Simultaneous observations of flux transfer events by THEMIS, Cluster, Double Star, and SuperDARN: Acceleration of FTEs

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We present simultaneous observations of flux transfer events (FTEs) made by the THEMIS spacecraft on 3 May 2007, along with supporting observations of fast flows in the dayside ionosphere observed by the SuperDARN radar network. The THEMIS spacecraft were in a string-of-pearls formation approximately 20,000 km long and crossed the postnoon magnetopause at low latitudes between 1200 UT (TH-C) and 1430 UT (TH-E). The Cluster spacecraft were situated in the magnetosheath at high latitudes in the Southern Hemisphere, approaching the magnetopause which was crossed at about 1600 UT. THEMIS observed “standard” polarity FTE signatures between 1100 and 1500 UT, while Cluster observed “reverse” polarity signatures at the same time. The two sets of signatures are consistent with being generated at the same small region of a subsolar reconnection line. Between 1100 and 1230 UT, the Double Star TC-1 satellite was near the magnetopause closer to local noon but still ~7 Re from the subsolar point. TC-1 only observed a single FTE, suggesting that the variability of the reconnection rate differed between these two locations on the X line. Fast poleward ionospheric flows were observed in the noon and prenoon sector, at similar magnetic local times to the footprints of both Cluster and THEMIS, after 1200 UT. The long string formation of the THEMIS constellation allows the motion of the FTE structures to be tracked, and the acceleration is found to be small but consistent with a model prediction.


1. Introduction

Flux transfer events, or FTEs [Russell and Elphic, 1978, 1979], are bursts of magnetic reconnection [Dungey, 1961] at the Earth’s magnetopause. The signature of an FTE observed by a spacecraft near the magnetopause consists of a bipolar variation in the component of the magnetic field normal to the magnetopause ($B_N$), and is often accompanied by an enhancement or a “crater” in the magnetic field magnitude [Paschmann et al., 1982]. Such signatures may be caused either by the entry of a spacecraft onto the magnetic structure formed by reconnection, or simply by observing the draped field lines around the structure. If only the draping signature is observed, there is no change to the plasma parameters. If the spacecraft enters onto open magnetic field lines, then field-aligned plasma signatures characteristic of the opposite side of the magnetopause are also observed [Daly et al., 1981, 1984]: in a magnetospheric FTE, a cool, dense magnetosheath population will be observed moving along the magnetic field away from the magnetopause (this population may mirror at lower altitudes causing a bidirectional population to be observed); in a magnetosheath FTE, escaping hot, rare plasma is observed.

At the dayside magnetopause, FTE signatures are observed predominantly when the IMF has a southward component [Rijnbeek et al., 1984; Berchem and Russell, 1984]. When the IMF is northward, reconnection may occur at high latitudes [Dungey, 1963], and FTEs are then observed at the postterminator magnetopause [Kawano and Russell, 1997a, 1997b; Fear et al., 2005]. The ionospheric signatures of FTEs are observed at the footprints of newly opened field lines, and take the form of optical and radar auroral features and fast ionospheric flows, which are sometimes pulsed [Sandholt et al., 1986, 1992; Elphic et al., 1990; Pinnock et al., 1993, 1995; Moen et al., 1995; Provan et al., 1998; Milan et al., 1999a, 1999b, 2000; McWilliams et al., 2000, 2004; Neudegg et al., 2001; Wild et al., 2001, 2007; Amm et al., 2005]. Ionospheric observations can provide information about the global scale and rate of reconnection, whereas in
situ satellite observations probe the small-scale structure. Observations of ultra violet and radar auroral features have shown that ionospheric reconnection signatures can extend over several hours of local time [Milan et al., 2000]. Magnetopause observations of FTE signatures by spacecraft at large separations have shown that FTEs occur both as large-scale features and smaller, more patchy events [Fear et al., 2008, 2009].

If an FTE is observed by more than one spacecraft, then difference(s) in the time of observation of the magnetic field signatures and the known separation(s) of the spacecraft can be used to determine components of the FTE velocity. Several studies have applied such multispacecraft techniques [Russell et al., 1983; Harvey, 1998] to FTEs observed by the four-spacecraft Cluster mission [Escoubet et al., 2001] in order to study the motion of FTEs, and therefore the motion of open magnetic field lines at the magnetopause, in three dimensions [Owen et al., 2001; Wild et al., 2005; Dunlop et al., 2005; Fear et al., 2005]. Some of the uncertainties in this method were examined by Fear et al. [2007], but one assumption that was not addressed was the assumption that the velocity of the FTE is constant as it crosses the spacecraft constellation. The recent launch of the THEMIS mission [Angelopoulos, 2008] has allowed observations of FTE structure at larger scales than those hitherto available with Cluster, although only in one dimension [Sibeck et al., 2008; Liu et al., 2008; Lui et al., 2008; Zhang et al., 2008].

In this paper we present observations from a four-way conjunction that occurred on 3 May 2007 between the THEMIS, Cluster and Double Star TC-1 satellites and the SuperDARN ionospheric radars. During the interval 1000 to 1500 UT reconnection took place at the dayside magnetopause and FTE structures were generated for several hours. THEMIS and Cluster, situated on the equatorial flank and high-latitude Southern Hemisphere magnetopause, respectively, both observed FTEs throughout the 5 h interval. THEMIS was aligned in a string broadly along the direction of motion of the FTEs, which allows the motion of the FTEs to be tracked along 17,000 km and the acceleration to be measured. TC-1 was situated nearer local noon (but at midlatitudes) and observed only one FTE, indicating that reconnection was less variable there than at the reconnection site responsible for the signatures observed by THEMIS and Cluster.

In section 2, we introduce the instrumentation used in this paper. This is followed by an outline of the in situ and ionospheric observations, and in section 4 we discuss the implications for the acceleration of FTEs and the extent of the reconnection line.

2. Instrumentation

We present magnetopause observations from three spacecraft missions: the five-spacecraft THEMIS constellation [Angelopoulos, 2008], the four-spacecraft Cluster constellation [Escoubet et al., 2001], and the Double Star TC-1 satellite [Liu et al., 2005]. The ionospheric response to magnetopause activity is shown using data from the Super Dual Auroral Radar Network (SuperDARN) array of high-latitude radars [Greenwald et al., 1995; Chisham et al., 2007]. The upstream conditions are provided by the OMNI high-resolution database, which consists of Wind observations [Lepping et al., 1995] which have been lagged to the magnetopause using a time-varying lag [King and Papitashvili, 2005].

