GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L16101, doi:10.1029/2010GL044219, 2010

Evidence for a flux transfer event generated by multiple X-line reconnection at the magnetopause

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Received 5 June 2010; revised 3 July 2010; accepted 8 July 2010; published 20 August 2010.

[1] Magnetic flux transfer events (FTEs) are signatures of unsteady magnetic reconnection, often observed at planetary magnetopauses. Their generation mechanism, a key ingredient determining how they regulate the transfer of solar wind energy into magnetospheres, is still largely unknown. We report THEMIS spacecraft observations on 2007-06-14 of an FTE generated by multiple X-line reconnection at the dayside magnetopause. The evidence consists of (1) two oppositely-directed ion jets converging toward the FTE that was slowly moving southward, (2) the cross-section of the FTE core being elongated along the magnetopause normal, probably squeezed by the oppositely-directed jets, and (3) bidirectional field-aligned fluxes of energetic electrons in the magnetosheath, indicating reconnection on both sides of the FTE. The observations agree well with a global magnetohydrodynamic model of the FTE generation under large geomagnetic dipole tilt, which implies the efficiency of magnetic flux transport into the magnetotail being lower for larger dipole tilt. **Citation:** Hasegawa, H., et al. (2010), Evidence for a flux transfer event generated by multiple X-line reconnection at the magnetopause, *Geophys. Res. Lett.*, *37*, L16101, doi:10.1029/2010GL044219.

1. Introduction

[2] A flux transfer event (FTE), often encountered by spacecraft at and around the magnetopause [*Russell and Elphic*, 1978], is characterized by an increase in the magnetic field intensity and bipolar variation in the field component normal to the nominal boundary surface. As summarized, e.g., by *Scholer* [1995] and *Raeder* [2006], there exist several mechanisms for the generation of FTEs. They differ in the spatiotemporal properties of magnetic reconnection at the magnetopause, and thus give rise to differences in the manner the solar wind energy is transferred to the magnetosphere. However, much remains unknown about the actual process of FTE formation, probably because of the lack of suitable multi-point measurements that allow us to reveal the FTE structure and link its properties to those of the formation site.

[3] FTEs have often been attributed to single X-line reconnection [e.g., *Fear et al.*, 2009]. *Lee and Fu* [1985], however, suggested that FTEs can result from a tearing instability or simultaneous formation of multiple X-lines in the dayside magnetopause current layer. In contrast, *Raeder* [2006, 2009] has shown based on global MHD simulations that, under large geomagnetic dipole tilt conditions, FTEs are created repeatedly between sequentially activated multiple X-lines (Figure 1b). In his simulations, an X-line forms somewhere between magnetic equator and the flow stagnation point in the subsolar region where the magnetopause current density has a maximum, is swept poleward/flankward by the magnetosheath flow, and eventually becomes inactive or less active. A new X-line then forms near the location of the old X-line formation, the result being a flux rope creation between the two X-lines. His results also indicate that the created FTEs move almost exclusively toward higher latitudes in the winter hemisphere. With no dipole tilt, on the other hand, the stagnation point and subsolar X-line can be nearly collocated so that the X-line may sit still for an extended period of time (Figure 1a), although *Dorelli and Bhattacharjee* [2009] suggest that such is not the case in a global simulation with an externally imposed, spatially uniform resistivity. To date, however, there is no observational confirmation of either of the above models, not even solid evidence of a magnetopause FTE resulting from multiple X-line reconnection [e.g., *Zhang et al.*, 2008], whereas there is a proof of such reconnection generating a magnetotail flux rope [*Eastwood et al.*, 2005].

[4] It is especially important to elucidate what type of (single or multiple X-line) reconnection leads to the FTE formation and under what condition. This is because whereas single X-line reconnection at the low-latitude magnetopause inevitably erodes closed geomagnetic field lines and leads to the transport and storage of open magnetic flux into the tail, which form the basis for many active phenomena in the magnetosphere, reconnection accompanied by more than

