have on average southward IMF at FTE detection time. In fact, the IMF $B_z$ curves of both FTE cascade groups in Figures 9b and 9c look very similar. This confirms the results from the case-by-case examination of FTE cascades during northward IMF conditions: Northward FTE cascades typically occur during solar wind conditions with high IMF magnitudes, as is typically the case during coronal mass ejection (CME) events. On the other hand, only a few of the dominant northward IMF cases among isolated FTEs appear during high IMF magnitudes, which explains the large difference of the plots in Figures 9b and 9c for isolated FTEs.

To find out where dayside reconnection FTEs and high-latitude lobe FTEs are located, Figure 10a shows the IMF clock angle dependence of the FTE distribution. The FTE location is plotted in the $yz$-plane with those FTEs that appear for IMF clock angles $<70^\circ$ (averaged over the last 10 min before FTE detection time) in black and those that appear during clock angles $>70^\circ$ in red. Figure 10 reveals that most FTE cascades that probably have formed as a result of the high-latitude lobe reconnection are actually observed near the dawn flank (black dots in Figure 10a, left and middle). In contrast, isolated FTEs with small IMF clock angles are randomly spread over the magnetopause area covered by Cluster. Apart from that, the plots in Figure 10a are in agreement with the findings of Figure 9. The number of events with small IMF clock angles is similar (about one quarter) for all FTE groups.
Figure 10b shows the FTE distribution projected on the $xy$-plane with red dots marking FTEs with 10-min averaged IMF magnitude $\leq 10$ nT and black dots marking those with 10-min averaged IMF magnitude $>10$ nT. Comparing Figures 10a and 10b confirms that the average IMF $B_z$ values gained through the superposed epoch analysis in Figure 9 also holds for individual FTEs: Most FTE cascades with small IMF clock angles appear during large IMF magnitudes, while nearly all isolated FTEs with small clock angles have small IMF magnitudes. The few isolated FTEs with high IMF magnitude are randomly spread over the area covered by Cluster data.

4.2.4. IMF Cone Angle Dependence

In Figure 11, the possible effect of dominant IMF $B_x$ on the FTE distribution is studied. Here the FTEs are color coded depending on whether the IMF cone angle (during the last 10 min before FTE detection time) is larger or equal to 30° (red dots) or smaller than 30° (black dots). The IMF cone angle is the angle between the Sun-Earth line and the IMF direction, and is defined as $\arccos (|B_x|/B_{\text{tot}})$ (i.e., $|B_x| \gg |B_y|$ and $B_x \gg |B_z|$ for small cone angles). Figure 11 shows that during IMF conditions where $B_x$ dominates over $B_y$ and $B_z$, FTE cascades are nearly absent (2% short separation time FTEs and 5% long separation time FTEs), while about 16% of all isolated FTEs appear during IMF conditions with a small IMF cone angle.

5. Discussion

The most important result of this study is the observed strong difference in FTE distribution between FTE cascades and isolated FTEs. This difference may be explained by the IMF conditions during which the FTEs of each subset typically form.

The exact IMF values at FTE formation are not known as we do not know the exact point of time at which the FTEs have formed before being detected in Cluster data. However, we can use the IMF values averaged over the last 10 min before FTE detection time as an estimate for that. The reason is that average IMF does not change considerably during the last 20 min before FTE detection in Cluster (see Figures 6, 8, and 9), while FTEs are assumed to propagate within only 10 min to the nightside magnetosphere. The semianalytical FTE propagation model by Cooling et al. (2001) predicts that flux tubes reconnecting along a dayside reconnection line in the ecliptic plane will propagate along the magnetopause to $-5 < x < -10$ Re within ~8–10 min for $|B| \approx 10$ nT and a solar wind speed of 500 km/s. These solar wind input values are only slightly higher than the average FTE values in our study ($v = 440$ km/s, IMF magnitude $= 7.5$ nT); thus, Cooling et al.’s (2001) propagation time calculations can be taken as an estimate for the maximal time span between FTE formation and FTE detection on the flanks. Most FTEs of our data set are identified when they are still on the dayside (Figure 2), which means that the time span between FTE formation and detection will be in most cases even shorter than 8–10 min. Hence, we are confident that the statistical results regarding IMF
conditions in this study (averaged over the last 10 min before FTE detection in Cluster) are also valid during FTE formation.

We will discuss the IMF impact on FTE distribution in the following subsections. First, we will analyze the possible effect of IMF on isolated FTEs and thereafter the IMF influence on FTE cascades with short and long separation times. For each FTE subgroup we have to consider dayside reconnection and high-latitude lobe reconnection events separately. To facilitate the discussion about the dayside reconnection cases, the expected reconnection regions for zero and nonzero IMF $B_y$ are illustrated in Figure 12. It shows the assumed FTE source region along the reconnection line (red) and expected subsequent FTE motion (blue arrows) to the region where they are discovered in Cluster (blue shaded area) for different IMF $B_y$ conditions. For illustrations of high-latitude lobe reconnection, we refer in the $B_y \sim 0$ case to Maezawa (1976) and in the nonzero $B_y$ case to Crooker and Rich (1993, their Figure 1).