2.1. THEMIS

The locations of the spacecraft near the magnetopause are shown in Figure 1 (top). In May 2007, the THEMIS spacecraft were in the “coast phase” of the mission, during which the five spacecraft formed a string, all following the same orbit. Between 1100 and 1500 UT on 3 May, the spacecraft crossed the postnoon magnetopause from the magnetosphere into the magnetosheath at low latitudes. In this paper, we primarily use magnetic field data from the Fluxgate Magnetometer instrument (FGM [Auster et al., 2008]). Between 1100 and 1314 UT, THEMIS was in its fast survey mode, and magnetic field data were available at 4 Hz cadence. Thereafter, the spacecraft were in a slow survey mode and the magnetic field data were only available at spin resolution (~3 s). Data at both resolutions are employed in this paper. We also show spin resolution electron spectrograms and quote lower-resolution ion moments from the Electrostatic Analyzer (ESA [McFadden et al., 2008]).

2.2. Cluster and Double Star

The Cluster spacecraft were situated in the magnetosheath near the dawn terminator and in the Southern Hemisphere. In this paper, we show magnetic field data at 5 Hz and spin (~4 s) resolution from the Cluster FGM instrument [Balogh et al., 2001] and spin resolution electron spectrograms from the Plasma Electron and Current Experiment (PEACE [Johnstone et al., 1997]).

The Double Star TC-1 satellite was near the magnetopause near local noon and in the Southern Hemisphere. Magnetic field data are provided at spin (~4 s) resolution from the Fluxgate Magnetometer [Carr et al., 2005]. Electron data are provided by the Double Star PEACE instrument [Fazakerley et al., 2005], which was in a mode that returned three-dimensional distributions every spin. The energy range of the instrument was sampled over two spins, so each pair of distributions has been combined resulting in a resolution of ~8 s. The distributions were then binned to pitch angles, which are shown in this paper. Ion moment parameters are provided by the TC-1 HIA instrument [Rème et al., 2005], which are also available at spin resolution.

2.3. SuperDARN

Four Northern Hemisphere radars are used: Pykivber, Stokkseyri, Goose Bay and Kapuskasing. The locations and fields of view of these radars are shown in Figure 1 (bottom). Each plot shows a polar grid of magnetic latitude (MLAT) and magnetic local time (MLT). As described by Milan et al. [1997], each radar transmits high-frequency radio waves, which are scattered from ionospheric electron density irregularities that move as part of the ionospheric convection process. When backscatter is observed, the ionospheric convection velocity and the backscatter power and spectral width are measured. Data points with a low velocity and low spectral width are flagged as ground scatter. A sweep of each field of view is performed every 2 min. The fields
of view of these radars were biased toward the prenoon sector at 1100 UT (except for Pykvibær), but had rotated to provide coverage of the prenoon and postnoon sectors by 1500 UT.

3. Observations

3.1. Solar Wind Conditions

The lagged solar wind conditions are given in Figure 2, which shows the GSM components and magnitude of the IMF observed by the Wind spacecraft, the IMF clock angle ($\theta_{CA} = \arctan(B_Y/B_Z)$), the solar wind density, radial velocity component and dynamic pressure, all from the OMNI database. Throughout the interval, the IMF was dominated by the $B_Y$ component, which was consistently directed dawnward. The $B_Z$ component was initially southward although there were some brief northward excursions in the first half of the interval, and after 1300 UT the IMF turned northward (but was still predominantly dawnward). After 1430 UT, the $B_Z$ component observed by Wind increased as $B_Y$ dropped to near zero. Figure 2 also shows the clock angle of the magnetic fields observed by Cluster 3 and THEMIS-C, which were situated in the magnetosheath. The clock angles observed by Wind and Cluster compare relatively well, except for the northward excursion observed by Wind after 1430 UT. This excursion was not observed by Cluster, although it was evident at THEMIS after 1440 UT.

3.2. Ionospheric Observations

Figure 3 summarizes the ionospheric observations made by the SuperDARN radars. Figures 3a–3d show spatial views of the ionospheric velocity deduced from the radar backscatter at 1040 and 1330 UT as observed by the Pykvibær, Stokkseyri, Goose Bay and Kapuskasing radars. Figures 3a and 3c show the data from Pykvibær and Stokkseyri at 1040 and 1330 UT, respectively, while Figures 3b and 3d show the data from Goose Bay and Kapuskasing at the same times. Each plot shows the same polar grid of magnetic latitude and magnetic local time as is used in Figure 1. They also show the Northern Hemisphere footprints of THEMIS-E and TC-1 (the footprint of TC-1 in Figures 3a and 3b is calculated from the position of TC-1 shortly after its magnetopause crossing into the magnetosphere at 1130 UT). Cluster 3 was in the magnetosheath throughout the interval; when it subsequently crossed into the magnetosphere at 1610 UT, it entered onto Southern Hemisphere lobe field lines, and therefore did not have a footprint in the Northern Hemisphere. The Southern Hemisphere footprint of these field lines was at 10 MLT; this magnetic local time is indicated by a thick dashed line in Figures 3a–3d for illustrative purposes.

[13] Figure 3 shows time series of the ionospheric velocity as a function of magnetic latitude for Pykvibær, Stokkseyri, Goose Bay and Kapuskasing, and Figures 3i–3l show the backscatter power for the same radars and in the...
same format. Each plot shows the data from one radar beam. The beams selected for Pykvibær and Stokkseyri are the most northward pointing beams. The beams selected for Goose Bay and Kapuskasing are those which contained the most backscatter. All four selected beams have an azimuthal component in their lines of sight. Each selected beam is marked in Figures 3a–3d.

The Kapuskasing radar observed fast flows away from the radar (poleward and/or duskward) throughout the interval from 1000 to 1500 UT (Figure 3h). As time progressed, the backscatter was observed at gradually higher magnetic latitudes. However, this may be a local time effect rather than indicating the migration of the open/closed field line boundary to higher latitudes. Between 1000 UT and 1500 UT, the fast flows were observed between ~6 and 11 MLT as the field of view of the radar rotated in local time.

