Generation and properties of in vivo flux transfer events

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[1]   Of the 3701 flux transfer event signatures that we identified in THEMIS data between May and October of 2007 and 2008 at low-latitudes on the magnetopause, 41 were distinctive in that the north-south flow components reversed direction during the ~1 min required for THEMIS spacecraft to traverse the structure. We have ruled out the possibility that these 41 "flow reversal events" (FREs) were single X-line structures in motion, and confirmed from their field and plasma properties that they indeed were flux ropes. We have interpreted the plasma flow reversal as evidence that we observed the flux ropes while they were being generated by a pair of X-lines that developed in sequence through component merging, a process that seems to play a significant role in forming flux ropes. Our analysis, which applies only to low latitude flux ropes, provides evidence to modify the updated multiple X-line reconnection scenario with component merging as the dominant associated reconnection process.

1.   Introduction

[2]   "Flux transfer event" (FTE) is a phenomenological definition for a type of event observed on the dayside magnetopause. FTEs were first identified by *Russell and Elphic* [1978] from the observations of ISEE 1 and 2 at the low-latitude magnetopause. Their characteristic signatures are bipolar perturbations in the component of the magnetic field normal to the magnetopause (B_N), accompanied by variations in the field magnitude (B_T). Although these signatures can be interpreted as deformation of the magnetopause surface by solar wind pressure pulses or as the results of surface waves traveling along the magnetopause [*Lemaire et al.*, 1979; *Sibeck et al.*, 1989; *Sanny et al.*, 1996], particle signatures imply that FTEs are magnetic reconnection-associated phenomena. In the absence of reconnection, the magnetopause is a tangential discontinuity magnetically separating the magnetosheath and the magnetosphere and no exchange of plasma takes place between these two regions. However, plasmas of both magnetosheath-origin and magnetosphere-origin have been detected [*Daly et al.*, 1981] within an FTE. The mixture of plasmas implies that the magnetosphere and the magnetosheath must have been magnetically connected within the FTE structures and that magnetic reconnection must have occurred on the magnetopause. In addition, FTEs typically occur during intervals of southward interplanetary magnetic field (IMF) or when the IMF has a significant B_Y component [*Berchem and Russell*, 1984; *Kawano and Russell*, 1997]. These are the conditions for which magnetic reconnection readily takes place.

[3]   It is widely accepted that the generation mechanism of FTEs relates to magnetic reconnection; however, how reconnection leads to an FTE remains under debate. In the literature, several models of the structure and formation mechanism of FTEs have been proposed. When FTEs were first discovered, *Russell and Elphic* [1978] proposed that they are generated by reconnection occurring at a transient X-line of limited width along the magnetopause. The model was called the transient and patchy reconnection model. In this model, the newly reconnected flux tube was regarded as a structure containing untwisted magnetic fields that produced FTE-like perturbations in the ambient plasma and field as it moved along the magnetopause. However, *Paschmann et al.* [1982] noticed that even inside the newly reconnected flux tube there were bipolar variations in the field component normal to the magnetopause, which indicated that the flux tubes were actually flux ropes. In fact, the inward gradient of the sum of plasma and magnetic pressures inside these structures also requires FTEs to be flux ropes with twisted fields so that the tension force from the

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helical magnetic field may counteract the pressure gradient forces [*Paschmann et al.*, 1982].

[4] Another single X line model for FTEs was developed independently by *Scholer* [1988] and *Southwood et al.* [1988]. In this model, a single X-line extends for a considerable distance along the magnetopause and reconnection at this X-line is also transient. Far from the reconnection site, the plasma and field remain undisturbed; while near the reconnection site plasma is accelerated abruptly, thus forming a bulged bubble-like magnetic structure that moves principally poleward away from the reconnection site. FTE signatures will be recorded if the magnetic bubble structure moves over a spacecraft at a location close to the magnetopause.

[5] *Lee and Fu* [1985] proposed a multiple X-line model for FTEs (flux ropes), in which at least two X-lines are needed. Reconnection occurs simultaneously at those X-lines and generates a helical magnetic flux rope in between. Recently, a global magnetohydrodynamic (MHD) simulation [*Raeder*, 2006] supported the multiple X-line scenario; however, in this updated model the two X-lines form successively and whether or not the second X-line forms depends on the tilt of the magnetic dipole of the Earth. Recent observations support this updated multiple X-line model [*Hasegawa et al.*, 2010; *Trenchi et al.*, 2011; *Oieroset et al.*, 2011].

[6] *Liu and Hu* [1988] and *Pu et al.* [1990] proposed a flow vortex-induced reconnection model for the flux rope-type structure and formation of FTEs. In this model, FTE structures consist of helical magnetic field lines rolled up by flow vortices that allow reconnection to occur in the interior. In fact, flow vortices are commonly observed near the magnetopause when the Kelvin-Helmholtz instability (KHI), driven by the strong flow shear between the fast solar wind and the stagnant magnetospheric plasma, has grown to a nonlinear phase. Observations also show that reconnection can occur within those KHI flow vortex structures [*Hasegawa et al.*, 2009]. A recent resistive MHD simulation [*Dorelli and Bhattacharjee*, 2009] supported this model. In this simulation the helical magnetic field lines rolled up by flow vortices produce FTE signatures before reconnection initiates. Thus, Dorelli and Bhattacharjee concluded that flow vortices, instead of reconnection, initiate the formation of FTEs and that reconnection can occur within the rolled-up structures.

[7] The aforementioned models make different predictions regarding the plasma flow within a developing FTE, which we refer to as an "in vivo FTE." For single X-line models, either the transient and patchy reconnection model or the magnetic bubble model, the newly formed structure moves away from a single X-line. If an observing spacecraft traverses this type of magnetic structure which is located on one side of the X-line, we expect that the plasma flow (the jet flow from the X-line) will deviate little in direction tangential to the local magnetopause during the encounter. However, in the multiple X-line model, because two X-lines are required to generate a flux rope and the jet flows from these two X-lines are oppositely directed inside the flux rope, one expects that a spacecraft crossing the in vivo FTE structure will observe a flow reversal. Obviously, for the 'flow vortex-induced reconnection model', there should be a flow vortex inside a developing FTE.

[8] For an investigation of the FTE-generation phase, previously published works shed little light because they do not focus on the generation phase of the structures. For example, in their study of FTE signatures, *Zhang et al.* [2011] identified flow vortices in the vicinity of FTEs but did not detect such signatures inside of FTEs. If a flow vortex exists within an FTE, bipolar variations in the flow component normal to the magnetopause should be seen inside of the structure. However, the failure to observe flow vortices inside FTEs cannot exclude the possibility that flow vortices can produce flux ropes (FTEs). *Zhang et al.* [2011] also reported that inside most of FTEs the flow component tangential to the magnetopause did not change sign. However, the failure to observe bi-directional flows in most events cannot be said to support any particular model, because these FTE structures were not necessarily observed during their formation. Most of the signatures were probably those of fully developed FTEs moving in nearly steady state along the magnetopause long after they were born. More recently, *Hasegawa et al.* [2010] reported one FTE event during which the magnetopause tangential plasma flow changed direction within the FTE structure. They concluded that the FTE was observed when it was developing as shown in Figure 1a and that their observations support the multiple X-line model of FTEs of *Lee and Fu* [1985] and *Raeder* [2006].

[9] Although, in the summary above, the bi-directional flow has been linked to the multiple X-line model of FTE generation, flow reversals in conjunction with bipolar B_N signatures can be observed in other situations. For example, a spacecraft can observe a flow reversal concurrent with a bipolar B_N perturbation as it traverses either a multiple X-line structure (see Figure 1a) or as it moves relative to a single X-line structure (from one jet flow region of reconnection to the other side [e.g., *Pu et al.*, 2005]) (see Figure 1b). The two different models can produce identical polarities of the bipolar B_N and V_L signatures (see Figure 1c) provided that the motion of the structures relative to the spacecraft is in opposite senses for the two scenarios as shown in Figures 1a and 1b. For a $+/-$ polarity of the bipolar B_N associated with a $-/+$ polarity of V_L as in Figure 1c, the signatures will be present if the flux rope structure in Figure 1a moves northward relative to the spacecraft, or if the single X-line moves southward in Figure 1b. This ambiguity will be kept in mind as we consider details of the observations. Figure 1 presents the case with X-line(s) extending purely in the M direction and the structures moving along the local magnetopause in the south-north direction. However, if the X line(s) tilt northward, motion of structures in the dawn-dusk direction can also produce the signatures shown in Figure 1c.