### 5.1. Isolated FTEs

The near-uniform distribution of isolated FTEs in the region covered by Cluster magnetopause crossings (Figure 5, right) can be expected from a near-equatorial reconnection line forming during southward IMF conditions with $B_y \sim 0$ (Figure 6b, right) according to both the antiparallel (Crooker, 1979) and component reconnection models (Sonnerup, 1970). As mentioned in section 1, the maximum magnetic shear model should not be used in the case of pure southward IMF, as it predicts reconnection along two branches of pure antiparallel regions that bifurcate close to noon to highest NH and SH latitudes, which deviates partly from observations (Trattner et al., 2012). Their magnetic shear maps for pure southward IMF are still interesting, as they show that a region of very high magnetic shear between the magnetosheath and the magnetosphere appears in a very broad region around the equatorial plane. Regardless of whether FTEs during $B_y \sim 0$ conditions form exactly along an equatorial reconnection line or in a broad region with the highest magnetic shear around the equatorial plane, they should appear at arbitrary longitudes along the dayside magnetopause. As shown in Figure 12 (left), the solar wind flow will drag the southern and northern parts of the newly created FTEs toward higher latitudes in the NH and SH (e.g., Cooling et al., 2001), where they are eventually detected in Cluster data. This scenario is correct for those FTEs that form as a result of dayside reconnection. As discussed above, reconnection is expected to occur at the dayside as long as the IMF clock angle is larger than 70° (e.g., Freeman et al., 1993). Nearly three quarters of isolated FTEs occur during such conditions (Figure 10a, right).

The 27% isolated FTEs appearing during IMF clock angles $<70°$ are rather uniformly spread as well (Figure 10a, right). Even that can be expected. It is well established that high-latitude lobe reconnection results in reoriented open field lines that are draped over the dayside and will be eventually dragged by the solar wind tailward along both flanks in case IMF $B_y \sim 0$ (see, e.g., Figure 19 in Maezawa, 1976).
Apparently, Cluster detects both FTEs that are still at high latitudes close to noon and FTEs that already have started to propagate along the dayside magnetopause toward dawn and dusk. This would explain the rather uniform distribution of isolated FTEs appearing during dominantly northward IMF.

An interesting new result is the discovery that 16% of all isolated FTEs appear during IMF conditions with dominant \( B_x \) (IMF cone angle <30°), while FTE cascades are nearly absent during such conditions (Figure 11). During dominant IMF \( B_x \) a large portion of the subsolar bow shock is in the quasi-parallel configuration, which is known to be associated with the creation of magnetosheath plasmoids and jets close to the equatorial plane (e.g., Hietala et al., 2012; Karlsson et al., 2015). The maximum occurrence frequency of jets appears for (normalized against the average IMF cone angle distribution) cone angles of 10–30° (Plaschke et al., 2013). Such high-momentum structures may trigger localized reconnection by compressing the originally thick magnetopause layer, until it is thin enough for reconnection to occur (see Karimabadi et al., 2014, for simulation results and Hietala et al., 2018, for satellite observations of reconnection caused by magnetosheath jets). We suggest that such localized reconnection events could form as isolated FTEs as well. The jets that form at arbitrary longitudes in the low-latitude magnetosheath (e.g., Dmitriev & Suvorova, 2015; Plaschke et al., 2013) would explain the random spread of isolated FTEs with low IMF cone angles <30° in Cluster data. A study searching for possible signatures of magnetosheath jets that can be linked to isolated FTEs is ongoing.

While the equal distribution of isolated FTEs in Cluster data can be explained by the near-zero IMF \( B_y \) conditions, the question why these appear as isolated events remains. It cannot be ruled out that (apart from those 16% isolated FTEs that may have been caused by magnetosheath jets) isolated FTEs belong to FTE cascades that have been missed by the Cluster satellites. FTEs forming at small longitudinal distances from each other along an equatorial merging line (e.g., due to small local \( B \)-field variations) will increase their azimuthal distance when being dragged by the solar wind around the magnetopause to higher latitudes and spread like a fan (Figure 12, left), considering the Russell and Elphic (1978) FTE model where elbow-shaped newly reconnected flux tubes originate through a single reconnection burst in a localized region, rather than the model by Lee and Fu (1985), who proposed (in the dawn-dusk direction) extended FTE structures that form between multiple X-lines during nonzero IMF \( B_y \). Thus, subsequent FTEs belonging to the same cascade could easily have been missed by Cluster at higher latitudes. This is not expected during nonzero \( B_y \) conditions. As will be explained in much detail below (see also Figure 12), FTEs forming during IMF \( B_y < 0 \) are expected to propagate rapidly duskward in the NH and dawnward in the SH. FTEs belonging to one cascade are due to the common azimuthal motion eventually detected in Cluster even if they originally formed at some distance from each other along an X-line. The FTE separation time in Cluster measurements would in that case be larger than the original FTE separation time at formation. This would also explain the much lower number of FTEs with large separation times in Kuo et al.’s (1995) statistical FTE study, which is based on ISEE1 and ISEE2 data and thus contains only FTEs close to the ecliptic plane (\( 1 \leq 5 \) Re).

On the other hand, there is a high probability that the subgroup of isolated FTEs contains many real isolated FTEs as their magnetic field characteristics deviate from those of FTE cascades. The statistical results of this data set indicate that isolated FTEs appear during weak IMF and show weak \( B \)-field signatures, including small peak-to-peak magnetic field values. Wang et al. (2006; examining FTE separation times up to 20 min only) observed a clear correlation between increasing FTE separation time, decreasing magnetic field signatures of FTEs (peak-to-peak values), and decreasing IMF magnitude. The latter also appears in the analysis of our FTE subgroups, revealing a decrease in IMF magnitude between FTE cascades with short separation times and long separation times and isolated FTEs. These results could mean that many isolated FTEs appear during IMF and solar wind conditions that are just above the threshold for which the formation of an FTE becomes possible. Small solar wind and IMF fluctuations around this threshold would make the formation of FTEs possible during only short periods of time, resulting in isolated FTEs.

### 5.1.1. FTE Cascades Formed by Dayside Reconnection

FTE cascades with short and long separation times appear, contrary to isolated FTEs, mainly during negative IMF \( B_x \) (Figures 6 and 7). The preferable occurrence of FTE cascades in the northern dusk and southern dawn regions of the magnetopause can be explained by the impact of IMF \( B_x \) on FTE formation and motion. Note that although FTE distribution and characteristic IMF conditions are more pronounced for the group of FTE cascades with short separation times as compared to the group of FTE cascades with
long separation times, they still have similar characteristics. We thus refer from here on to both subgroups as “FTE cascades.”