At 1200 UT, the radio frequencies used by the Kapuskasing and Goose Bay radars changed. Consequently, the backscatter power decreased temporarily at Kapuskasing, but strong and persistent flows were observed by Goose Bay (at 82° MLAT and 10 MLT). Some structure is visible in the backscatter power (Figures 3k and 3l) which indicates the propagation of regions of high backscatter power to higher magnetic latitudes. Such features are referred to as Poleward Moving Radar Auroral Forms (PMRAFs [Milan et al., 2000; Wild et al., 2001]), and indicate the occurrence of time-varying reconnection at the magnetopause in this local time sector. At their largest extent (1300 UT onward), PMRAFs were observed by both Goose Bay and Kapuskasing, between 7 and 14 MLT, as shown in Figure 3d.

The more northerly beams of the Stokkseyri radar observed a long-lasting patch of radar backscatter between 78 and 81° MLAT (Figure 3f). The field of view of Stokkseyri overlaps with that of Goose Bay, and both radars observed backscatter from the same region of the ionosphere. The flows observed at Stokkseyri were weaker than those observed at Goose Bay, indicating that the bulk of the ionospheric flow was perpendicular to the Stokkseyri beam directions. However, there was a clear, repeated variation between flows with components toward the Stokkseyri radar (equatorward and/or duskward) and away from the

Figure 2. Solar wind conditions observed by the Wind satellite (OMNI high-resolution data set) and the clock angle observed by Cluster 3 and THEMIS-C (after 1202 UT), which were situated in the magnetosheath.
radar (poleward and/or dawnward), and there was also modulation in the backscatter power (Figure 3j). Observed ionospheric velocity components along the line of sight of the Stokkseyri radar were typically of order ±200 km s\(^{-1}\), but some flow bursts directed away from the radar peaked at velocity components of 400 km s\(^{-1}\). These pulsed flows...
were observed between 1000 and 1400 UT, and correspond to the same region of the ionosphere as is observed by the Goose Bay radar, suggesting that the lack of fast flows observed by Goose Bay before 1200 UT is due to the sounding frequency used by Goose Bay.

[18] The line-of-sight velocities in Figure 3 can be combined with the “map potential” model of ionospheric flow to derive two-dimensional velocities [Ruohoniemi and Baker, 1998]. The line-of-sight velocities are mapped onto a polar grid, and then fitted to an expansion of the electrostatic potential in spherical harmonics, which is stabilized by a statistical model in regions where there are no observations. This analysis is shown for half-hourly snapshots in Figure 4, which shows the brief burst of near-noon poleward flow observed at 1040 UT (Figure 4b). The fast flows observed by the Goose Bay and Kapuskasing radars start near local dawn in Figure 4c, are visible near local noon in Figure 4e, become enhanced in Figures 4g–4i and decay in Figures 4j–4l.

3.3. Magnetopause Observations

[19] The orientation and separations of the THEMIS and Cluster spacecraft at 1300 UT are shown in boundary normal coordinates [Russell and Elphic, 1978] in Figure 5, and an overview of the magnetic field and electron observations made by these spacecraft is shown in Figure 6. The string of THEMIS spacecraft was led by TH-C, followed by TH-B, TH-D, TH-A and TH-E. At 1300 UT, TH-C and TH-E were separated by 4,600 km in the direction normal to the magnetopause, and 21,600 km tangential to the magnetopause. Between 1105 and 1202 UT, all five spacecraft were situated in the magnetosheath, observing a hot, rare electron plasma and a magnetic field dominated by the strongly positive $B_L$ component. At 1202 UT, TH-C crossed the magnetopause into the magnetosheath where it observed: a cooler, denser plasma; a weaker, generally negative $B_L$ component and a positive $B_M$ component. The THEMIS string then straddled the magnetopause until TH-E crossed into the magnetosheath at 1435 UT, at which point the magnetosheath magnetic field was positive in both the $B_L$ and $B_M$ components (corresponding to the northward turning of the IMF observed at 1430 UT). The Cluster spacecraft were oriented in an elongated triangle, since Clusters 3 and 4 were only separated by 700 km, where the three sides of the triangle (C3–C1, C1–C2, C2–C3) were 7900 km, 3200 km and 6500 km. All four spacecraft were situated in the magnetosheath throughout the interval.

[20] The boundary normal coordinates were derived independently for THEMIS and Cluster. For THEMIS, the normal was determined by applying minimum variance analysis (MVA [Sonnerup and Cahill, 1967; Sonnerup and Scheible, 1998]) to the 4 Hz magnetic field data from TH-D as the spacecraft crossed the magnetopause between 1208:00 and 1208:40 UT ($\lambda_m/\lambda_{min} = 4.52$). The corresponding minimum variance eigenvector was taken to be the magnetopause normal ($\mathbf{n} = (0.842, 0.530, -0.099)_{GSE}$). The vector $l = (0.120, -0.006, 0.993)_{GSE}$ was derived by projecting the Earth’s magnetic dipole onto the plane defined by $\mathbf{n}$, and $\mathbf{m} = \mathbf{n} \times l = (0.525, -0.848, -0.069)_{GSE}$ completes the set. $\mathbf{m}$ is directed largely downward, and $l$ is predominantly in the $z_{GSE}$ direction, consistent with the low-latitude, postnoon location of the spacecraft.

[21] Since Cluster did not cross the magnetopause in this interval (Figure 6), the rotation matrix to boundary normal coordinates was determined from the Roelof and Sibeck [1993] magnetopause model: $\mathbf{n} = (0.519, -0.599, -0.609)_{GSE}$, $l = (0.486, -0.379, 0.787)_{GSE}$ and $\mathbf{m} = (-0.703, -0.705, 0.095)_{GSE}$.

3.3.1. THEMIS

[22] FTEs can be identified from their characteristic bipolar $B_y$ signatures throughout the interval 1100 to 1500 UT in Figure 6. Some enlargements of the $B_y$ traces are provided in Figure 7, which shows $B_y$ traces for the whole interval in four 1-h plots. Each plot shows a trace from a different spacecraft, and for a different 1-h block from 1100 through to 1500 UT. FTEs were first observed at 1100 UT by TH-C, the outermost spacecraft and therefore the nearest to the magnetopause (Figure 7a). At this time, the THEMIS spacecraft were all in the magnetosphere, identified by the positive $B_L$ components in Figure 6. At the same time, the other THEMIS spacecraft observed lower-frequency Pc5 oscillations in the $B_y$ component (Figure 6). The Pc5 variations persisted at TH-A, TH-B and TH-D until 1200 UT, when these three spacecraft started to observe FTEs (e.g., TH-B, Figure 7b). At the same time, TH-C crossed the magnetopause into the magnetosheath. Between 1300 and 1400 UT TH-B and TH-D crossed the magnetopause several times (Figure 6) and FTEs continued to be observed by these spacecraft (e.g., Figure 7c). By 1400 UT, TH-E was close enough to the magnetopause that it was able to observe FTEs (Figure 7d), and shortly after 1430 UT two FTEs were observed by all five THEMIS spacecraft simultaneously (Figure 8).