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0094-8276/10/2010GL044219

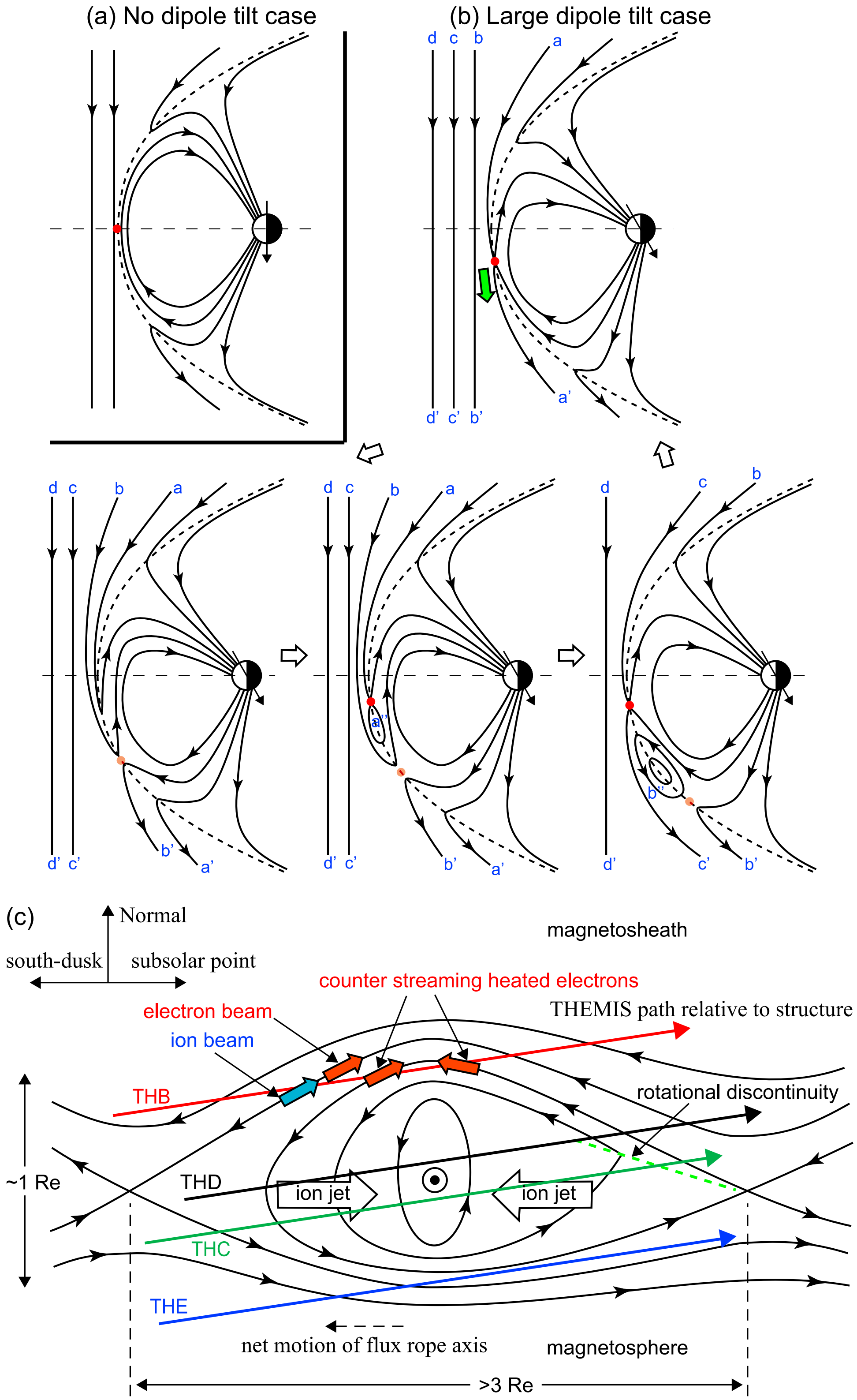

Figure 1. Two-dimensional views, from the duskside, of the field line evolution in global MHD simulations by *Raeder* [2006, 2009] for (a) no dipole tilt and (b) large tilt cases. Under large dipole tilt, reconnection at new X-line(s) initially occurs on already open field lines and thus does not create new open field lines. Such reconnection has no contribution to net transport of open magnetic flux into the tail. It is thus speculated that, if Raeder's model is right, a smaller amount of open flux will be transported into the tail for larger dipole tilt, under the assumption that the average reconnection rate (time-averaged amount of magnetic flux reconnected) at the X-line closest to the subsolar point does not depend on the dipole tilt. (c) Schematic summarizing our FTE.