[10] In this paper, we analyze bi-directional flows associated with FTE-like signatures, and we confirm that they are in vivo flux rope structures by excluding the possibility of single X-lines in motion. Initially we identified signatures of FTEs in the data collected by THEMIS during their magnetopause crossings from May to October, 2007 and 2008 using magnetic and plasma data. We obtained a total of 3701 instances of FTE signatures. Next, we examined the flow signatures associated with these magnetic structures. We found 41 events during which the flow components in the south-north direction changed sign within the FTE
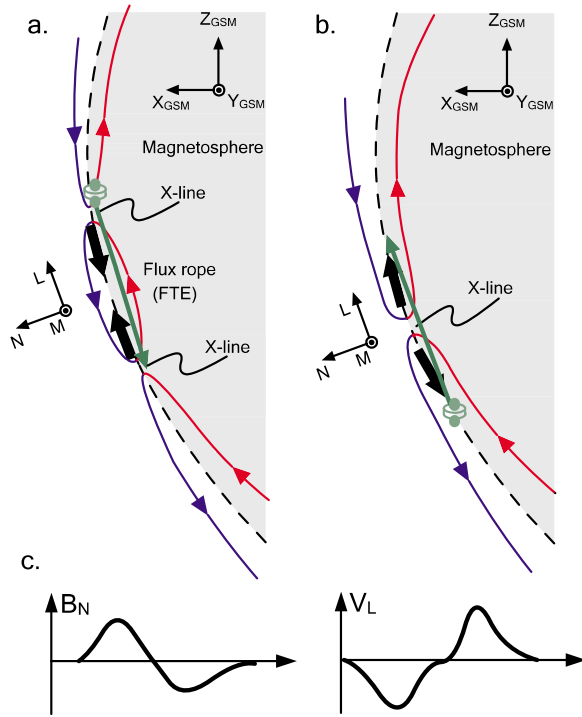
Figure 1. Two interpretations of flow reversal observed on the dayside magnetopause. (a) A flux rope is being generated by reconnection occurring on two X-lines. Blue lines show the field lines initially from the magnetosheath, the red lines show the field lines from the magnetosphere, and the dashed line indicates the initial location of the undisturbed magnetopause. The thick black arrows indicate the flow jets from reconnection site and the green arrow denotes the trajectory of an observing spacecraft. (b) Magnetic reconnection is going-on on a single X-line. The color code is the same as for Figure 1a. (c) The signatures of B_N and V_L observed by spacecraft in Figures 1a and 1b.

signatures. We have named events with such signatures: "flow reversal events" (FREs). Further analysis confirms that all these FREs are developing FTEs, and that they are not structures produced by single X-lines in motion. The flow reversals inside the FTEs suggest that they are generated by two X-lines, supporting the multiple X-line reconnection model.

[11] In the next section, we present case studies of two FREs and discuss the statistics of all 41 FREs in our data set. We discuss the FTE generation mechanism in section 3, and summarize our observations and conclusions in section 4.

2. THEMIS Observations

2.1. Instrumentation and Event Selection

[12] The THEMIS mission includes five low-latitude spacecraft. During the months from May to October 2007–2008, they crossed the dayside magnetopause twice per orbit [*Sibeck and Angelopoulos*, 2008]. The data presented in the current paper were collected during those magnetopause crossings by the electrostatic analyzers (ESA) [*McFadden et al.*, 2008] and the fluxgate magnetometers (FGM)

[*Auster et al.*, 2008]. All the data were used at the time resolution of 3 s.

[13] For studies of structures near the magnetopause, it is helpful to rotate data into a magnetopause local coordinate system (LMN). We establish the coordinate system as follows: First of all, we determine the outward normal to the local magnetopause, $\vec{N}$, by using an empirical magnetopause model [*Shue et al.*, 1998]; then we determine the azimuthal unit vector $\vec{M}$ from $\left(\vec{Z}_{GSM} \times \vec{N}\right)/\left|\vec{Z}_{GSM} \times \vec{N}\right|$, positive toward dusk; finally, $\vec{L} = \vec{N} \times \vec{M}$ completes the orthogonal coordinate system with $\vec{L}$ positive northward. From May to October in 2007 and 2008, we identified a total of 3701 instances of bipolar magnetic variations in the magnetopause normal direction associated with enhancements of field magnitude and total pressure as FTEs previously reported by *Zhang et al.* [2011]. Examining the flows associated with these FTE signatures, we found that in some events the flow component tangential to the magnetopause along the north-south direction (V_L) changed sign. These events are the ones that we call 'flow reversal events' (FREs). We selected 41 of these events during which the flow component V_L changed by more than 100 km/s, and they form the database for the present paper.

2.2. Two FRE Event Studies
2.2.1. Event of July 27, 2008

[14] At about 20:10 UT on July 27, 2008, two spacecraft, THEMIS-D (THD) and THEMIS-E (THE), were inbound near their apogees on the duskside magnetopause. Figure 2a shows data collected by THE from 20:10:30 UT to 20:14:30 at (9.67, 4.64, −3.50) R_E in the GSM coordinate system. From top to bottom, Figure 2a shows the magnetic field and the plasma velocity in the LMN coordinate system, the number density and the temperature of ions and electrons, the energy spectrum of ions and the pitch angle distribution of ions with energy below 10 keV. Before 20:12 UT, THE was located within the magnetosphere. In this region, the magnetic field was about 50 nT, dominantly in the L direction; there was no significant plasma velocity; the number densities of ions and electrons were ∼1.0 and ∼2.0 cm^{-3}, respectively; the ion temperature was about 1 keV and high energy magnetospheric ions (above 4 keV) were present as clearly seen in the 5th panel. After 20:12 UT, the spacecraft entered into the low latitude boundary layer (LLBL). Here, the magnitude of the magnetic field was close to that in the magnetosphere and, although the field remained closely aligned with the L-direction, the B_M component became stronger (∼10 nT); the number density and temperature of ions and electrons were typical of the magnetosheath (number density about 10.0/cm^3 and ion temperature: 300 eV; electron temperature: 50 eV); both high-energy (above 4 keV) and low-energy ions were seen in the energy spectrum plot.