[23] The observation of two FTEs by all five THEMIS spacecraft allows us to carry out multispacecraft timing analysis [Russell et al., 1983; Harvey, 1998] to investigate the velocities of the FTEs. At 1438 UT, the spacecraft were aligned in a string roughly tangential to the magnetopause. The maximum spacecraft separation was approximately 17,700 km in the $\mathbf{m}$ direction, 4,800 km in the $l$ direction and 2,200 km normal to the magnetopause. The normal separation was less than the typical scale size of an FTE normal to the magnetopause as determined by Saunders et al.

Figure 3. Observations from four SuperDARN radars. Spatial views of the ionospheric velocity deduced from dayside radar backscatter at (a and b) 1040 UT and (c and d) 1330 UT by the Pykviður and Stokksneyri radars (Figures 3a and 3c) and by the Goose Bay and Kapuskasing radars (Figures 3b and 3d). The grid shown represents magnetic latitude (70° to 90°, dotted circular lines) and magnetic local time (6 to 18 MLT, dotted radial lines). The symbols indicate the footprints of the THEMIS and TC-1 spacecraft (in Figures 3a and 3b the TC-1 footprint was calculated using the position of the spacecraft after its 1130 UT magnetopause crossing), and a thick dashed line indicates the magnetic local time of the footprint of Cluster 3 after its magnetopause crossing at 1610 UT. Time series of the ionospheric velocity for one beam for each radar as a function of magnetic latitude: (e) Pykviður, (f) Stokksneyri, (g) Goose Bay, and (h) Kapuskasing. (i–l) Corresponding time series of radar backscatter power.
Figure 4
Since the spacecraft were aligned in a string, it is only possible to derive the component of velocity in the dimension along the string, which is largely the $\mathbf{m}$ direction. However, as there are five spacecraft it is possible to assess whether this velocity component is constant as the FTE moves downtail.

The time between each FTE being observed at TH-A (taken to be the reference spacecraft) and each of the other spacecraft is plotted against the distance of each spacecraft from TH-A in Figure 9. The time between the FTE being observed at each spacecraft was determined by identifying the midpoint of each $B_N$ signature (indicated in Figure 8 by vertical gray lines), and the error bars reflect the variation which would be introduced by aligning the positive or negative peaks of the bipolar signature instead [e.g., Fear et al., 2007]. The minimum error assumed is the resolution of the data used for this analysis (3 s). The distance plotted is the separation of the spacecraft in the $\mathbf{l}$-$\mathbf{m}$ plane. The timing uncertainties are larger for the second FTE than the first, due to the fact that the $B_N$ signatures are less clear (Figure 8).

The solid line in each plot of Figure 9 is a linear best fit line of the form $s = s_0 + vt$. Here, $s$ is the displacement of the FTE, $v$ is the component of the FTE velocity along the spacecraft string, $t$ is time and $s_0$ is the displacement at $t = 0$ (which should be zero as the displacement and time are defined relative to TH-A). The gradients of the graphs are $v = 263$ km s$^{-1}$ and 189 km s$^{-1}$ for the FTEs at 1434 and 1442 UT, respectively, which correspond to the components of the FTE velocities along the THEMIS string. The offsets are $s_0 = -1064$ km and +109 km, which are small compared with the spacecraft separations. These speeds are typical of those that have been observed by Cluster [see Fear et al., 2007, Figure 6c].

The hatched line in each plot of Figure 9 is a quadratic best fit, of the form $s = s_0 + vt + \frac{1}{2}at^2$. This introduces an acceleration, $a$, to the fitting process. The best fit velocity components (at TH-A) are $v = 301$ km s$^{-1}$ and 185 km s$^{-1}$, the offsets are $s_0 = -1153$ km and +88 km, and the acceleration terms are $a = -1.4$ km s$^{-2}$ and +0.12 km s$^{-2}$ (therefore the hatched line for the 1442 UT FTE is barely distinguishable from the solid line).

The acceleration terms are small, and we conclude that these are negligible on the separation scale of the THEMIS spacecraft. In fact, the acceleration term for the 1442 UT FTE represents a slight acceleration, while the term of Figure 4. Two-dimensional model fits of the observed ionospheric flows in 2-min windows separated by 30 min, starting at 1008–1010 UT and ending at 1538–1540 UT. Each plot shows the ionospheric flows observed by each of the Northern Hemisphere SuperDARN radars, fitted to the map potential model. The black contours are the ionospheric electric potential, based on a statistical model but fitted to the observed flows (where observations are available). Colored points indicate “true” velocity vectors, which are the combination of the observed ionospheric velocities (line-of-sight components) and the component perpendicular to the line of sight derived from the ionospheric potential model. The diamond and asterisk represent the footprints of THEMIS-E and TC-1, and the dashed radial line represents the magnetic local time of the footprint of Cluster 3 after its 1610 UT magnetopause crossing.

Since the spacecraft were aligned in a string, it is only possible to derive the component of velocity in the dimension along the string, which is largely the $\mathbf{m}$ direction. However, as there are five spacecraft it is possible to assess whether this velocity component is constant as the FTE moves downtail.

The time between each FTE being observed at TH-A (taken to be the reference spacecraft) and each of the other spacecraft is plotted against the distance of each spacecraft from TH-A in Figure 9. The time between the FTE being observed at each spacecraft was determined by identifying the midpoint of each $B_N$ signature (indicated in Figure 8 by vertical gray lines), and the error bars reflect the variation which would be introduced by aligning the positive or negative peaks of the bipolar signature instead [e.g., Fear et al., 2007]. The minimum error assumed is the resolution of the data used for this analysis (3 s). The distance plotted is the separation of the spacecraft in the $\mathbf{l}$-$\mathbf{m}$ plane. The timing uncertainties are larger for the second FTE than the first, due to the fact that the $B_N$ signatures are less clear (Figure 8).

The solid line in each plot of Figure 9 is a linear best fit line of the form $s = s_0 + vt$. Here, $s$ is the displacement of the FTE, $v$ is the component of the FTE velocity along the spacecraft string, $t$ is time and $s_0$ is the displacement at $t = 0$ (which should be zero as the displacement and time are defined relative to TH-A). The gradients of the graphs are $v = 263$ km s$^{-1}$ and 189 km s$^{-1}$ for the FTEs at 1434 and 1442 UT, respectively, which correspond to the components of the FTE velocities along the THEMIS string. The offsets are $s_0 = -1064$ km and +109 km, which are small compared with the spacecraft separations. These speeds are typical of those that have been observed by Cluster [see Fear et al., 2007, Figure 6c].