As mentioned in section 1, Fuselier et al. (2002) observed that both antiparallel and component reconnection may occur at the dayside magnetopause. This led Trattner et al. (2007) to suggest the maximum magnetic shear model where a (season- and IMF clock angle-dependent) tilted component reconnection line connects the high-latitude antiparallel regions close to noon. From Fear et al. (2007) it is known that FTEs also have their source region partly in the antiparallel reconnection regions, partly along a component merging line. They compared the velocity of FTEs observed by Cluster with predicted velocities from the Cooling et al. (2001) model of the open field line motion, which allowed them to trace the FTEs back toward their source region. Here we use the maximum magnetic shear model by Trattner et al. (2007) to estimate the possible source region of FTE cascades. The FTE cascades in our study appear during those IMF conditions (southward IMF with a strong \( B_x \) component) for which the maximum magnetic shear model gives an excellent agreement with observations of normal reconnection events (Trattner et al., 2007, 2012, 2017, 2018).

In Figure 12 the antiparallel and component regions for south-dawnward IMF (during zero dipole tilt) are shown in two separate plots. Figure 12 (middle) illustrates that for south-dawnward IMF, antiparallel conditions are fulfilled only at high latitudes in NH dawn and SH dusk. A recently opened field line will have a strong azimuthal kink, as \( |B_z| \) is much larger than \( |B_r| \) in our data set (the average IMF clock angle is 87–98°, ±20 min around FTE for all three FTE subgroups). The green dashed line in Figure 12 (middle) symbolizes such a strongly kinked new field line. The tension force exerted by the field-line kink will cause a duskward motion of a recently opened field line in the NH and a dawnward motion in the SH (blue arrows in Figure 12, middle). Reconnection near noon, on the other hand, appears according to the maximum magnetic shear model for nonzero IMF \( B_y \) in the region with the highest magnetic shear, resulting in a tilted merging line. As illustrated in Figure 12 (right), the northern and southern FTE flux tube branches that form along this tilted reconnection line during \( B_y < 0 \) and will move as well to northern dusk and southern dawn due to the draped solar wind flow around the magnetopause. In conclusion, all FTEs will move toward northern dawn and southern dusk, independent of whether they originated in the antiparallel region or in the component reconnection region.

The azimuthal motion of recently opened field lines during IMF conditions with \( |B_y| \gg |B_r| \) is also reflected in the ionospheric convection pattern. As the frozen field line conditions apply to open field lines, the plasma motion above the polar cap ionosphere is coupled to the motion of the corresponding magnetic field line foot point. Thus, the plasma convection in the polar cap can be used as an estimate for how fast and in which direction recently opened magnetic field lines move along the magnetopause. The ionospheric convection pattern for IMF \( |B_y| > |B_r| \) and \( B_y < 0 \) is well known (e.g., Heppner & Maynard, 1987; Ruohoniemi & Greenwald, 2005; Weimer, 1995), consisting (in the NH) of a round cell on the dawn and a crescent cell on the dusk side. Rapid duskward flows appear just poleward of the dayside open-closed field line boundary between the (slightly dawnwardly displaced) cusp and the polar cap region at dusk where the flow turns tailward and slows down. This region with duskward flows spans over about ~786 km (1/6 circle with \( r = 750 \) km/1/4 circle would give 1,180 km). Typical velocities of fast flows close to the dayside polar cap boundary for \( |B_y| > |B_r| \) are about 800–1,000 m/s (e.g., Fear et al., 2009; Kullen et al., 2015). This means that the plasma flows from the cusp to the duskside polar cap within 13–17 min. The foot points of the recently opened field lines will move with the same speed, which gives us the maximal time span between FTE formation and Cluster detection of an FTE signature at the NH dusk flank. Plasma and field line motion in the SH will be the same but in the opposite direction. As most FTEs in our data set are detected at the dayside (much before they have reached the flanks), the time span between formation and detection will be in most cases much shorter than 13–17 min. Note that this estimation for FTE propagation between the source region and Cluster detection is a slightly higher than predicted by Cooling et al. (2001), but the numbers have the same order of magnitude.

5.1.2. FTE Cascades Formed by High-Latitude Lobe Reconnection
For FTE cascades that form during dominantly northward IMF conditions (IMF clock angle < 70°) a different magnetic topology has to be considered than shown in Figure 12. High-latitude lobe reconnection during dawnward IMF results in the NH in open field lines that are draped over the dayside with their open end south-duskward of the equatorial plane. These draped field lines will be eventually dragged by the solar wind...
wind along the dusk flank in the tailward direction (see Figure 1 in Crooker and Rich, 1993). Open field lines originating in the SH will be bent toward dawn and eventually propagate tailward along the dawn flank. Our data analysis shows that about one quarter of all FTEs in the two FTE cascade subgroups appear during such conditions. A majority of these have been detected at the dawnside magnetopause flank (Figure 10a).

The Cooling et al. (2001) model indicates that the motion of new open field lines from the NH high-latitude lobe to the dawn flanks at $x = -10\, \text{Re}$ takes less than 4 min in case the IMF is in the sector Parker spiral direction with $B_z > 0$. This means that FTE cascades forming during northward IMF are expected to travel much faster than those forming during southward IMF (8–10 min according to Cooling et al., 2001), which could explain why Cluster sees so many northward FTE cascades close to the dawn flank and much less at higher latitudes (Figure 10a). The fast propagation toward the tail flanks is explained by the effect of super-Alfvénic magnetosheath flow at the high-latitude reconnection site, which results in some FTEs being swept equatorward (Fear et al., 2005; Kawano & Russell, 1997). Another possible reason for the near absence of northward IMF FTE cascades close to noon is that high-latitude lobe reconnection appears probably at too high latitudes to be captured by Cluster measurements. The Cluster magnetopause crossings do not exceed $z (\text{GSM}) = 11\, \text{Re}$ (see Figure 10), while high-latitude lobe reconnection appears poleward of $z (\text{GSM}) = 11\, \text{Re}$, as shown by Trattner et al. (2004).