[15] Just after THE entered the LLBL, it recorded an FRE in which the plasma flow, V_L, was initially positive (northward) and then became negative (southward). Within this duskside LLBL, the velocity in the M direction (V_M) was positive (duskward) at an averaged flow velocity of ∼100 km/s (the instant peak of V_M was as big as 200 km/s). These flow perturbations were closely associated with the bipolar B_N variation. Within the bipolar B_N, the field magnitude of B_T varied, increasing slightly above the magnitude
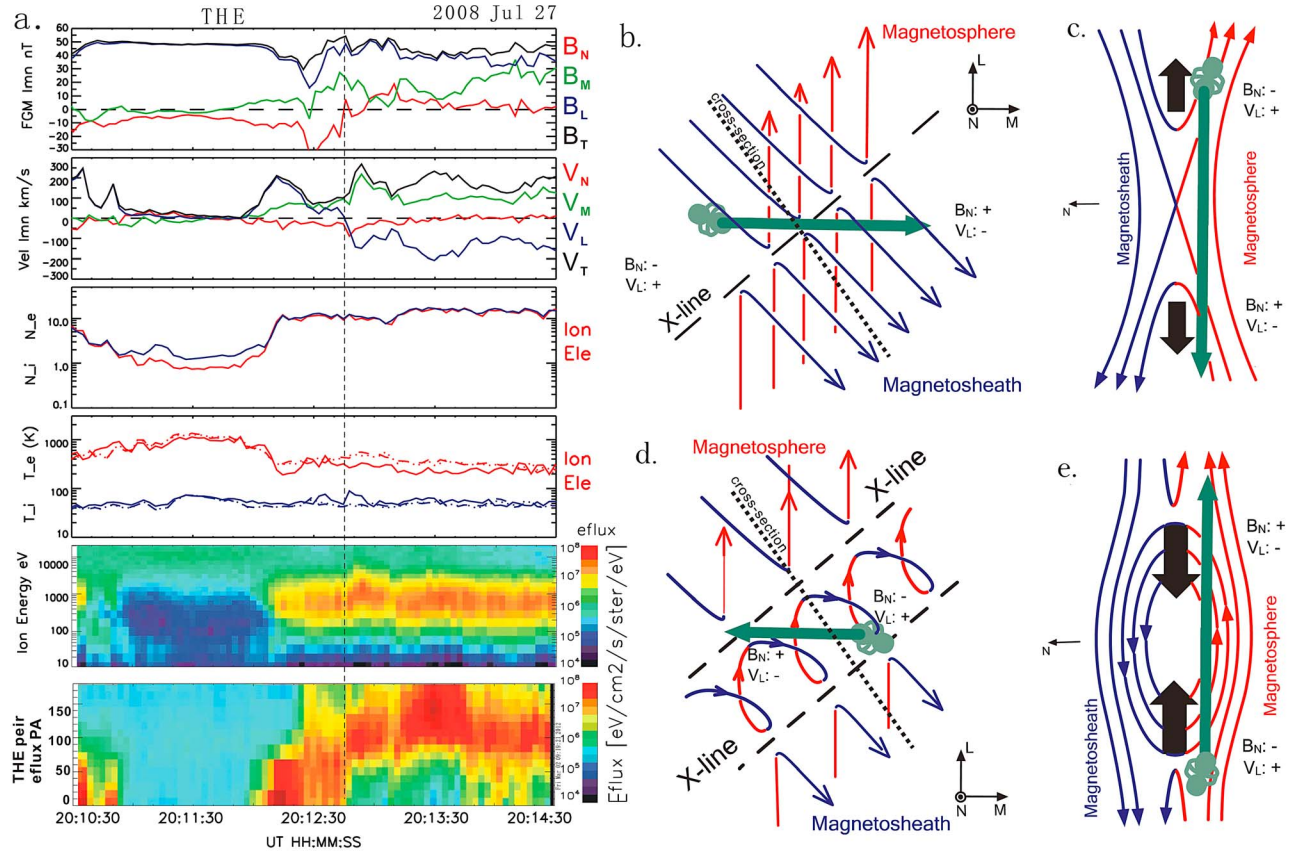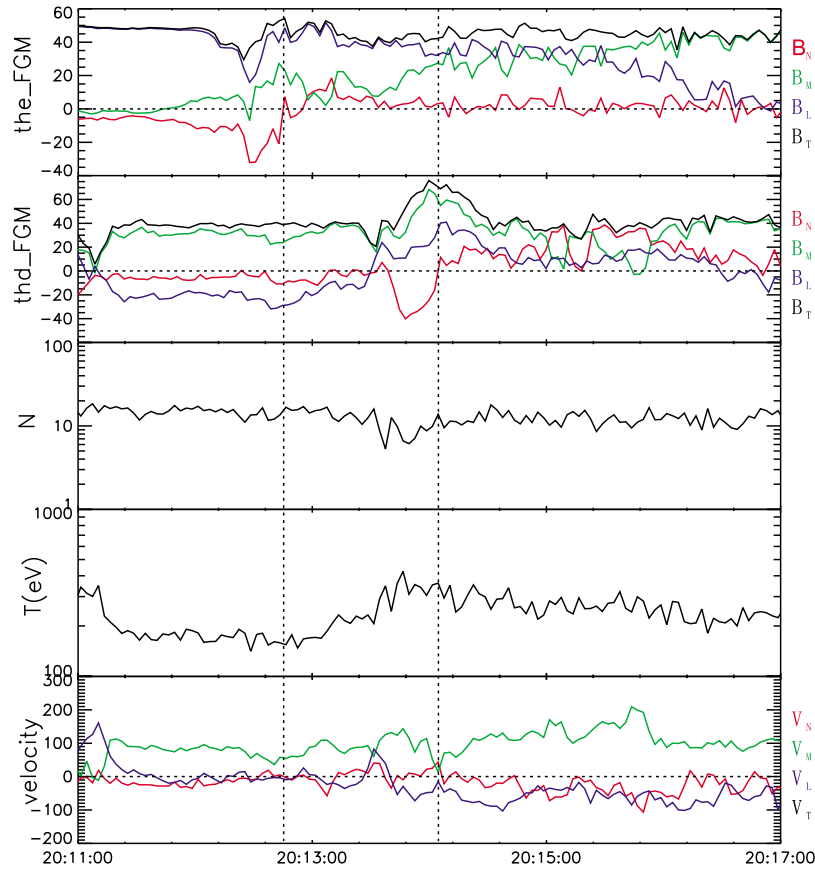
Figure 2. The FRE on July 27, 2008. (a) The observations from THE. From top to bottom are: the magnetic field in the LMN coordinate system; the plasma velocity in the LMN coordinate system; the number densities of ions (red) and electrons (blue); the temperatures of ions (red) and electrons (blue); the energy spectrum of ions and the pitch angle distribution of ions with energy below 10 keV. (b) The observations in Figure 2a can be interpreted as those that would be found if an observing spacecraft crossed from the northern branch to the southern of a single X-line which extended along the low-latitude magnetopause, trending northward and duskward corresponding to a 120 degree IMF clock angle. Figure 2b plots the view looking inward along the magnetopause normal direction. The blue curves show the portions of field lines initially from the magnetosheath and the red curves denote the portions of field lines initially from the magnetosphere, and the spacecraft was located in the 'red' magnetic field region (LLBL). Here, the spacecraft traversed the structure from the northern branch to the southern branch mainly because of the motion of the tilted X-line structure in the dawnward direction. The green arrow indicates that the spacecraft moved duskward in the frame of a fixed X-line. (c) The projections of the magnetic field and the spacecraft trajectory on a cross section plane shown by the dotted line in Figure 2b (view along the X-line). (d) The observations in Figure 2a can also be interpreted as those that would be found if the observing spacecraft traversed from the southern branch to the northern branch of a flux rope which was being generated by two X-lines extending along the low-latitude magnetopause, trending northward and duskward. The color codes are the same as for Figure 2b and the spacecraft was in the 'red' field region (LLBL). The spacecraft traversed the structure from the southern branch to the northern branch mainly because of the motion of the flux rope in the duskward direction. The green arrow denotes the dawnward motion of the spacecraft relative to the structure. (e) The projections of the magnetic field and the spacecraft trajectory on a cross section plane shown by dotted line in Figure 2d.

of the background magnetospheric and LLBL field. Near the center of the bipolar B_N signature, the field magnitude dipped a bit (around 20:12:50 UT, right after the vertical dashed line in Figure 2a). The polarity of B_N was $(-/+)$, which was opposite to the polarity of V_L $(+/-)$.

[16] The observations noted that the bipolar B_N and the bipolar V_L can be interpreted as the signature of a single X-line in motion relative to the observing spacecraft, as

shown in Figures 2b and 2c. Let us assume that magnetic reconnection was taking place on an X-line on the duskside magnetopause. During this FRE, the ACE spacecraft, located close to the first Lagrange point (L1 point), monitored the solar wind and the interplanetary magnetic field (IMF). There was no significant variation in ram pressure in the solar wind. The IMF was observed to be $[-3.48, 4.17, -2.99]$ nT in the GSM coordinate system, corresponding to

Figure 3. The observations from THD for the FRE event on July 27, 2008. From top to bottom are: the magnetic field observed by THE, which is used for time reference; the magnetic field observed by THD; the ion number density observed by THD; the ion temperature and the plasma velocity in the LMN coordinate system.

a 126 degree IMF clock angle. For this IMF clock angle, it is reasonable to assume that the X-line extended along the low-latitude magnetopause northward and duskward as shown in Figure 2b [*Cooling et al.*, 2001; *Moore et al.*, 2002; *Eriksson et al.*, 2004]. If the initial position of THE was north of the X-line, the observations at THE could be interpreted as the result of the motion of the reconnection structure relative to the spacecraft. Northward of the reconnection line, B_N would initially be negative, V_L would be positive, and the sheath-origin ions would flow into the magnetosphere (LLBL) along the magnetic field direction (both V_L and B_L are positive; see Figure 2c). With continued dawnward and/ or northward motion of the X-line, for example, dawnward motion of the X-line as shown in Figure 2b (the observing spacecraft moved duskward relatively to the X-line), THE would eventually find itself in the southern branch of the structure (see Figure 2c). In this region, B_N would be positive, V_L would be negative, and the sheath-origin ions would flow antiparallel to the magnetic field (V_L is negative and B_L is positive) into the magnetosphere (LLBL), as in the data. That is to say, it is possible that this event with a bipolar B_N signature is an X-line structure in motion instead of an FTE.

[17] However, all these observations can also be interpreted in the context of an in vivo flux rope generated by reconnection on two X-lines [*Lee and Fu*, 1985; *Raeder*, 2006], but in this case, the whole magnetic structure would

be moving duskward and/or southward over the observing spacecraft. Figures 2d and 2e show the case of duskward motion of the flux rope (so the observing spacecraft, THE, moved dawnward relatively). With THE starting in the southern branch, the magnetic structure would be seen as a negative B_N and positive V_L. In the northern branch of the structure, the signs of B_N and V_L would change. The field magnitude increased slightly above background during the event (the black curve in the first panel in Figure 2a), and this local field maximum suggests that the structure was more likely to have been a flux rope (Figures 2d and 2e) rather than a single X line since such a field enhancement is not expected for a reconnection structure of the form shown in Figure 2c.