The hatched line in each plot of Figure 9 is a quadratic best fit, of the form $s = s_0 + vt + \frac{1}{2}at^2$. This introduces an acceleration, $a$, to the fitting process. The best fit velocity components (at TH-A) are $v = 301$ km s$^{-1}$ and 185 km s$^{-1}$, the offsets are $s_0 = -1153$ km and +88 km, and the acceleration terms are $a = -1.4$ km s$^{-2}$ and +0.12 km s$^{-2}$ (therefore the hatched line for the 1442 UT FTE is barely distinguishable from the solid line).

The acceleration terms are small, and we conclude that these are negligible on the separation scale of the THEMIS spacecraft. In fact, the acceleration term for the 1442 UT FTE represents a slight acceleration, while the term...
for the 1434 UT FTE represents a small deceleration. Since
the separation of the THEMIS spacecraft is significantly
greater than the maximum proposed separation of the
Cluster spacecraft for the entire lifetime of that mission, we
can conclude that the assumption of constant velocity used
in multispacecraft timing is reasonable, at least on the
magnetopause flanks.

3.3.2. Cluster

[28] The magnetic field observed by Cluster is also shown
in boundary normal coordinates in Figure 6. Throughout
the interval, the Cluster spacecraft were situated in the
magnetosheath, and moved toward the magnetopause and
Southern Hemisphere cusp. Reverse polarity FTEs were
observed by all four spacecraft throughout the interval; the

Figure 6. Electron and magnetic field observations by the (top) THEMIS quintet and (middle) Cluster
quartet of spacecraft. Shown are electron spectrograms (omnidirectional spectra from TH-C and TH-E
and parallel pitch angles from Cluster 1), the magnetic field observed by all spacecraft tangential to the
magnetopause ($B_L$ and $B_M$), the normal components of the magnetic field for each spacecraft ($B_N$), and
the magnetic field strength $|B|$. (bottom) The IMF clock angle from Figure 2.
magnetic field signatures were initially weak (Figure 10), but became gradually stronger as the spacecraft approached the magnetopause (Figure 6).

The observation of standard polarity FTEs at THEMIS and reverse polarity FTEs at Cluster for the entire interval from 1100 to 1500 UT demonstrates that reconnection was occurring at the dayside magnetopause throughout this period, as also evident from the SuperDARN observations (Figure 3).

3.3.3. Double Star

TC-1 was located in the magnetosheath at 1100 UT (Figure 11), and crossed the magnetopause between 1132 and 1134 UT into the magnetosphere. The magnetopause normal was determined from minimum variance analysis over the interval 1130 to 1136 UT; the tangential vectors were determined using the same procedure as for THEMIS: $\mathbf{n} = (0.748, 0.434, -0.502)_{GSE}$, $\mathbf{l} = (0.457, 0.211, 0.864)_{GSE}$, and $\mathbf{m} = (0.481, -0.976, -0.040)_{GSE}$.

Figure 11 shows the electron, magnetic field and ion observations made by the Double Star TC-1 satellite between 1100 and 1230 UT. Figure 11 shows electron spectrograms for pitch angles parallel, perpendicular and antiparallel to the magnetic field; the magnetic field in boundary normal coordinates and the ion density and velocity (also in boundary normal coordinates). Electron data are full three-dimensional distributions which have been binned to pitch angles. The spacecraft was initially in the magnetosheath (evidenced by the cool, dense, isotropic electron distribution and large ion densities), where it observed a southward and dawnward directed magnetic field ($B_z < 0, B_y > 0$). At 1133 UT, TC-1 crossed the magnetopause, after which it observed a northward magnetic field ($B_z > 0$) and generally a hotter, rarer plasma distribution. There is some evidence for boundary layer structure shortly after the magnetopause crossing, corresponding to two brief reductions in the $B_z$ component, which remained positive, at 1136 and 1139 UT. At these times, the electron spectrum changed to one that was more magnetosheath-like but with lower fluxes. The spacecraft then remained in the magnetosphere until 1200 UT, when it reentered the magnetosheath for 15 min, and then reentered the magnetosphere. Between 1130 and 1150 UT, the ion bulk velocity was highly variable, with peaks in magnitude that were greater than the magnetosheath bulk speed.

During this entire 90 min period, during which the spacecraft was near the magnetopause, only one clear flux transfer event was observed (a reverse polarity FTE at 1113 UT, highlighted by red lines in Figure 11). Figure 12 shows an enlargement of the electron and magnetic field data and the bulk ion speed for the 25 min period around the magnetopause crossing at 1133 UT. Just before the magnetopause crossing, the magnetosheath electron population appeared to be heated slightly (e.g., $\sim$1129 UT). After the magnetopause crossing at 1133 UT, a hotter, bidirectional, field-aligned electron distribution was observed, interrupted by two magnetosheath-like boundary layer entries and corresponding $B_z$ reductions noted in the previous paragraph. High-energy electrons with peak fluxes near 90° pitch angles, more typical of the magnetosphere proper, were initially weak in flux but became clearer by 1144 UT. The bidirectional field-aligned population was intermediate in energy between that of the 90° pitch angle magnetospheric population and the magnetosheath population.