Those northward IMF FTE cascades that appear southward of the equatorial plane at the dawn flank in Figure 10 are probably the same events that have been studied extensively in Fear et al. (2005) as the time period of their Cluster study (November 2002 to June 2003) overlaps to some extent with that of the present study (February 2001 to June 2003). By tracing back the FTE velocities to their source region with the help of the Cooling et al. (2001) model, Fear et al. (2005) concluded that those FTEs most likely did not propagate from a NH high-latitude lobe region to the low-latitude dawn flanks but originated instead from a SH high-latitude reconnection line that extends to low latitudes at the dawn flank. For a more detailed discussion of these results, we refer to their paper (Fear et al., 2005).

A new finding from the present study is that northward IMF-FTE cascades appear typically during IMF conditions with large IMF magnitudes (>10 nT) including high values of northward IMF (Figures 9 and 10). Such IMF conditions are typical for CME events, which have large IMF magnitude values, and include sustained periods of strong (in average 14 nT) positive or negative $B_y$ (Lindsay et al., 1995). Note that for isolated FTEs and FTE cascades occurring during southward IMF we found much lower average IMF magnitudes, indicating that most of these do not appear during CME events.

### 5.2. Seasonal Effects on FTE Distribution

The predominant occurrence of FTE cascades during dawnward IMF is at first sight surprising, especially as the IMF is most of the time in the duskward direction during the time period of the Cluster FTE observations (Wang et al., 2006, their Figure 2). Only a minority of FTE cascades with short separation times (22%) and long separation times (44%) appear during duskward IMF conditions. This is also in contrast to the statistical results by Kuo et al. (1995) whose observations show that FTEs mainly appear during positive IMF $B_y$.

The bias toward negative IMF $B_y$ in our study is most likely related to seasonal effects. As shown in Figure 1, the orbit of the Cluster satellites changed during the years 2001–2003 in such a way that they cross the dayside magnetopause during the NH winter close to dusk and the NH summer close to dawn. This means that most FTEs in our data set appear in the winter hemisphere. This has already been pointed out by Wang et al. (2005, 2006). In the present study, we show that this bias occurs only for FTE cascades, not for isolated FTEs (Figure 5). Note that a preferable occurrence of FTEs in the winter hemisphere has been confirmed in later observational studies as well (Fear et al., 2012; Korotova et al., 2008). The winter hemisphere bias explains why most FTE cascades appear during dawnward IMF in our data set: FTEs are expected to propagate to northern dusk and southern dawn only when the IMF $B_y$ component is negative, which are the regions that are passed by Cluster during the winter months in 2001–2003.

Both Wang et al. (2005, 2006) and Fear et al. (2012) point to Raeder's (2006) simulation results for a possible explanation for a seasonal bias of the FTE distribution. As already described in section 1, Raeder's (2006) MHD simulations for strong Earth dipole tilts show how one new X-line after the other forms in the
winter hemisphere between the subsolar point and the magnetic equatorial plane, while the X-line that has formed earlier at the same location has already been dragged by the solar wind flow further poleward/flankward where it becomes eventually inactive/decays. The magnetic field structure that forms each time between the new and old X-lines is interpreted as an FTE, which is dragged by the solar wind flow toward higher latitudes/flanks as well (for an illustration, see Hasegawa et al., 2010, their Figure 1). The reason why these X-lines form in the winter hemisphere during nonzero Earth dipole tilt is a geometrical one. As Trattner et al. (2007) showed, the region of maximum magnetic shear is for nonzero dipole tilts not anymore close to the solar wind flow stagnation point but displaced toward the winter hemisphere. This is also the reason why the once formed FTEs are dragged by the solar wind toward the winter hemisphere only.

The formation of subsequent FTEs that move toward the winter hemisphere in Raeder’s (2006) simulations fit well with our observations for FTE cascades. As pointed by Raeder (2006), the original Russell and Elphic (1978, 1979) scenario of FTE formation as spontaneous reconnection bursts recreates all observed magnetic signatures of FTEs, as well as their subsequent poleward/flankward motion, but does not provide any explanation why these would occur recurrently. Thus, it seems more likely that recurrently appearing FTEs are the result of sequentially activated X-lines, especially since Hasegawa et al. (2010) found an event that seems to confirm Raeder’s (2006) simulations. Whether isolated FTEs (which are by definition not appearing recurrently) form instead as a result of spontaneous, localized reconnection bursts, resulting in localized elbow-shaped flux tubes surrounded by helical magnetic field structures, as suggested in Russell and Elphic’s (1978,1979) FTE formation mechanism, remains to be shown.

Note that according to Raeder’s (2006) simulations for a zero dipole tilt case, only one stable X-line appears at the subsolar point, and no FTE forms. This means that FTE cascades should be rare around equinox, which fits quite well with our results. As shown in Figure 1, Cluster is during mid-March (spring equinox) close to noon (at $0 < y < -2$ Re in the NH and at $-6 < y < -8$ Re in the SH), where only a few FTE cascades appear (see Figure 5). As discussed above, a minority of FTE cascades with long separation times may erroneously have been classified as isolated FTEs due to Cluster’s short magnetopause crossing close to noon. However, no such bias should occur for FTE cascades with short separation times; that is, the near absence of FTEs with short separation times close to noon is real. Still, it cannot be ruled out that the near absence of cascades close to noon has also to do with the fast motion of recently formed FTEs toward the NH dusk and SH dawn flanks combined with the fact that Cluster appears many more hours close to the magnetopause when passing the flanks than when passing noon (see Figures 1 and 5).