[18] Although interpretations of THE observations are ambiguous, the magnetic structure observed nearly concurrently at THD is hard to explain other than as a flux rope (Figure 3). When THE encountered the structure (20:12:45 UT), THD was located at (9.51, 5.70, −3.28) R_E in GSM, 1 R_E eastward and slightly northward (0.2 R_E) of THE. At that time, THD was in the magnetosheath and observed southward B_L (−20 nT) and duskward B_M (35 nT) (the second panel in Figure 3), on the basis of which, we found that the IMF clock angle for this event was about 120°, which was consistent with the ACE observations. The ions had typical sheath properties with a number density of
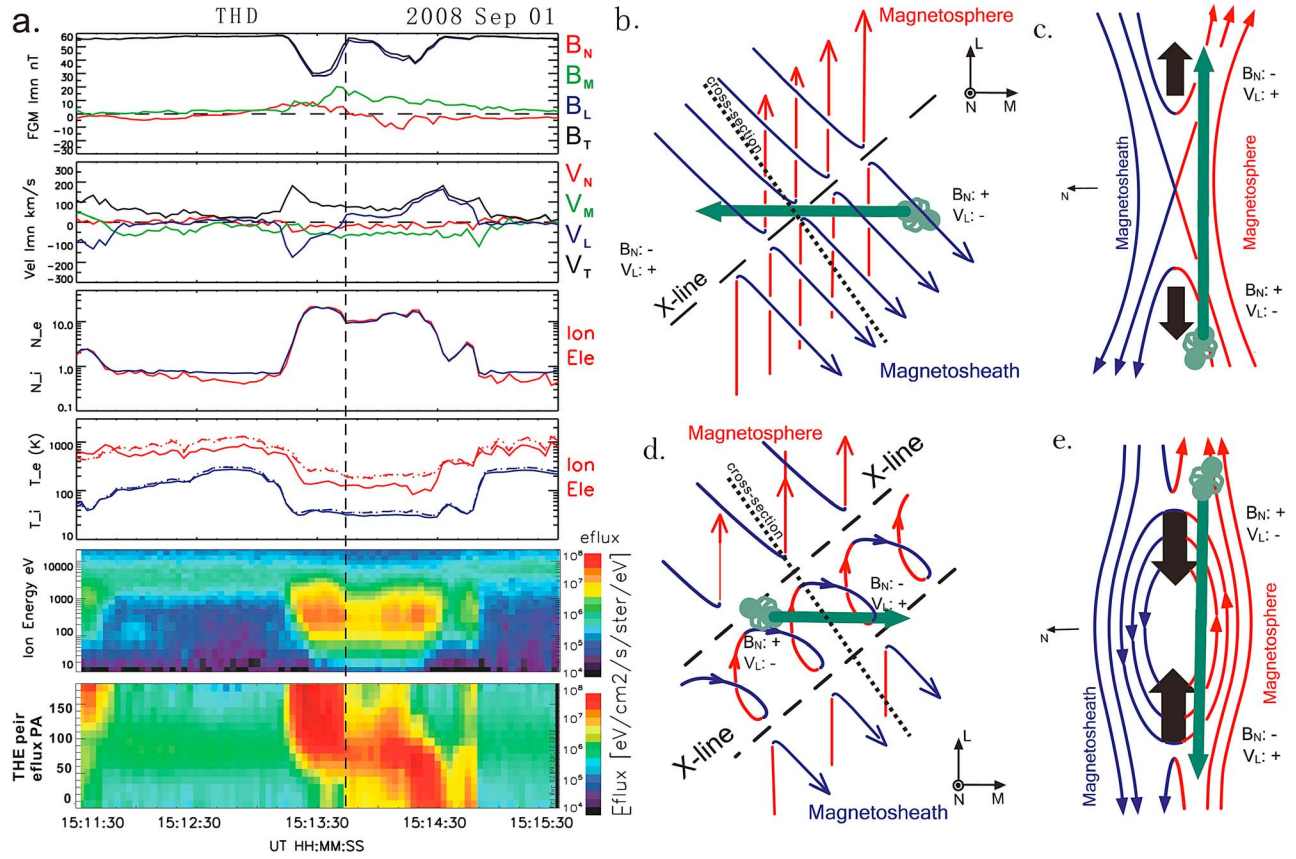
Figure 4. The FRE on September 1, 2008. All the formats are the same as in Figure 2. This event was detected on the dawnside magnetopause and the polarities of B_N and V_L were opposite to those in the previous event.

$10/cm^3$ and a temperature of 150 eV (the third and fourth panels in Figure 3). In the magnetosheath, the background velocity was 100 km/s, dominantly duskward (the fifth panel in Figure 3). About 1 min later, THD detected a bipolar variation in the B_N component with the same $-/+$ polarity observed at THE. The field magnitude B_T increased significantly from a background level of 40 nT to almost 80 nT. The plasma flow inside this magnetic structure did not reverse direction. Particularly because of the strong core field, the observations indicate that the magnetic structure that passed over THD was not a single reconnection line in motion but rather a flux rope (FTE). THE and THD were separated by 1 R_E in the M direction. From the 70 s time delay of signatures at these two spacecraft and the assumption that they were observing the same structure, we can estimate that the component of the structure's velocity in the M-direction was 97 km/s, although to determine the velocity of the flux rope motion in the ML plane by timing analysis we need to know the axis orientation of the flux rope. Because of the flow reversal observed within the structure, we interpret the THE signature as that of an FRE, an in vivo flux rope (see Figures 2d and 2e). The dip in the field magnitude B_T near the center of the signature at THE suggests that the form of the flux rope was that of a crater FTE, a flux rope in an early stage of formation [*Zhang et al.*, 2010]. When the structure reached THD, it had evolved into a typical FTE with a strong core field. Although the

timing argument above provides only the M-component of the velocity, we will show in section 2.3 that the time lag between THE and THD probably relates principally to duskward motion of the structure. That is why in Figures 2d and 2e we consider only the duskward motion of the magnetic structure (flux rope).

2.2.2. Event of September 1, 2008

[19] Now we analyze another FRE, observed by THD on the dawnside magnetopause rather than the duskside magnetopause at about 15:11 UT on September 1, 2008. The observing spacecraft was approaching its apogee along an outbound orbit near the equator at $(10.37, -2.70, -2.00)$ R_E in the GSM coordinate system. Figure 4a shows the data collected by THD from 15:11:30 UT to 15:15:30 UT. Before 15:13:10 UT, THD was moving within the magnetosphere where the field orientation was strongly northward. The ion and electron temperatures were as high as 1 keV and 300 eV, respectively, and the ion population mainly consisted of ions with energy above 500 eV (the fifth panel in Figure 4a). There was no significant plasma flow in this region (the second panel in Figure 4a). After 15:13:10 UT, THD entered into the LLBL; the magnetic field remained dominantly in the L direction. The ion temperature (100 eV) and the ion number density $(10/cm^3)$ were typical for magnetosheath plasma, although both high energy (magnetospheric particles: >1 keV) and low energy (magnetosheath particles:
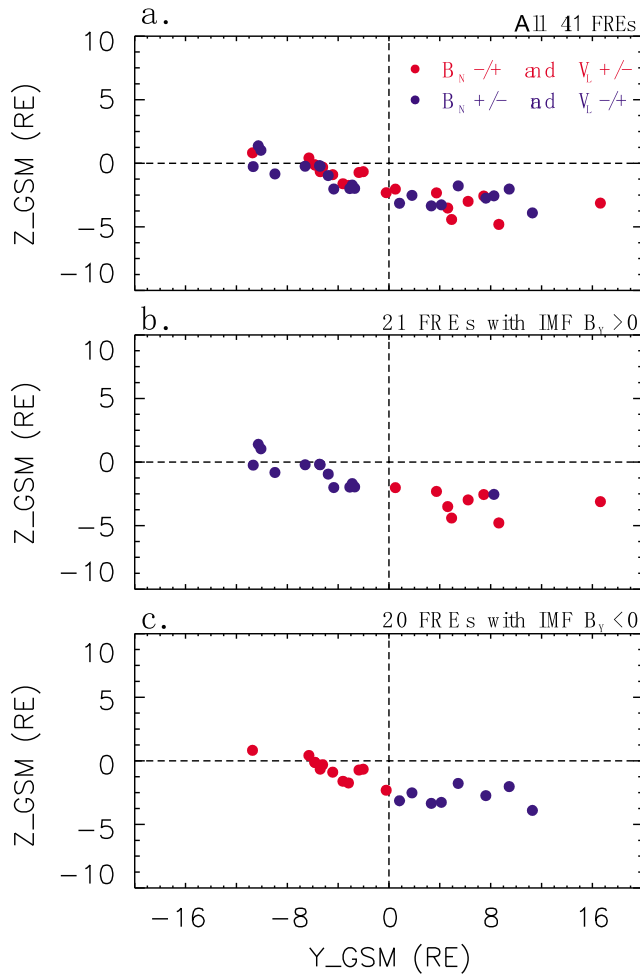
Figure 5. The locations of all the 41 FREs in the Y-Z plane of the GSM coordinate system. In all panels, the red dots represent those events with $-/+B_N$ or $+/-V_L$, and the blue dots are those events with $+/-B_N$ or $-/+V_L$. (a) The distribution of all the 41 events in Y-Z GSM. Colors denote the polarities of B_N or V_L. (b) The distribution of the 21 events with positive IMF B_Y. (c) The location distribution of the 20 events with negative IMF B_Y.

<1 keV) particles were present. THD reentered the magnetosphere at 15:14:50 UT.

[20] When THD entered the LLBL, it encountered an FRE and the V_L component of the flow changed sign from negative (southward) to positive (northward). At the dawnside low latitude position of the spacecraft, the average of the flow component in the M direction, V_M, was -65 km/s (dawnward). THD observed a bipolar variation of B_N with a $(+/-)$ polarity; the field magnitude peaked at the center of the bipolar B_N and was surrounded by two dips.

[21] As for the previous event, the observations in this event can be interpreted in two ways, shown in Figures 4b and 4c and Figures 4d and 4e, respectively. The observations in this event are similar to those in the previous event but the polarities of B_N and V_L are reversed. ACE spacecraft detected that the IMF was [3.34, 1.82, -1.03] nT in the GSM coordinate system and that the corresponding IMF clock angle was 119 degrees, close to that of the previous

event. If the observed signatures were associated with reconnection occurring on X-line(s), the X-line(s) extended also northward and duskward but on the dawnside magnetopause as shown in Figures 4b and 4d and the geometries of the field lines and plasma flows were the same as the previous event shown in Figures 2b, 2c, 2d and 2e. One must assume a reversal of the direction of motion of the structure relative to the spacecraft to understand the difference of the polarities of B_N and V_L compared to those present in the previously analyzed event. For example, if we assume that THD encountered a single X-line, the X-line would have been moving southward and/or duskward and the spacecraft would have traversed the whole reconnection structure from its southern branch to its northern branch. Figures 4b and 4c show the case when a single X-line structure moves only in the duskward direction. If what THD encountered was a flux rope being generated by two X-lines, the flux rope would have been moving northward and/or dawnward relative to the spacecraft. Figures 4d and 4e show an example that assumes that the flux rope structure moved dominantly in the dawnward direction, which is believed to have been the case for this event. We will discuss this later. The local maximum of the field magnitude in the center of the event is not expected at the crossing on an X-line and suggests that this event is most likely to be a flux rope.