The boundary layer structure observed by TC-1 and the observation of an FTE at 1113 UT suggest that reconnection also occurred near the location of TC-1. To test this hypothesis, we carried out a series of Walén tests [Walén, 1944; Sonnerup et al., 1987; Khrabrov and Sonnerup, 1998] on the ion velocities observed by TC-1 in a range of intervals about the magnetopause crossing time. Following the method of Khrabrov and Sonnerup [1998], we sought a so-called de Hoffmann–Teller frame with constant acceleration, in which the convection electric field ($E_C = -\mathbf{v} \times \mathbf{B}$) transformed to zero [de Hoffmann and Teller, 1950]. We found such a frame for the interval 1133:07 to 1133:32 UT (indicated by red lines in Figure 12). During this interval, there was a brief gap in the magnetometer data (see Figure 12), so the magnetic field data were interpolated where necessary. The velocity of the de Hoffmann–Teller frame was $\mathbf{V}_{HT} = \mathbf{V}_{HT0} + \mathbf{a}_{HT} \cdot t$, where $\mathbf{V}_{HT0}$ was (-171, 227, -138) km s$^{-1}$ and $\mathbf{a}_{HT}$ was (-4.15, -5.75, -8.27) km s$^{-2}$. The normal components $V_{HTn}$ and $a_{HTn}$ were 40 km s$^{-1}$ and -1.5 km s$^{-2}$, respectively, corresponding to an outward moving frame (consistent with the magnetopause moving outward across the spacecraft as observed). Figure 13a is a scatterplot of the convection electric field of the plasma in the GSE frame ($E_{C}$) against the electric field induced by the motion of the spacecraft.
Frame \( \mathbf{E}_{HT} = -\mathbf{V}_{HT} \times \mathbf{B} \)). The points relying on the interpolated magnetic field are identified by circles. The correlation is good (0.996), giving confidence that this procedure has found the de Hoffmann–Teller frame. If reconnection is ongoing and the magnetopause is therefore a rotational discontinuity, the Walén test should be satisfied: the velocity of the ions in the de Hoffmann–Teller frame should be equal to the Alfvén velocity \( \mathbf{V}_A = \mathbf{B} \sqrt{1/\rho_0 a} \), where \( \rho \) is the mass density, the pressure anisotropy \( a \) is \( (\rho_p - \rho_L)/\mu_0 B^2 \), and \( \mu_0 \) is the permeability of free space. It is shown in Figure 13b that this is the case for some of the data points. Those points in black represent the velocities in the de Hoffmann–Teller frame observed during the first four spins, when the density was above 1.5 cm\(^{-3}\), and all four points correspond well to the Alfvén velocity. Therefore the ion distributions with magnetosheath density but faster speeds correspond well to reconnection flows. The points in gray represent the following three spins, during which densities below 1.5 cm\(^{-3}\) were observed. Although these flows were indeed faster than the background magnetosheath velocity, they were slower than the calculated Alfvén velocity. However, it has been noted by Paschmann and Sonnerup [2008] that contrary to the MHD-based theoretical prediction, \( \rho(1 - \alpha) \) does not always remain constant within a rotational discontinuity. The reason for this discrepancy is not understood, but it has been found that the quality of the Walén test is often improved by replacing the observed plasma density by \( \rho = \rho_1(1 - \alpha_1)/(1 - \alpha) \), where \( \rho_1 \) and \( \alpha_1 \) are the mass density and anisotropy at a reference point upstream [Paschmann et al., 1986; Sonnerup et al., 1987; Phan et al., 2004; Retinó et al., 2005]. The results of the Walén test using this substitution in the calculation of the Alfvén velocity is shown in Figure 13c. \( \rho_1 \) and \( \alpha_1 \) refer to the parameters at 1128 UT. The substitution has a significant effect on the Alfvén velocity in the low-density region, and the Walén test is satisfied.

[34] We therefore find evidence for the magnetopause being open in the vicinity of TC-1 at the time of the magnetopause crossing. Furthermore, the prior passage of an FTE and the fast flows observed by the Pykviðar radar

Figure 8. Two FTEs which were observed by all THEMIS spacecraft. The spacecraft are ordered by position of the spacecraft along the magnetopause. Spectrograms are omnidirectional spectra of the electron differential energy flux observed by TH-C, TH-D, and TH-E, and line traces are the \( B_L, B_M, \) and \( B_N \) components observed by all five spacecraft.
Multispacecraft timing analysis. Each plot shows the time between the FTE being observed at TH-A and each of the other spacecraft against the separation of the spacecraft in the magnetopause plane. The solid line in each plot is a linear best fit; the hatched line is a quadratic best fit, and the dashed line is a straight line whose gradient is the speed given by the Cooling model discussed in section 4.

at 1040 UT, indicate that the magnetopause must also have been open nearby beforehand, and the observation of FTE signatures at THEMIS-C (Figure 7a) and Cluster (Figure 10) at the same time as the TC-1 magnetopause crossing indicates that reconnection continued elsewhere.

4. Discussion

[35] We shall now seek to understand the above observations in terms of a simple model of reconnected field line motion developed by Cooling et al. [2001] (hereinafter referred to as the Cooling model). This model is based on earlier work by Cowley and Owen [1989], who developed a simple expression for the velocity of a reconnecting magnetic field line as a function of the local magnetosheath magnetic field, density and velocity, based on stress balance at the magnetopause. The Cooling model evaluates this velocity at any given position on the magnetopause based on upstream IMF input by using models by Spreiter et al. [1966] and Kobel and Flückiger [1994] to evaluate the magnetosheath density/speed and magnetic field. The model has been used by several authors to explain observed FTE motion [e.g., Wild et al., 2005; Dunlop et al., 2005; Fear et al., 2005], and it has been tested in a statistical study by Fear et al. [2007].

[36] Figure 14 shows the results of the model run, using IMF conditions from 1113 UT, shortly before the TC-1 magnetopause crossing \[B_{\text{IMF}} = (-2, -4, -1)\text{GSM} \, \text{nT}, n_{\text{SW}} = 6 \, \text{cm}^{-3}, V_{\text{SW}} = 335 \, \text{km s}^{-1}\]. Figure 14 represents a view of the magnetopause as seen from the Sun; dotted concentric circles represent contours in \(X_{\text{GSM}}\). The Cooling model allows the user to specify an initial reconnection site, from which a component reconnection X line is traced for a user-specified length. The black line in the center of Figure 14 represents an X line, which has been initiated at the subsolar point with an arbitrary length of 12 \(R_E\). The length of the X line has been selected to illustrate a scenario where reconnection signatures are observed at THEMIS, Cluster and TC-1. The solid and dashed lines emanating from the X line are model flux tube paths for open magnetic field lines connected to the Northern and Southern Hemisphere, respectively; the lines represent the progression of the points at which specific open field lines thread the magnetopause as time progresses (from a time \(t = 0\) to a time 600 s later), and pairs of paths have been initiated at 2 \(R_E\) intervals. As expected for a period of dawnward \(B_y\)-dominated IMF, the flux tubes connected to the Northern Hemisphere move northward and duskward, while those connected to the Southern Hemisphere move southward and dawnward. Flux tubes connected to the Northern Hemisphere move predominantly northward at the dawnward end of the X line, and duskward at the dusk end; similarly flux tubes connected to the Southern Hemisphere moved predominantly southward/dawnward at the duskward/ dawnward ends.