With the present study, it cannot be determined with certainty whether FTE cascades appear as a result of multiple X-lines or as a result of Russell and Elphic (1979)-type localized flow bursts along a static reconnection line. The maximum magnetic shear model gives a good estimate where to expect reconnection, in case FTEs form along one static reconnection line. The location of the maximum magnetic shear model reconnection line for strong Earth dipole tilts is illustrated in Figure 13 for NH summer (left) and NH winter (right) during south-dawnward IMF conditions. In this figure, the antiparallel and component parts of the reconnection line are shown in one plot. The plots show that even if FTEs are formed along a static reconnection line, they will propagate only toward the winter hemisphere in case the Earth dipole tilt is large. The reason is the displacement of the reconnection region from the ecliptic plane (where the solar wind flow deflects into a northern branch and a southern branch) toward the winter hemisphere. Thus, both branches of a recently formed FTE will be dragged by the solar wind toward the winter hemisphere.

It remains unclear why the distribution of isolated FTEs does not show any seasonal bias (Figure 5). If isolated FTEs, as suggested above, appear as isolated reconnection bursts along a near-equatorial reconnection line during near-zero IMF $B_y$, this line also should be displaced away from the subsolar point for large dipole tilts, with the result that also isolated FTEs should end up in the winter hemisphere. Two explanations are possible: As already mentioned above, it could be that isolated FTEs do not necessarily form exactly along the equatorial reconnection line but at arbitrary latitudes within the rather broad region of extremely high magnetic shear during pure southward IMF (see maximum magnetic shear plots in Trattner et al., 2012), such that not all FTEs move toward the winter hemisphere. Another possible reason could be that due to the closeness of an equatorial reconnection line to the ecliptic plane, its location is affected by diurnal dipole tilt variations leading to a nonstable situation with reconnection that sometimes appears in the northern
6. Summary and Conclusions

In this paper, we investigated 984 unique flux transfer events that have been originally identified in Cluster data from February 2001 to June 2003 by Wang et al. (2005) and were made publicly available in Karimabadi et al. (2009). Due to Cluster’s orbit, FTEs are detected only on the high-latitude dayside and low-latitude flanks of the magnetopause.

The focus of this study is on the role of separation times between successive FTEs. For this, the data set was sorted into three subgroups: (a) FTE cascades with a short separation time (previous and next FTE less than 10 min away from each FTE), (b) FTE cascades with a long separation time (previous and next FTE 10–70 min away from each FTE), and (c) isolated FTEs (no FTEs within 70 min before and after each FTE).

A detailed investigation of the three FTE subgroups shows that there exist significant differences for FTEs with different separation times. This concerns both the FTE distribution along the magnetopause and the IMF conditions during which these FTEs typically occur.

The results for FTE location as well as the results for IMF $B_x$, IMF $B_y$, and IMF magnitude show the same continuous change between the three FTE subgroups. FTEs with short separation times have the strongest distribution asymmetry with an occurrence maximum at the northern dusk and southern dawn magnetopause. FTEs with long separation times have a weaker distribution asymmetry, and isolated FTEs show no dawn-dusk asymmetry at all. Average IMF $B_x$, IMF $B_y$, and IMF magnitude become increasingly weaker as the FTE separation time increases. Average IMF $B_z$ is negative and $B_x$ positive during FTE cascades, while both IMF components are near zero for isolated FTEs. The opposite trend is found for IMF cone angles, with increasingly more events appearing for small IMF cone angles between FTE cascades with short and long separation times and isolated FTEs. This shows that FTE separation time and location depend strongly on IMF $B_x$, IMF $B_y$, and IMF magnitude.

The results for IMF $B_z$ are more complicated. IMF $B_z$ seems to have no clear influence on the separation time of the 76% FTEs that have formed during IMF clock angle $>70^\circ$ (dayside reconnection expected). FTEs forming during dominantly northward IMF conditions (IMF clock angle $<70^\circ$; i.e., high-latitude lobe reconnection is expected) seem to exist as two distinctly different subsets. Dominantly northward FTE cascades appear preferably close to the magnetopause flanks and during large IMF magnitudes, while dominantly northward isolated FTEs are found in the entire magnetopause region covered by Cluster and appear during average IMF magnitude values.

Figure 13. Schematic of the expected motion of the northern and southern branches of the newly opened flux tubes (thick blue arrows) after formation in the reconnection region (red line) according to the maximum magnetic shear model by Trattner et al. (2007) during dawn-southward interplanetary magnetic field (IMF) for (left) Northern Hemisphere (NH) summer and (right) NH winter conditions. The reconnection line (red) is shifted from the ecliptic plane (orange dotted line) toward the winter hemisphere when the Earth dipole tilt becomes large, causing flux transfer events (FTEs) to move only to the winter hemisphere.
The observed difference in FTE distribution along the magnetopause can be explained by the respective IMF conditions during which each FTE subgroup typically occurs, assuming that FTEs form at the reconnection regions predicted in the maximum magnetic shear model by Trattner et al. (2007) and are dragged subsequently by the solar wind in poleward/flankward direction, as described by the Cooling et al. (2001) model. This holds for both FTEs that are assumed to originate from dayside reconnection and those that originate from high-latitude lobe reconnection.

The strong bias of FTE cascades toward negative IMF $B_y$ is most probably a seasonal effect. FTEs have been reported to preferably move to the winter hemisphere (Fear et al., 2012; Korotova et al., 2008; Wang et al., 2006). During the time period covered by our study, Cluster is in the winter hemisphere when crossing the magnetopause at NH dusk and SH dawn. That explains both the occurrence maximum of FTE cascades in these regions and the sign of IMF $B_y$. FTEs are expected to move to northern dusk and southern dawn only in case the IMF $B_y$ component is negative.