[22] Additional evidence supporting the flux rope interpretation comes from the observations of another spacecraft, THE, that recorded signatures consistent with a flux rope in motion (not shown). THE was located at (9.28, -3.52, -1.72) R_E, 0.8 R_E dawnward of and slightly northward (0.3 R_E) of THD, and within the magnetosphere with an ion temperature of 2 keV, ion density of 0.4 cm^{-3} and magnetic field of 55 nT mainly in the L direction. Just 1.5 min after THD encountered the FRE, THE detected a bipolar flow variation in the direction normal to the magnetopause (V_N with a $-/+$ polarity) and an enhancement of the flow tangential to the magnetopause (negative V_M). These are the typical flow perturbations produced by the motion of FTEs in their ambient plasma [e.g., *Farrugia et al.*, 1987; *Liu et al.*, 2008; *Korotova et al.*, 2009; *Zhang et al.*, 2011]. Assuming that the two spacecraft were observing the same structure, the 75 s time delay between observations of the signatures at THD and THE, separated about 1 R_E in the M direction near the magnetopause, implies a velocity in the $-M$ direction of about 76 km/s. We cannot exclude that the motion had a component along the south-north direction, but we will argue later in a statistical sense that the motion was dominantly in the M direction.

2.3. Statistical Studies

[23] From May to October in 2007 and 2008, we identified 41 FREs on the low latitude dayside magnetopause. They were found at a large range of local times. Their locations are shown in Figure 5a in the Y-Z GSM plane. The observing time, spacecraft and the polarities of the bipolar B_N and V_L signatures for each event are listed in Table 1. We summarize their common features as follows:

[24] 1. A bipolar flow variation is seen in V_L with either $+/-$ or $-/+$ polarity.

[25] 2. A bipolar magnetic perturbation is seen in B_N with either $+/-$ or $-/+$ polarity, but its polarity is always opposite to that of V_L.

Table 1. Event List of the FREs Observed by THEMIS From May to October in 2007 and 2008

Event Date and Time	SC	B_N Polarity	V_L Polarity	Event Date and Time	SC	B_N Polarity	V_L Polarity
20070525-1444:51	THA	+/−	−/+	20080729-2302:29	THE	−/+	+/−
20070531-0941:51	THC	+/−	−/+	20080807-2126:21	THE	+/−	−/+
20070614-0359:45	THD	−/+	+/−	20080810-1929:03	THD	+/−	−/+
20070617-1043:31	THE	−/+	+/−	20080828-2219:16	THE	+/−	−/+
20070628-1214:24	THB	+/−	−/+	20080901-1513:49	THD	+/−	−/+
20070712-0704:00	THD	−/+	+/−	20080907-2221:07	THE	−/+	+/−
20070720-1613:00	THE	+/−	−/+	20080913-1428:34	THD	−/+	+/−
20070814-1259:54	THE	+/−	−/+	20080915-1301:18	THD	−/+	+/−
20070825-1846:31	THC	−/+	+/−	20080916-1905:10	THE	+/−	−/+
20070903-0232:09	THC	+/−	−/+	20080921-1543:21	THE	−/+	+/−
20070911-1505:33	THB	+/−	−/+	20080921-1600:12	THA	−/+	+/−
20070912-0606:07	THB	+/−	−/+	20080921-1637:23	THA	−/+	+/−
20070912-0713:23	THB	+/−	−/+	20080923-1430:09	THD	+/−	−/+
20071022-1616:18	THD	−/+	+/−	20080924-1451:45	THD	+/−	−/+
20071026-1823:15	THE	+/−	−/+	20080927-1317:29	THD	−/+	+/−
20080521-0940:45	THC	−/+	+/−	20080927-2053:14	THA	+/−	−/+
20080629-2013:42	THE	−/+	+/−	20081001-2226:55	THE	−/+	+/−
20080704-2015:40	THD	+/−	−/+	20081001-2252:27	THE	−/+	+/−
20080705-0014:38	THE	+/−	−/+	20081020-2036:20	THE	−/+	+/−
20080720-2343:54	THE	+/−	−/+	20081020-2036:21	THE	−/+	+/−
20080727-2012:47	THE	−/+	+/−				

[26] 3. All these FREs are observed in the LLBL. Throughout the events, the dominant component of the magnetic field is in the L (north) direction. The ion number density is typically 5–10/cm^3, and both magnetospheric and magnetosheath particles are present.

[27] 4. The flow component along the M direction (V_M) for all the events is significant, but experiences no clear bipolar variation.

[28] 5. All these FREs occurred at times when the IMF clock angle was in a range from 75° to 165°, with the IMF B_Y either positive or negative.

[29] Let us focus on the analysis of the polarities of B_N or V_L. In Figure 5a, colors denote the polarities of B_N and V_L: blue for events with +/−B_N and −/+V_L and red for events with −/+B_N and +/−V_L. Clearly, these two types of events are distributed randomly around the low-latitude magnetopause as shown in Figure 5a.

[30] However, the IMF B_Y organizes these two types of events well. We determine the IMF B_Y using observations made by any other THEMIS spacecraft located within the magnetosheath either simultaneously or, if simultaneous observations were not available, during any interval within 20 min before each event. We classify our events into two groups: IMF $B_Y > 0$ and IMF $B_Y < 0$. The distributions for these two types of events with different IMF B_Y are shown in Figures 5b and 5c, respectively. For the IMF $B_Y > 0$ events (Figure 5b), it is clear that all the events but one on the duskside magnetopause have the −/+ bipolar B_N and the +/− bipolar V_L, whereas all the events on the dawnside magnetopause have the opposite polarities of B_N and V_L. When the IMF B_Y is <0, the polarities of B_N and V_L are reversed on the two sides of the magnetopause (Figure 5c). We also shifted the magnetic field data observed by the ACE spacecraft to the nose of the magnetopause to determine the polarity of the IMF B_Y, and found the same results.

[31] The motion of the structures is critical in interpreting the distribution of polarities of B_N and V_L. The flankward motion of these structures is supported by observations made by pairs of spacecraft. In 29 of these 41 events, a second spacecraft was located near the magnetopause and not far from the one that observed the FREs, and these nearby spacecraft detected FTE-related signatures within 2 min before or after FREs were observed. These signatures include bipolar variations in B_N and enhancement of B_T [*Russell and Elphic*, 1978], or transient enhancement in total pressure (the dayside traveling compression regions caused by the motion of FTEs) [e.g., *Liu et al.*, 2008], or bipolar flow perturbations in V_N in the magnetosphere [e.g., *Farrugia et al.*, 1987; *Liu et al.*, 2008; *Korotova et al.*, 2009; *Zhang et al.*, 2011]. Figure 6a shows the locations of the pairs of spacecraft that made these observations. The red dots denote the spacecraft that detected the signatures first, and the blue dots, connected with the red ones, show the locations of spacecraft that recorded a related signature some time later (within 2 min). For most events, two spacecraft are separated mainly in the M direction and the red dot is, in all cases, closer to the noon meridian (12 MLT) than the blue dot. That is to say, signatures always appear to move away from the noon meridian. Although we do not know the axis of orientation of the flux ropes whose motion is of interest, we can rule out motion only in the L direction as an explanation of the observations. The spacecraft are separated mainly in the M direction (east-west). The structures, be they single X-lines or flux ropes, can have arbitrary orientation, extending from southwest to northeast or from southeast to northwest depending on the sign of the IMF B_Y. If the structures were moving only in the L direction, the spacecraft further away from the noon meridian should, at least for some events, have encountered the signatures first. Clearly, that is not the case in our observations. In other words, these observations imply that any motion of structures in the L direction (north-south) must have been supplemented by some motion in the flankward direction in order to account for our observations.