[37] Flux tubes that are opened at the X line in Figure 14 move past both the THEMIS and Cluster spacecraft. The model flux tubes that move past Cluster are connected to the Southern Hemisphere, consistent with the observation of heated electrons moving parallel to the magnetic field (visible after 1300 UT in Figure 6) while those moving past THEMIS are connected to the Northern Hemisphere. Since the solar wind conditions are largely stable, similar model results are obtained using other solar wind inputs from the rest of the interval up to 1430 UT, when the IMF turned strongly northward (although the strong northward turn was not observed by THEMIS until after 1440 UT). Using the lagged IMF observed at 1435 UT \[B_{\text{IMF}} = (1.4, -1.9, 4.1)\text{GSM} \, \text{nT}\], the model FTE velocity at the location of TH-A is \((-125, -200, -60)_{\text{LMN}} \, \text{km s}^{-1}\), and the component along the THEMIS string is 226 km s\(^{-1}\). While the lagged IMF at this time is strongly northward and does not favor dayside reconnection, we note that this was during the interval between the strong northward rotation being observed in the lagged IMF data and at THEMIS. The magnetosheath clock angle observed by THEMIS was nearer to 65\(^\circ\)/70\(^\circ\) and therefore more favorable for dayside reconnection. Furthermore, the model FTE velocity is dominated by the magnetosheath velocity at this point (using an IMF of \((-0.5, -4.2, 1.3)\text{GSM} \, \text{nT}\) results in an FTE velocity of
This speed compares well with the speeds calculated in section 3.3.1 for the two FTEs which were observed by all five THEMIS spacecraft. It is indicated in Figure 9 by a dashed line in both plots which passes through the origin (representing TH-A) and which has a gradient of 226 km s\(^{-1}\). The dashed line is very similar to the best fit line for the FTE observed at 1434 UT, but is somewhat steeper than the best fit line for the 1442 UT FTE. Nevertheless, the Cooling model velocity is still consistent with the delay times between the FTE signatures being observed at almost all of the spacecraft within the stated error bars. The acceleration of the model flux tubes at the location of THEMIS is \(0.4\) km s\(^{-2}\), which is similar in magnitude to the acceleration values determined from Figure 9. However, this is clearly small compared with the uncertainties in the observational determination of the acceleration, since the difference between the two values obtained observationally was of the same order as the values themselves.

Snapshots of the plasma moments were available from TH-C, TH-D and TH-E every few minutes. At around this time, the magnetosheath velocity observed by TH-D was \((-30, -130, -30)_{\text{LAMN}}\) km s\(^{-1}\). The component of this velocity along the projection of the spacecraft string onto the magnetopause was \(-130\) km s\(^{-1}\). Therefore both FTEs appeared to be moving faster than the background magnetosheath flow, as a result of the magnetic tension acting on the FTE (which is incorporated into the Cooling model). The model magnetosheath velocity at TH-D was \((-43, -187, -55)_{\text{LAMN}}\) km s\(^{-1}\) (191 km s\(^{-1}\) along the string). The discrepancy of 60 km s\(^{-1}\) between the observed and modeled magnetosheath speeds is one factor in the 37 km s\(^{-1}\) model overestimation of the observed velocity component of the 1442 UT FTE, although the model FTE velocity was a slight underestimate for the 1434 UT FTE.

The speeds quoted above (both those derived from observations and from the Cooling model) are estimates for the components of the FTE velocity along the spacecraft string. Since the THEMIS spacecraft were aligned in the azimuthal \((\mathbf{m})\) direction, this corresponds broadly to the tailward components of the FTE velocities. Since the spacecraft were aligned in a string, we cannot derive the three-dimensional velocity from multispacecraft methods, but we note that the 3-D Cooling model velocity was only 22° from the projection of the spacecraft string onto the magnetopause surface, therefore it is likely that the velocity components calculated from the observations are very similar to the total FTE speeds.

We can compare this direction of the model velocity vector with single-spacecraft estimates of the FTE axial orientation; one way to estimate the FTE axis is by applying minimum variance analysis to magnetic field data in modeled flux ropes, and found that the eigenvector corresponding to the axis depended critically on the path of the spacecraft relative to the flux rope and on the model of flux rope assumed. They found that if their modeled spacecraft path crossed only the region of draped magnetic field around the flux tube (as previously modeled by \textit{Farrugia et al.} [1987]), the axial direction was indicated by the minimum variance direction, since in the assumption of incompressible flow made by \textit{Farrugia et al.} [1987] the magnetic field line was not deflected in the axial direction. If the modeled spacecraft cut through a force-free flux rope, the intermediate variance direction indicated the axial orientation of the flux tube.
Figure 11. Electron and magnetic field observations from TC-1. Electron spectrograms for pitch angles parallel, perpendicular, and antiparallel to the magnetic field; the magnetic field; and ion moments in boundary normal coordinates are shown. The red lines indicate an FTE observed by TC-1.
The electron spectra, magnetic field, and the ion bulk speed observed by TC-1 at the magnetopause. The red lines indicate the interval used for the Walén test in Figure 13.

Figure 13. The results of the Walén test carried out on data between 1133:07 and 1133:32 UT. (a) The electric field caused by magnetic field convection observed in the GSE frame \( \mathbf{E}_C = -\mathbf{v} \times \mathbf{B} \), where \( \mathbf{v} \) is the ion bulk velocity) plotted against the electric field induced by the accelerating de Hoffmann–Teller (dHT) frame \( \mathbf{E}_{HT} = -\mathbf{v}_{HT} \times \mathbf{B} \), where \( \mathbf{v}_{HT} \) is the time-varying velocity of the frame in GSE coordinates). The good correlation between the two quantities shows that the selected transformation has correctly identified the dHT frame. (b) The ion bulk velocity in the dHT frame plotted against the Alfvén velocity, which is calculated using the observed ion density. Points corresponding to a density lower than 1.5 cm\(^{-3}\) are shaded gray, and points using interpolated magnetic field measurements are encircled. The flows observed in higher-density regions are at the Alfvén velocity in the dHT frame and can therefore be identified as reconnection jets. The flows observed in this interval while the density is low are also faster than the magnetosheath velocity, but the calculated Alfvén velocities are higher than the observed flows. (c) The ion bulk velocity in the dHT frame plotted against the Alfvén velocity calculated using the substitution \( \rho = \rho_0 (1 - \alpha_1) (1 - \alpha) \).
direction reasonably well, and if the spacecraft cut through a flux rope with a strong core field, then either the maximum or intermediate eigenvectors approximated the axis (depending on the proximity of the spacecraft pass to the center of the flux rope). Therefore interpretation of MVA results on FTE signatures must be treated with caution.