We propose that FTE cascades are formed in between sequentially activated and poleward-moving multiple X-lines during strong Earth dipole tilts, which according to the simulation results by Raeder's (2006) move toward the winter hemisphere only. In opposite to isolated FTEs, FTE cascades form (by definition) in sequences, appear mainly in the winter hemisphere, and are nearly absent in the regions with low Earth dipole tilt (Cluster's orbit is at spring equinox close to noon).

Isolated FTEs, on the other hand, appear equally distributed in Cluster data and show no seasonal bias. While the random distribution at Cluster latitudes can be explained by their expected formation along a (for IMF $B_y \sim 0$ expected) near-zero reconnection line at arbitrary longitudes, the absence of a seasonal bias remains to be explained. It can be speculated that isolated FTEs occur as the result of local reconnection bursts, as originally suggested by Russell and Elphic (1978).

Here we suggest that a large minority of isolated FTEs (at least one sixth of these) may form as a result of magnetosheath jets. These FTEs appear during dominant IMF $B_y$ conditions (cone angle <30°), which is a favorable condition for magnetosheath jets to form (e.g., Plaschke et al., 2013). These jets have recently been reported to locally trigger reconnection (Hietala et al., 2018), which could cause FTEs that appear only as isolated events. Whether they truly are caused by magnetosheath jets requires further investigation.

Acknowledgments
We are very thankful for helpful discussion with R. Fear and J. Coxton during the ongoing project. We also would like to thank M. Kullen and M. Memedi for the first draft of the computer programs used in this study, which they produced as part of their final school project at the MEG Gymnasium, Stockholm. This project is partially financed by the Swedish National Space Agency SNSA Project 155A/17. The FTE list used in this paper appears as auxiliary material S3 in Karimabadi et al. (2009). This list is based on magnetic field measurements from Cluster data, which are available to the general public through the Cluster Science Archive CSA (www.cosmos.esa.int/web/csa). The IMF data used in this study have been downloaded from the OMNI data set at the CDAWeb (cdaweb.gsfc.nasa.gov/ istp_public/).

References
Balogh, A., Carr, C. M., Acu’na, M. H., Dunlop, M. W., Bee, T. J., Brown, P., et al. (2001). The Cluster Magnetic Field Investigation: Overview of in-flight performance and initial results. Annales Geophysicae, 19, 1207–1217. https://doi.org/10.5194/angeo-19-1207-2001
Carter, J. A., Milan, S. E., Fear, R. C., Kullen, A., & Hairston, M. R. (2015). Dayside reconnection under IMF By dominated conditions: The formation and movement of bending arcs. Journal of Geophysical Research: Space Physics, 120, 2967–2978. https://doi.org/10.1002/2014JA020809
Cooling, B. M. A., Owen, C. J., & Schwartz, S. J. (2001). Role of the magnetosheath flow in determining the motion of open flux tubes. Journal of Geophysical Research, 106(A9), 18,763–18,775. https://doi.org/10.1029/2000JA000455
Cowley, S. W. H., & Owen, C. J. (1989). A simple illustrative model of open flux tube motion over the dayside magnetopause. Planetary and Space Science, 37(11), 1461–1475. https://doi.org/10.1016/0032-0633(89)91116-5
Crooker, N. U. (1979). Dayside merging and cusp geometry. Journal of Geophysical Research, 84(A3), 951–959. https://doi.org/10.1029/JA084iA03p00951
Crooker, N. U., & Rich, F. J. (1993). Lobe cell convection as a summer phenomenon. Journal of Geophysical Research, 98(A8), 13,403–13,407.
Dmitriev, A. V., & Suvorova, A. V. (2015). Large-scale jets in the magnetosheath and plasma penetration across the magnetopause: THEMIS observations. Journal of Geophysical Research: Space Physics, 120, 4423–4437.
Dungey, J. W. (1963). The structure of the exosphere or adventures in velocity space. In C. DeWitt, J. Hiebrot, & A. Lebeau (Eds.), The Earth’s environment, (pp. 505–550). New York: Gordon and Breach.
Escofet, C. P., Febringer, M., & Goldstein, M. (2001). The Cluster mission. Annales de Geophysique, 19(10/12), 1197–1200. https://doi.org/10.5194/angeo-19-1197-2001
Farrugia, C. J., Southwood, D. J., Cowley, S. W. H., Rijnbeek, R. P., & Daly, P. W. (1987). Two-regime flux transfer events. Planetary and Space Science, 35(6), 737–744. https://doi.org/10.1016/0032-0633(87)90033-X
Fear, R. C. (2006). Cluster multi–spacecraft observations of flux transfer events. PhD thesis, Mullard Space Sci. Lab., University College London.
Fear, R. C., Fazakerley, A. N., Owen, C. J., & Lucek, E. A. (2005). A survey of flux transfer events observed by Cluster during strongly northward IMF. Geophysical Research Letters, 32, L13805. https://doi.org/10.1029/2005GL023811
Fear, R. C., Milan, S. E., Fazakerley, A. N., Fornac`on, K.-H., Carr, C. M., & Dandouras, I. (2009). Simultaneous observations of flux transfer events by THEMIS, Cluster, Double Star, and SuperDARN: Acceleration of FTEs. Journal of Geophysical Research, 114, A10213. https://doi.org/10.1029/2009JA014310
Fear, R. C., Milan, S. E., Fazakerley, A. N., Owen, C. J., Asikainen, T., Taylor, M. G. G. T., et al. (2007). Motion of flux transfer events: A test of the Cooling model. Annales de Geophysique, 25(7), 1669–1680. https://doi.org/10.5194/angeo-25-1669-2007
Fear, R. C., Palermo, M., & Milan, S. E. (2012). Seasonal and clock angle control of the location of flux transfer event signatures at the magnetopause. Journal of Geophysical Research, 117, A04202. https://doi.org/10.1029/2011JA017235
Freeman, M. P., Farrugia, C. J., Burlaga, L. F., Hairston, M. R., Greenspan, M. E., Ruschioniemi, J. M., & Lepping, R. P. (1993). The interaction of a magnetic cloud with the Earth: Ionospheric convection in the Northern and Southern Hemispheres for a wide range of quasi-steady interplanetary magnetic field conditions. *Journal of Geophysical Research*, 98(A5), 7633–7655. https://doi.org/10.1029/92JA02350