[32] Figure 6b shows the separation of pairs of spacecraft in the M direction (dM) plotted as a function of the time delay between the signatures observed (dT). It is clear that dM has a systematic dependence on dT, which confirms the
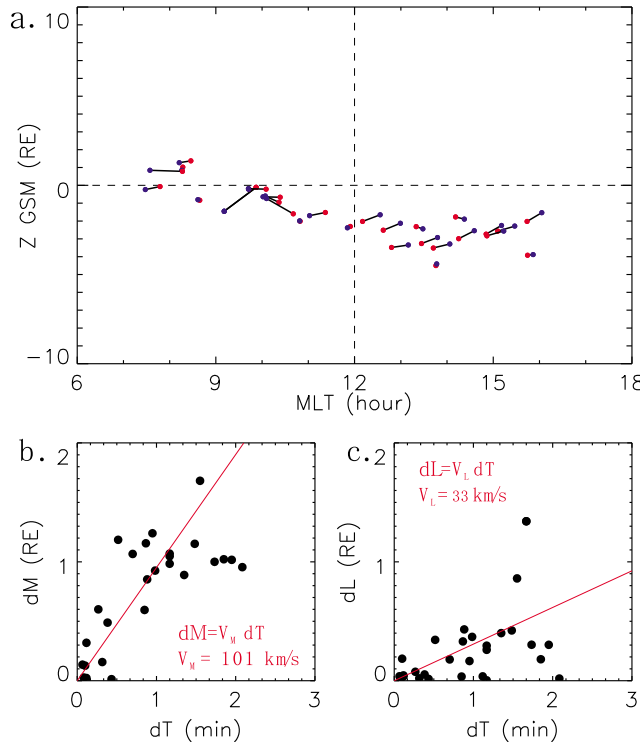
Figure 6. (a) The locations of pairs of spacecraft which made observations within 2 min. The red dots denote the spacecraft who detected signatures first, and the blue dots connected with the red ones show the locations of spacecraft who obtained signatures some time later (within 2 min). (b) The separation of pairs of spacecraft in the M direction (dM) plotted as a function of the time delay (dT) of signatures at the two spacecraft. The red straight line is the least squares fitting of data to a linear function dM = $V_M \cdot d$T, where V_M = 101 km/s. (c) The separation of pairs of spacecraft in the L direction plotted as a function of time delay of signatures at the two spacecraft. The red straight line is the least squares fitting of data to a linear function dL = $V_L \cdot d$T, where V_L = 33 km/s.

flankward motion of the structures. We carried out a linear least squares fitting of dM and dT to dM = $V_M \cdot d$T (shown in red in Figure 6b), and the result indicates that the velocity of the flankward motion of these structures (V_M) is about 101 km/s. We also plot (Figure 6c) the separation of spacecraft in the L direction (dL) as a function of time delay of signatures (dT). It seems that dL varies less rapidly with dT than does dM; the linear least squares fitting shows that the typical velocity of motion in the L direction is about 33 km/s.

3. Discussion

[33] In this section, we discuss our observations. Our results support the conclusion that all the events in our database are likely to be flux ropes being generated by component reconnection on two X-lines. Before reaching at our conclusion, we have to answer two questions.

[34] The first question is whether the reversed flows in our FRE database are indeed reconnection jets. Ideal MHD predicts that the accelerated reconnection flow is Alfvenic in

a frame of reference referred to as "de Hoffmann-Teller (HT)" frame [*Paschmann et al.*, 1979; *Sonnerup et al.*, 1981]. The HT frame exists only when the corresponding magnetic structure is in a steady state [*de Hoffmann and Teller*, 1950]. Following that, for a particular pair of reversed flow, $\vec{V}_1$ and $\vec{V}_2$, assuming that their associated magnetic structure is in a steady state, we can determine whether they arise from magnetic reconnection by examining the relations of their velocities in the HT frame, $\vec{V}_1 - \vec{V}_{HT,1}$ and $\vec{V}_2 - \vec{V}_{HT,2}$, to their associated Alfven velocities, $\vec{V}_{A1}$ and $\vec{V}_{A2}$. Here $\vec{V}_{HT,1}$ and $\vec{V}_{HT,2}$ are the velocities of the HT frames for each flow jet as shown on the bottom of Figure 7. If these flows arise from reconnection, we expect that $\vec{V}_1 - \vec{V}_{HT,1} = \vec{V}_{A1}$ and $\vec{V}_2 - \vec{V}_{HT,2} = \vec{V}_{A2}$. The HT frame velocities $\vec{V}_{HT,1}$ and $\vec{V}_{HT,2}$ are probably different but not significantly different since they relate to the same structures. To avoid estimating $\vec{V}_{HT,1}$ and $\vec{V}_{HT,2}$, we simply assume that $\vec{V}_{HT,1} = \vec{V}_{HT,2}$ and subtract the two equations. We thereby obtain $\left| \vec{V}_1 - \vec{V}_2 \right| = \left| \vec{V}_{A1} - \vec{V}_{A2} \right|$. Note that $\vec{V}_{A1}$ and $\vec{V}_{A2}$ are oppositely directed, so $\left| \vec{V}_{A1} - \vec{V}_{A2} \right| = 2V_A$. Thus we only compare $\left| \vec{V}_1 - \vec{V}_2 \right|$ with $2V_A$ for all the events in our database and the result is shown in Figure 7. We find that $\left| \vec{V}_1 - \vec{V}_2 \right|$ is statistically proportional to $2V_A$, suggesting that these flows arise from magnetic reconnection. Fluctuations may arise from departures from $\vec{V}_{HT,1} = \vec{V}_{HT,2}$, and the data points do not fall strictly along the diagonal in Figure 7.

[35] Now we discuss by what kind of reconnection these flows have been produced. It is generally believed that magnetic reconnection can occur both near the subsolar point and in regions where the geomagnetic field and the IMF are anti-parallel [*Dungey*, 1961]; the latter type of reconnection is called anti-parallel reconnection. Particularly, when the IMF has a B_Y component comparable to B_Z (This is typical for our events, the IMF clock angles of which vary in the range from 75° to 165°), anti-parallel reconnection may occur at high latitudes in both hemispheres. When the IMF B_Y is >0, such reconnection could occur on X-lines located to the east of the polar cusp in the northern hemisphere and to the west of the polar cusp in the southern hemisphere; when the IMF B_Y is <0, anti-parallel reconnection occurs to the west of the northern polar cusp and to the east of the southern hemisphere polar cusp [*Crooker*, 1979; *Luhmann et al.*, 1984]. However, anti-parallel reconnection appears not to relate directly to the formation of the FREs in our data set because all of our events were observed at low latitudes. If structures form at high latitudes, they would have to move to the low latitude region following their formation in order to be observed by a THEMIS spacecraft. However, we are not aware of any mechanism that can move the structures from a formation region at high latitude beside the polar cusp to locations near the subsolar point (we identified many events near that point), particularly in the face of background flows away from the subsolar point along the magnetopause [e.g., *Sibeck and Lin*, 2011]. Alternatively, the component magnetic reconnection model predicts that reconnection occurs along an X-line that crosses the low latitude region near the subsolar point and extends continuously along the dayside magnetopause [*Cooling et al.*, 2001; *Trattner et al.*, 2007]. That is where
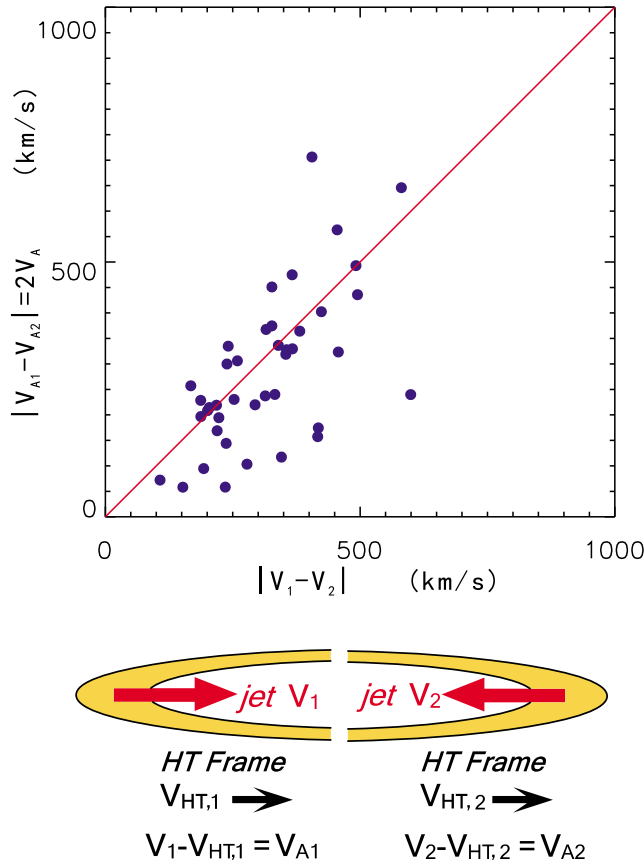
Figure 7. Relation between the observed flow magnitudes in the HT frame and Alfven velocities. V_1 and V_2 are the velocities of the two reversed flows, V_{HT} is the velocity of the HT frame, and V_{A1} and V_{A2} are the Alfven velocities associated with the reversed flows. Statistically, $|V_1 - V_2|$ is shown to be proportional to $|V_{A1} - V_{A2}|$, suggesting that these flows arise from magnetic reconnection. See text for details. The red line is the line predicted theoretically with $|V_{A1} - V_{A2}| = |V_1 - V_2|$.

our events were observed. For these reasons, we rule out antiparallel reconnection and argue that component reconnection contributes to the formation of the structures observed.

[36] If component reconnection is, one may expect that bipolar variations would exist also in the V_M component as well as in the V_L component since the flows we observed are interpreted as being generated by component reconnection at low latitudes. However, the bipolar variations of V_M are seen in some of our events, for example, the event on July 27, 2008 (second panel in Figure 2a), while it could be weak and hard to be identified in other cases, for example, the event on September 1, 2008 (second panel in Figure 4a).