None of the spacecraft observed a strong core field during either FTE (Figure 8). We can determine whether the spacecraft entered onto the reconnected “core” of the FTEs by examining the electron spectrograms for each spacecraft, which are available from TH-C, TH-D and TH-E and are shown in Figure 8. TH-C and TH-D were situated in the magnetosheath, and observed no significant change in the electron distribution during the passage of either FTE. Therefore these spacecraft only observed the region of draped flux around the FTE core. (A slight heating was observed in the ions, not shown, but this may be a remote sensing effect as the spacecraft moved closer to open field lines and were therefore able to observe heated ions due to their larger gyroradii.) TH-E observed the 1434 UT FTE as it crossed the magnetopause, and therefore it is likely that TH-E entered onto open magnetic field lines although there is no sign that the magnetosheath plasma observed during the FTE has been heated. TH-E observed a slight increase in the flux of hot electrons ($\sim 300–1000$ eV) during the passage of the 1442 UT FTE. No plasma observations were available from TH-A or TH-B, but by this time both spacecraft were located further out into the magnetosheath than TH-C, so the absence of reconnection signatures at TH-C suggests that TH-A and TH-B both only observed the field line draping around the FTEs.

The results of MVA on the magnetic signatures of both FTEs are shown in Table 1. The minimum and intermediate variance eigenvectors were not very well defined in any of the cases (the ratios of the intermediate to minimum variance eigenvalues ranged between 1.66 and 2.20 for the first FTE), which is in part due to the small number of FGM data points during each FTE passage, since high-resolution data were not available after 1314 UT. It is therefore likely that in some cases the MVA technique fails to recover the axial direction. However, four of the five minimum variance eigenvectors were aligned within $\sim 25^\circ$ of $l$ (the exception being TH-C). Since it appears likely that TH-E observed open magnetic field lines, it is surprising that the minimum variance eigenvector is similar to three of the other four vectors. One would expect the intermediate eigenvector, $(0.092, 0.991, 0.093)$, to indicate the axial direction if TH-E did make a crossing of the flux tube (the eigenvalue ratio $\lambda_{\text{max}}/\lambda_{\text{int}}$ was 2.11). For the second FTE there was more variation, but we note that the magnetic field signatures observed by TH-B, TH-C and TH-D were weak (Figure 8), and the minimum variance eigenvalue for TH-E was particularly poorly defined ($\lambda_{\text{int}}/\lambda_{\text{min}} = 1.3$). The minimum variance eigenvector for TH-A was again close to $l$. To summarize, MVA results from TH-A (both FTEs) and TH-B and TH-D (1434 UT) indicate that the axial
Table 1. Results of Minimum Variance Analysis on the Flux Transfer Events Observed by All Five THEMIS Spacecraft

<table>
<thead>
<tr>
<th>Time</th>
<th>Spacecraft</th>
<th>Minimum Variance Eigenvector</th>
<th>λ_{max}/λ_{min}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1434 UT</td>
<td>TH-A</td>
<td>(0.926, -0.011, -0.378)</td>
<td>2.15</td>
</tr>
<tr>
<td>1434 UT</td>
<td>TH-B</td>
<td>(0.893, 0.167, -0.419)</td>
<td>1.66</td>
</tr>
<tr>
<td>1434 UT</td>
<td>TH-C</td>
<td>(0.315, 0.724, -0.614)</td>
<td>2.09</td>
</tr>
<tr>
<td>1434 UT</td>
<td>TH-D</td>
<td>(0.929, 0.043, -0.368)</td>
<td>1.99</td>
</tr>
<tr>
<td>1434 UT</td>
<td>TH-E</td>
<td>(0.921, -0.049, -0.386)</td>
<td>2.20</td>
</tr>
<tr>
<td>1442 UT</td>
<td>TH-A</td>
<td>(0.962, -0.272, -0.019)</td>
<td>2.54</td>
</tr>
<tr>
<td>1442 UT</td>
<td>TH-B</td>
<td>(0.644, 0.620, 0.499)</td>
<td>2.11</td>
</tr>
<tr>
<td>1442 UT</td>
<td>TH-C</td>
<td>(0.495, 0.743, -0.450)</td>
<td>1.70</td>
</tr>
<tr>
<td>1442 UT</td>
<td>TH-D</td>
<td>(0.417, 0.909, -0.125)</td>
<td>1.49</td>
</tr>
<tr>
<td>1442 UT</td>
<td>TH-E</td>
<td>(0.638, 0.725, -0.260)</td>
<td>1.34</td>
</tr>
</tbody>
</table>

*The minimum variance eigenvector is an estimator of the flux tube orientation and is quoted in boundary normal coordinates. Results from weak B_y signatures are marked by italics.

5. Conclusions

[46] We have presented observations from a 5-h interval on 3 May 2007, throughout which signatures of time-varying reconnection were observed by the THEMIS and Cluster spacecraft and some of the SuperDARN ionospheric radars. Cluster was situated in the high-latitude, prenoon magnetosheath, and THEMIS was at the postnoon equatorial magnetopause. THEMIS and Cluster observed flux transfer event signatures throughout the interval (standard and reverse polarity), which can be traced back using a model to within ~2 R_E of the subsolar point. TC-1 crossed the magnetopause approximately 7 R_E from the subsolar point, and was near the magnetopause for approximately 90 min. During this time, TC-1 only observed a single (reverse polarity) flux transfer event. A Walén test was carried out on the ion velocity data from the magnetopause crossing, which showed that the enhanced ion velocities were consistent with those expected from ongoing reconnection. Therefore the reconnection line extended by at least 2 R_E from the subsolar point into the postnoon sector throughout the period 1100–1500 UT, and at the time of the TC-1 magnetopause crossing extended to at least 7 R_E from the subsolar point. Ionospheric observations suggest the X line covered several hours of local time in the prenoon sector, but the different rates of FTE occurrence observed TC-1 and THEMIS/Cluster suggest that the variation in reconnection rate differed between the subsolar point and the location of TC-1.

[47] The observation of two flux transfer events by all five of the THEMIS spacecraft allowed the motion of the structures to be tracked for over a minute. It was found that, consistent with the predictions of the Cooling model, the acceleration of the FTEs was small (less than 1 km s^{-2}), demonstrating that determination of FTE velocities from multispacecraft timing techniques is reliable.

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References