Fuselier, S. A., Berchem, J., Trattner, K. J., & Friedel, R. (2002). Tracing ions in the cusp and low-latitude boundary layer using multispacecraft observations and a global MHD simulation. *Journal of Geophysical Research*, 107(A9), 1226. https://doi.org/10.1029/2002JA009610

Gonzalez, W. D., & Mozer, F. S. (1974). A quantitative model for the potential resulting from reconnection with an arbitrary interplanetary magnetic field. *Journal of Geophysical Research*, 79(28), 4186–4194. https://doi.org/10.1029/JA079iA28p04186

Haeberli, G., Paschmann, G., Schopke, N., Rosenbauer, H., & Hedgecock, P. C. (1978). The frontside boundary layer of the magnetosphere and the problem of reconnection. *Journal of Geophysical Research*, 83(A7), 3195–3216. https://doi.org/10.1029/JA083iA07p03195

Hasagawa, H., Wang, J., Danlop, M. W., Pu, Z. Y., Zhang, Q. H., Lavraud, B., et al. (2010). Evidence for a flux transfer event generated by multiple X-line reconnect at the magnetopause. *Geophysical Research Letters*, 37, L16101. https://doi.org/10.1029/2010GL044219

Heppner, J. P., & Maynard, N. C. (1987). Empirical high-latitude electric field models. *Journal of Geophysical Research*, 92(A5), 4467. https://doi.org/10.1029/JA092iA05p04467

Hietala, H., Partamies, N., Laitinen, T. V., Claussen, L. B. N., Fiskö, G., Vaivads, A., et al. (2012). Supermagnetosonic subauroral magnetosheath jets and their effects: From the solar wind to the ionospheric convection. *Annales de Geophysic*, 30(1), 33–48. https://www.angeo.net/30/33/2012/

Hietala, H., Phan, T. D., Angelopoulos, V., Oieroset, M., Archer, M. O., Karlsson, T., & Plaschke, F. (2018). In situ observations of a magnetosheath high-speed jet triggering magnetopause reconnection. *Geophysical Research Letters*, 45, 1732–1740. https://doi.org/10.1029/2017GL076525

Hölttöjoki, S., Souza, V. M., Walsh, B. M., Janhunen, P., & Palmroth, M. (2014). Magnetopause reconnection and energy conversion as influenced by the dipole tilt and the IMF Bz. *Journal of Geophysical Research: Space Physics*, 119, 4484–4484. https://doi.org/10.1002/2013JA019693

Kariabadi, H., Roytershteyn, V., Vu, H. X., Omelchenko, Y. A., Scudder, J., Daughton, W., et al. (2014). The link between shocks, turbulence, and magnetic reconnection in collisionless plasmas. *Physics of Plasmas*, 21, 062308. https://doi.org/10.1063/1.4882875

Kariabadi, H., Sipes, B., Wang, Y., Lavraud, B., & Roberts, A. (2009). A new multivariate time series data analysis technique: Automated detection of flux transfer events using Cluster data. *Journal of Geophysical Research*, 114, A06216. https://doi.org/10.1029/2009JA014200

Korotova, G. I., Sibeck, D. G., & Rosenberg, T. (2008). Seasonal dependence of Interball flux transfer events. *Geophysical Research Letters*, 35, L05106. https://doi.org/10.1029/2008GL033254

Kullen, A., Fear, R. C., Milan, S. E., Carter, J. A., & Karlsson, T. (2015). The statistical difference between bending arcs and regular polar arcs. *Journal of Geophysical Research: Space Physics*, 120, 10,443–10,465. https://doi.org/10.1002/2015JA021298

Kuo, H., Russell, C. T., & Le, G. (1995). Statistical studies of flux transfer events. *Journal of Geophysical Research*, 100(A3), 3513–3519. https://doi.org/10.1029/94JA02498

Lee, L. C., & Fu, Z. F. (1985). A theory of magnetic flux transfer at the Earth’s magnetopause. *Geophysical Research Letters*, 12(2), 105–108.

Lindsay, G. M., Russell, C. T., & Luhmann, J. G. (1995). Coronal mass ejection and stream interaction region characteristics and their potential geomagnetic effectiveness. *Journal of Geophysical Research*, 100(A9), 16,999–17,013. https://doi.org/10.1029/95JA00525

Lockwood, M., & Wild, M. N. (1993). On the quasi-periodic nature of magnetopause flux transfer events. *Journal of Geophysical Research*, 98(A4), 5935–5940. https://doi.org/10.1029/92JA02375

Lockwood, M., Sandholt, P. E., & Cowley, S. W. H. (1989). Dayside auroral activity and magnetic flux transfer from the solar wind. *Geophysical Research Letters*, 16, 33–36.

Luhmann, J. R., Walker, R. J., Russell, C. T., Crooker, N. U., Speiter, J. R., & Sahara, S. S. (1984). Patterns of potential magnetic field merging sites on the dayside magnetopause. *Journal of Geophysical Research*, 89(A3), 1739–1742. https://doi.org/10.1029/JA089iA03p01739

Maetzka, K. (1976). Magnetospheric convectioninduced by the positive and negative Z components of the interplanetarymagnetic field: Quantitative analysis using polar cap magnetic records. *Journal of Geophysical Research*, 81(13), 2289–2303.