[37] The second question we should answer is whether the magnetic structures associated with these FREs are flux ropes. For 2 of the 41 events in which flow reversals were observed, we found support for the hypothesis that the structures were flux ropes, instead of single X-lines. For the event of July 27, 2008, the observations strongly support this interpretation because it is consistent with data provided by two spacecraft with a separation of about 1 R_E. A structure

with the properties of a flux rope (FTE) was encountered by THE 1 min before it was encountered by THD; a detailed analysis of the observations of the two spacecraft shows that they are fully consistent with the flux rope interpretation. However, the event of September 1, 2008 was observed directly by just one spacecraft, THD. Thus, the evidence distinguishing a flux rope from a single X-line structure in motion is less clear. There is, nonetheless, evidence that in this second case we were again observing a flux rope. In particular, at THD the field magnitude has a local maximum at the time when the L-component of the flow reversed and flux rope-associated signatures were obtained by a second spacecraft, THE at a location further toward the flanks 1.5 min later, a delay consistent with convective transport in the magnetosheath, again suggesting that the magnetic structure was most likely a flux rope.

[38] We know that in the two cases we studied the structures were most likely to have been flux ropes. We have not yet commented on whether the remaining 39 structures in our data set were single X-lines or flux ropes, although we assert that we know they result from component reconnection at low latitudes. Next, by analyzing the polarities of the bipolar B_N (or V_L), we can determine what kind of magnetic structures the reversed flows are associated with, single X-lines or flux ropes.

[39] First, let us discuss the signs of B_N (or V_L) in different branches of a single X-line or a flux rope. The orientation of the X-line for component reconnection is thought to be controlled by the IMF B_Y [*Cooling et al.*, 2001; *Moore et al.*, 2002; *Eriksson et al.*, 2004]. When the IMF B_Y is >0, the X-line tends to extend northward and duskward; and when the IMF B_Y is <0, the X-line extends northward and dawnward. Figure 2 shows an example of the field line geometries on the duskside of the magnetopause when the IMF B_Y is >0 in a single X-line context (Figures 2b and 2c) and in a flux rope context (Figures 2d and 2e). If reconnection occurs on the single X-line and an observing spacecraft is located within the northern branch of the structure, it will observe negative B_N and positive V_L; whereas in the southern branch, B_N will be positive and V_L negative. However, if there are two X-lines, component reconnection occurring on these two X-lines can generate a flux rope between them [*Lee and Fu*, 1985] as shown in Figures 2d and 2e. Now in the northern part of the developing flux rope, the B_N will be positive and V_L negative, whereas in the southern half of the flux rope the B_N will be negative and V_L positive, that is: opposite to the situation in the single X-line context. Certainly, such structures can also develop on the dawnside of the magnetopause when the IMF $B_Y > 0$, and the signs of B_N and V_L in the southern and northern branches would not change compared to the duskside case (for example, see Figures 4b, 4c, 4d and 4e). The analogous analysis for the IMF $B_Y < 0$ case is also obvious. The only difference is that the orientation of the X-line or the axis of the flux rope will be rotated to the northward and dawnward direction. The signs of B_N and V_L will remain the same as in the positive IMF B_Y case in both the northern and southern parts of the X-line or the developing flux rope.

[40] Obviously, the observed polarities of the variations of B_N and V_L depend not only on the type of the magnetic structure, but also depend on how an observing spacecraft
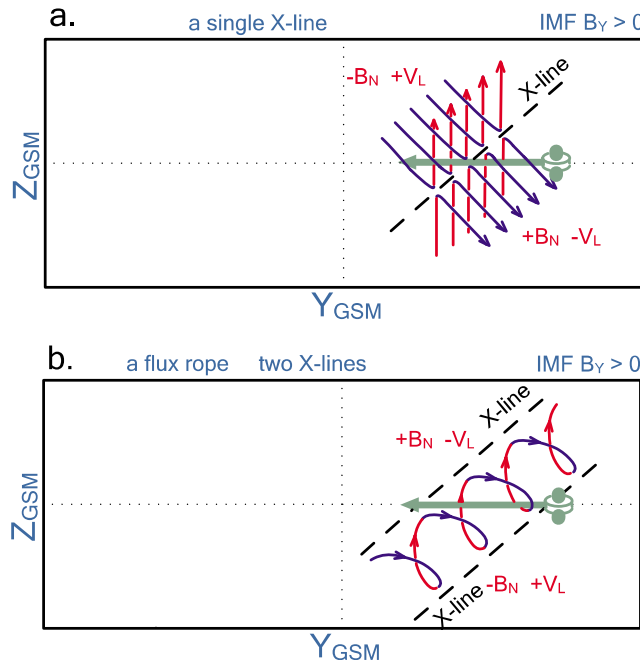
Figure 8. The configurations of field lines and X-lines on the duskside magnetopause under different assumptions of the type of magnetic structures when the IMF B_Y is >0. (a) A single X-line structure. (b) An in vivo flux rope generated by reconnection on two X-lines. The red curves represent the field lines initially from the magnetosphere, and the blue curves represent the field lines initially from the magnetosheath. The dashed lines indicate X-lines, and the green arrows indicate the trajectories of an observing spacecraft relative to the magnetic structures.

traverses the magnetic structure. Our statistical studies have shown that these magnetic structures, whether interpreted as single X-lines or flux ropes being generated by multiple X-lines, were moving toward flanks on both sides of the magnetopause. This result is consistent with that predicted by *Sibeck and Lin* [2011] on the basis of a component reconnection model. For a given IMF B_Y and a given location of observations, the polarity of the variation of B_N or V_L can be anticipated both in the single X-line context and in the flux rope context. For example, when the IMF B_Y is >0 and an event is observed on the duskside magnetopause (Figure 8), in the single X-line context (Figure 8a), we expect that B_N will experience a (+/−) bipolar variation and V_L will have a (−/+) variation. The polarity follows from the expectation that the observing spacecraft must traverse the reconnection structure from its southern branch to its northern branch as a result of the mainly duskward motion of the X-line. However, if the X-line is observed on the dawnside, the polarities of B_N and V_L will reverse because, as a result of dawnward motion of the structure on the dawnside magnetopause, the observing spacecraft will traverse the reconnection structure from its northern to its southern branch. In the flux rope context, however, we expect to obtain a (−/+) B_N variation and a (+/−) V_L perturbation on the duskside magnetopause (Figure 8b) and a (+/−) B_N and a (−/+) V_L on the dawnside magnetopause. In an analogous manner, we can predict the polarities for a

negative IMF B_Y condition. Table 2 gives the expected polarities of B_N for different assumptions of the type of the magnetic structure, different IMF B_Y polarity (different orientation of X-lines) and different locations of events.

[41] By comparing the polarities of B_N in our observations in Figures 5b and 5c with Table 2, we find that the distributions of the observed polarities of B_N are consistent with those expected in the flux rope context. The consistency suggests that all 41 FREs are flux ropes. Thus, the reversed flows inside these flux ropes indicate that these flux ropes were being generated by component reconnection on two X-lines. That is to say, the multiple X-line model [*Lee and Fu*, 1985; *Raeder*, 2006] is the generation mechanism for the group of flux ropes discussed in this paper.

[42] Clearly, the updated multiple X-line model [*Raeder*, 2006] is different from the original one proposed by *Lee and Fu* [1985], and data in our work supports Raeder's scenario. In the original multiple X-line model, the two X-lines responsible for the generation of flux ropes form simultaneously. However, Raeder's updated multiple X-line model based on his 3-D MHD simulation proposes that the two X-lines occur successively and that the flux ropes form only after reconnection begins on the second X-line. If reconnection occurs simultaneously on two X-lines, there must be field lines undergoing reconnection processes simultaneously on both of the X-lines and magnetically linked. On these field lines, counterstreaming particle beams are expected. For example, in the event on July 27, 2008, only 9 s were needed for the sheath-origin ions (∼1 keV, corresponding thermal velocity about 460 km/s) to travel from one side to the other side of the structure, whose dimension was about 4000 km (the motion velocity of the structure was about 100 km/s and it took 40 s for the structure to pass through the observing spacecraft). If the two X-lines formed simultaneously, during the 40 s required for the THEMIS spacecraft to traverse the structure, these ions would have gotten enough time to travel between the two X-lines and counterstreaming ion beams should have been clearly detected. That is to say, even near one X-line, the plasma could be either toward or away from it and the velocity of the bulk flow will be irregular depending in magnitude and direction on the reconnection rates on the two X-lines. However, counterstreaming ions were not detected and in our data the polarities of V_L and B_N were systematically anti-correlated, in the way anticipated if the plasma flow near an X-line was always away from the X-line. This systematic relation between V_L and B_N is what would occur if the flux rope were formed by reconnection occurring successively on the two X-lines. Thus, our analysis of the THEMIS data from 41 events on the dayside low latitude

Table 2. The Expected Polarities of the Variation of B_N for Different IMF Clock Angles and Different Assumptions About the Type of Structure on the Dawnside and Duskside Magnetopause