Plaschke, F., Hietala, H., & Angelopoulos, V. (2013). Anti-sunward high-speed jets in the subauroral magnetosheath. *Annales de Geophysique*, 31, 1877–1889. https://doi.org/10.5194/angeo-31-1877-2013

Raeder, J. (2006). Flux transfer events: 1. Generation mechanism for strong southward IMF. *Annales de Geophysique*, 24, 381–392. https://doi.org/10.5194/angeo-24-381-2006

Rijnbeek, R. P., Cowley, S. W. H., Southwood, D. D., & Russell, C. T. (1984). A survey of dayside flux transfer events observed by ISEE 1 and 2 magnetometers. *Journal of Geophysical Research*, 89(A2), 786. https://doi.org/10.1029/JA089iA02p00786

Ruschioniemi, J. M., & Greenwald, R. A. (2005). Dependencies of high-latitude plasma convection: Consideration of interplanetary magnetic field, seasonal, and universal time factors in statistical patterns. *Journal of Geophysical Research*, 110, A09204. https://doi.org/10.1029/2004JA010815

Russell, C. T., & Elphic, R. C. (1978). Initial ISEE magnetometer results: Magnetopause observations. *Space Science Reviews*, 22(6), 681–715. https://doi.org/10.1007/BF00212619

Russell, C. T., & Elphic, R. C. (1979). ISEE observation of flux events at the dayside magnetopause. *Geophysical Research Letters*, 6(1), 33–36. https://doi.org/10.1029/GL006i001p0033

Sandholt, P., & Farrugia, C. (2007). Poleward moving auroral forms (PMFs) revisited: Responses of aurorae, plasma convection and Birkeland currents in the pre- and postnoon sectors under positive and negative IMF Bz conditions. *Annales de Geophysique*, 25, 1629–1652. https://doi.org/10.5194/angeo-25-1629-2007

Senior, C., Cerisier, J.-C., Rich, F., Lester, M., & Parks, G. K. (2002). Strong sunward propagating flow bursts in the night sector during quiet solar wind conditions: SuperDARN and satellite observations. *Annales Geophysique*, 20(6), 771–779. https://doi.org/10.5194/angeo-20-771-2002
Shue, J.-H., Song, P., Russell, C. T., Steinberg, J. T., Chao, J. K., Zastenker, G., et al. (1998). Magnetopause location under extreme solar wind conditions. *Journal of Geophysical Research, 103*, 17,691–17,700. Sibeck, D. G. (1990). A model for the transient magnetospheric response to sudden solar wind dynamic pressure variations. *Journal of Geophysical Research, 95*, 3755–3771.

Sonnepurp, B. U. O. (1970). Magnetic field re-connection in a highly conducting incompressible fluid. *Journal of Plasma Physics, 4*(1), 161–174. https://doi.org/10.1017/S0022377800004888

Taylor, M. G. G. T., Escoubet, C. P., Laakso, H., Masson, A., & Goldstein, M. L. (2010). The Cluster mission: Space plasma in three dimensions. In H. Laakso, M. Taylor, & C. Escoubet (Eds.), *The Cluster active archive, Astrophysics and Space Science Proceedings*, (pp. 309–330). Dordrecht: Springer. https://doi.org/10.1007/978-90-481-3499-1_21

Trattner, K. J., Burch, J. L., Cassak, P. A., Ergun, R., Eriksson, S., Fuselier, S. A., et al. (2018). The transition between antiparallel and component magnetic reconnection at Earth’s dayside magnetopause. *Journal of Geophysical Research: Space Physics, 123*(12), 10,177–10,188. https://doi.org/10.1029/2018JA026081

Trattner, K. J., Burch, J. L., Ergun, R., Eriksson, S., Fuselier, S. A., Giles, B. L., et al. (2017). The MMS dayside magnetic reconnection locations during phase 1 and their relation to the predictions of the maximum magnetic shear model. *Journal of Geophysical Research: Space Physics, 122*, 11,991–12,005. https://doi.org/10.1002/2017JA024488

Trattner, K. J., Fuselier, S. A., & Petrinec, S. M. (2004). Location of the reconnection line for northward interplanetary magnetic field. *Journal of Geophysical Research, 109*, A03219. https://doi.org/10.1029/2003JA009975

Trattner, K. J., Mulcock, J. S., Petrinec, S. M., & Fuselier, S. A. (2007). Location of the reconnection line at the magnetopause during southward IMF conditions. *Geophysical Research Letters, 34*, L03108. https://doi.org/10.1029/2006GL028397

Trattner, K. J., Petrinec, S. M., Fuselier, S. A., & Phan, T. D. (2012). The location of reconnection at the magnetopause: Testing the maximum magnetic shear model with THEMIS observations. *Journal of Geophysical Research, 117*, A01201. https://doi.org/10.1029/2011JA016959

Trenchi, L., Marcucci, M. P., Fallocchia, G., Consolini, G., Bavassano Cattaneo, M. B., di Lellis, A. M., et al. (2008). Occurrence of reconnection jets at the dayside magnetopause: Double Star observations. *Journal of Geophysical Research, 113*, A07S10. https://doi.org/10.1029/2007JA012774

Wang, Y. J., Elphic, R. C., Lavraud, B., Taylor, M. G. G. T., Birn, J., Raeder, J., et al. (2005). Initial results of high-latitude magnetopause and low-latitude flank flux transfer events from 3 years of Cluster observations. *Journal of Geophysical Research, 110*, A11221. https://doi.org/10.1029/2005JA011150

Wang, Y. J., Elphic, R. C., Lavraud, B., Taylor, M. G. G. T., Birn, J., Russell, C. T., et al. (2006). Dependence of flux transfer events on solar wind conditions from 3 years of Cluster observations. *Journal of Geophysical Research, 111*, A04224. https://doi.org/10.1029/2005JA011342

Weimer, D. R. (1995). Models of high-latitude electric potentials derived with a least error fit of spherical harmonic coefficients. *Journal of Geophysical Research, 100*(A10), 19,595–19,607. https://doi.org/10.1029/95JA01755