	Type of Structure			
	Single X-Line		Flux Rope in Vivo	
IMF B_Y	Dawnside	Duskside	Dawnside	Duskside
>0	−/+	+/−	+/−	−/+
<0	+/−	−/+	−/+	+/−
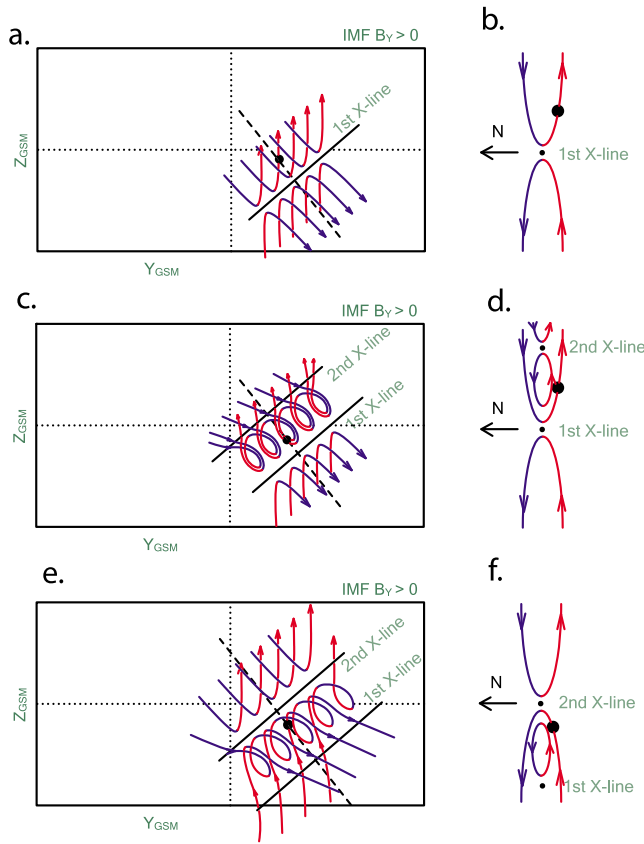
Figure 9. A model of the evolution of the magnetic field configuration on the duskside magnetopause when the IMF B_Y is positive and two X-lines form sequentially. The evolution follows three steps. (a) A northeast-oriented single X-line first occurs at or moves to the region far from the subsolar point. The blue lines denotes the portions of field lines initially from the magnetosheath and the red curves denote the portions of field lines initially from the magnetosphere, and the observing spacecraft (thick black dot) was located in the 'red' magnetic field region (LLBL). (b) The projection of the magnetic field lines on a cross section plane shown by the dotted line in Figure 9a (view along the X-line). (c) A second X-line occurs near the subsolar point. A flux rope begins to form between the two sequentially formed X-lines. The observing spacecraft is located within the flow from the first X-line. The flux rope is wrapped by open field lines generated by the first X-line and connecting the north polar region of the Earth. The observing spacecraft is expected to detected sheath ions traveling along field lines (the pitch angle of sheath ions is >0). (d) The projection of the magnetic field lines on a cross section plane shown by the dotted line in Figure 9c (view along the X-lines). (e) Reconnection continues on the second X-line, and it dramatically changes the configurations of the open field lines wrapping the flux rope. Now the open field lines connect to the south polar region of the Earth. The observing spacecraft is expected to detected sheath ions traveling against field lines into the magnetosphere (the pitch angle of sheath ions is >0). (f) The projection of the magnetic field lines on a cross section plane shown by the dotted line in Figure 9e (view along the X-lines).

magnetopause supports the description of flux rope formation by successive reconnections provided by the updated multiple X-line model of *Raeder* [2006].

[43] Our analysis cannot establish where the two X lines initially form, i.e., whether or not they form at the same point. The only conclusion we can draw is that within the time interval we studied for each event, the observing spacecraft remained in a region between two sequentially formed X-lines. We cannot determine their initial formation locations from our data. Two situations are possible. The first possibility is that the two X-lines form successively on opposite sides of the observing spacecraft, and Figure 9 illustrates such a situation for a case with the IMF $B_Y > 0$ on the duskside magnetopause. An X-line forms first further away from the subsolar point and to the southeast of the spacecraft (Figures 9a and 9b), and the observing spacecraft detects negative B_N and positive V_L. The second X-line develops later nearer the subsolar point and to the northwest of the spacecraft (Figures 9c and 9d). A flux rope begins to form between the two sequentially formed X-lines. At the initial stage of the formation of the second X-line, the flux rope is wrapped by the open field lines generated by reconnection on the first X-line as shown in Figures 9c and 9d. At this stage, in the LLBL, we see the sheath ions penetrate into the magnetosphere along the magnetic field (ion pitch angle is >0), and the observing spacecraft can still detected negative B_N and positive V_L which arise from the first X-line. As reconnection proceeds on the second X-line, it overwhelms reconnection on the first X-lines which may already have quenched, and the flux rope moves toward the duskside flank and the observing spacecraft enters into the magnetic kink from the second X-line with positive B_N and negative V_L (the V_L reverses now). The open field lines wrapping the flux rope now are generated by reconnection on the second X-line (Figures 9e and 9f). At this stage, the sheath ions penetrate into the magnetosphere against the field lines (ion pitch angle is <0). Thus, we do not need any X-line to pass the observing spacecraft, and the dynamic process can produce the bipolar B_N and V_L signatures that we observed. Although this scenario explains why the observations do not reveal a pair of flow reversals associated with moving X-lines, it is unclear why the first of the pair of X-lines forms at a locus further away from the subsolar point than the second.

[44] Alternative interpretations are possible. It is possible that the two X-lines may form successively at the same locus near the subsolar point. The first X-line would have to move away from its generation locus, allowing the second X-line to occur at the same location, and generating a flux rope between the two sequential X-lines. For example, when the IMF $B_Y > 0$ on the duskside magnetopause, the first X-line illustrated forms initially to the northwest of the spacecraft near the subsolar point (not shown in Figure 9), and then it passes the spacecraft and moves duskward with the background sheath flow to the locus shown in Figures 9a and 9b. Reconnection on a second X-line completes the formation of the flux rope as shown in Figures 9c, 9d, 9e and 9f. In this scenario, at least the first X-line must pass by the observing spacecraft, and we would expect to observe flow reversal not only within the flux rope but also at the leading edge of the flux rope. Such an initial flow reversal was not detected in our data. It is possible that when the first X-line forms and

passes the observing spacecraft, the local magnetopause has not yet eroded and the spacecraft is located relatively deep in the magnetosphere. After the first X-line passes the observing spacecraft, the spacecraft enters into the LLBL as the consequence of significant erosion of the magnetopause by reconnection on the first X-line. Thereafter the spacecraft would observe the jet flow from the first X-line. In this way, the observing spacecraft could miss the flow reversal at the first X-line but detects the reconnection flow only from one side of this X-line. However, even if the pairs of X-lines form successively at the same locus, generating the flux ropes in our data set, the mechanism that moves X-lines from their generation loci is not well known. On the basis of our data at low latitudes, we suggest that the present of flankward flows may play a role in carrying X-lines away from their formation loci.

[45] The mechanism for generation of FTEs in our scenario may differ from that in Raeder's FTE generation picture. In Raeder's simulation, in which the IMF was strictly southward, flux ropes formed repeatedly only when the tilt of Earth's magnetic dipole (in the X-Z GSM plane) was relatively large. An X-line follows the motion of a previous flux rope, due to the background northward or southward magnetosheath flow, toward high latitudes when the dipole tilts are strong. Sequentially forming X-line appears near the flow stagnant point and complete a flux rope structure between the two X lines. This argument, developed for the case of strongly southward-oriented IMF, precludes flux rope formation in the absence of dipole tilt. On the other hand, in our data set, flux ropes can be generated for either large or small dipole tilts on the magnetopause. In particular, 7 of 41 events occurred within a few days of fall equinox (see events in Table 1 near September 22, 23 or 24) for small dipole tilt angle. Near fall equinox, the magnetic dipole tilt angle is small with a daily variation between $11°$ and $-11°$ in the GSM coordinate system. For most of our events, we found that IMF B_Y was also non-negligible, as evident from the range of clock angles ($75°$ to $165°$) in our data set. We suggest that Raeder's requirement of strong dipole tilt applies only when IMF B_Y is small, a situation that occurs relatively infrequently. When the IMF B_Y is significant, independent of the dipole tilt, flux ropes may form. In addition, there was no reversed flow inside flux ropes in their simulation, which is also significantly different with our observations.

4. Summary

[46] Of the 3701 FTE signatures that we identified in THEMIS data between May and October of 2007 and 2008 at low-latitudes on the magnetopause, 41 were distinctive in that the north-south flow components reversed direction during the ~1 min required for THEMIS spacecraft to traverse the structure. We have ruled out the possibility that these 41 "flow reversal events" (FREs) were single X-line structures in motion, and confirmed from their field and plasma properties that they indeed were flux ropes. We have interpreted the plasma flow reversal as evidence that we observed the flux ropes as they were being generated by a pair of X-lines developing in sequence through component merging, a process that seems to play a significant role in forming flux ropes. In summary, our analysis, which applies

only to low latitude flux ropes, provides evidence to modify the updated multiple X-line reconnection scenario of *Raeder* [2006] with component merging as the dominant formation processes.

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