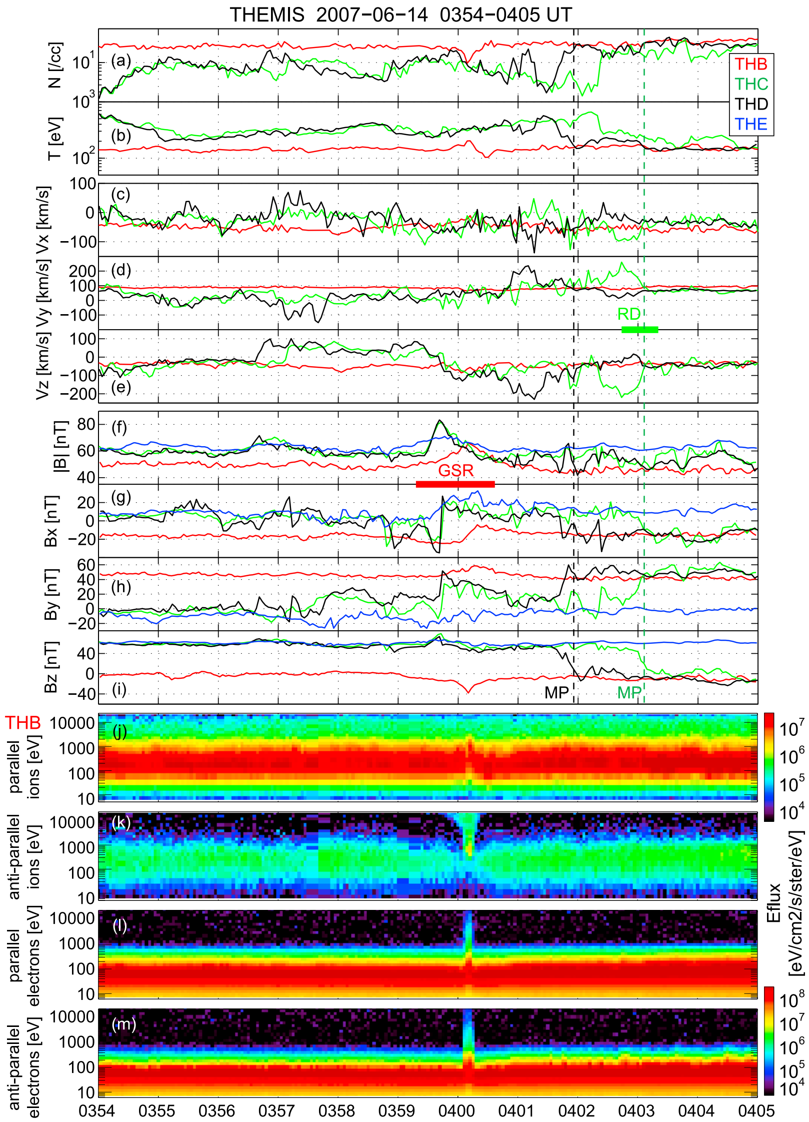

Figure 2. (a–i) Plasma (ion) and magnetic field data in GSM coordinates for 14 June 2007, 0354–0405 UT, from four THEMIS probes (THB, THC, THD, and THE) which encountered an FTE at ~0400 UT. No plasma information was available from THE. Green and red bars mark the intervals of Walén test (Figure 3b) and Grad-Shafranov reconstruction (GSR) (Figure 3c), respectively, and vertical dashed lines mark approximate times of magnetopause crossing. The bottom four panels show energy-time spectrograms from THB of (j) field-aligned and (k) anti-field-aligned streaming ions and (l, m) those of electrons.

one X-line does not necessarily occur on closed field lines and thus may not transport magnetic flux as efficiently into the tail (Figures 1a and 1b). In this paper, we report THEMIS multi-spacecraft observations near the summer solstice in the northern hemisphere of an FTE that provide support for the generation process seen in Raeder's simulations. Data from the fluxgate magnetometer [*Auster et al.*, 2008] and the ion and electron plasma instruments [*McFadden et al.*, 2008] are used.

2. Observations and Analysis

[5] At 0400 UT on 14 June 2007 when the five THEMIS probes had a string-of-pearls configuration, THEMIS-C (THC) was at (10.2, 3.7, −2.3) R_E in GSM coordinates. Figure 2 shows the data from the four probes which detected FTE signatures (negative-then-positive perturbation of B_x and/or $|B|$ enhancement) at ~0400 UT. For the interval shown, THB was mostly in the magnetosheath where the interplanetary magnetic field (IMF) was strongly duskward, THE was in the magnetosphere, while THC and THD traversed the post-noon magnetopause boundary layer from the magnetosphere into the magnetosheath (Figures 2f–2i). THA was about 1 R_E closer to the Earth than THE, so that it did not see the FTE.

[6] At around 0357:15 UT before the FTE, both THC and THD encountered a northward and dawnward flow, despite that the adjacent magnetosheath flow seen by THB was southward and duskward (Figures 2d and 2e). This type of flow reversal across the magnetopause has been taken as a signature of reconnection at the dayside low-latitude magnetopause for strong IMF B_y conditions [*Gosling et al.*, 1990]. The flow direction suggests that an X-line was on

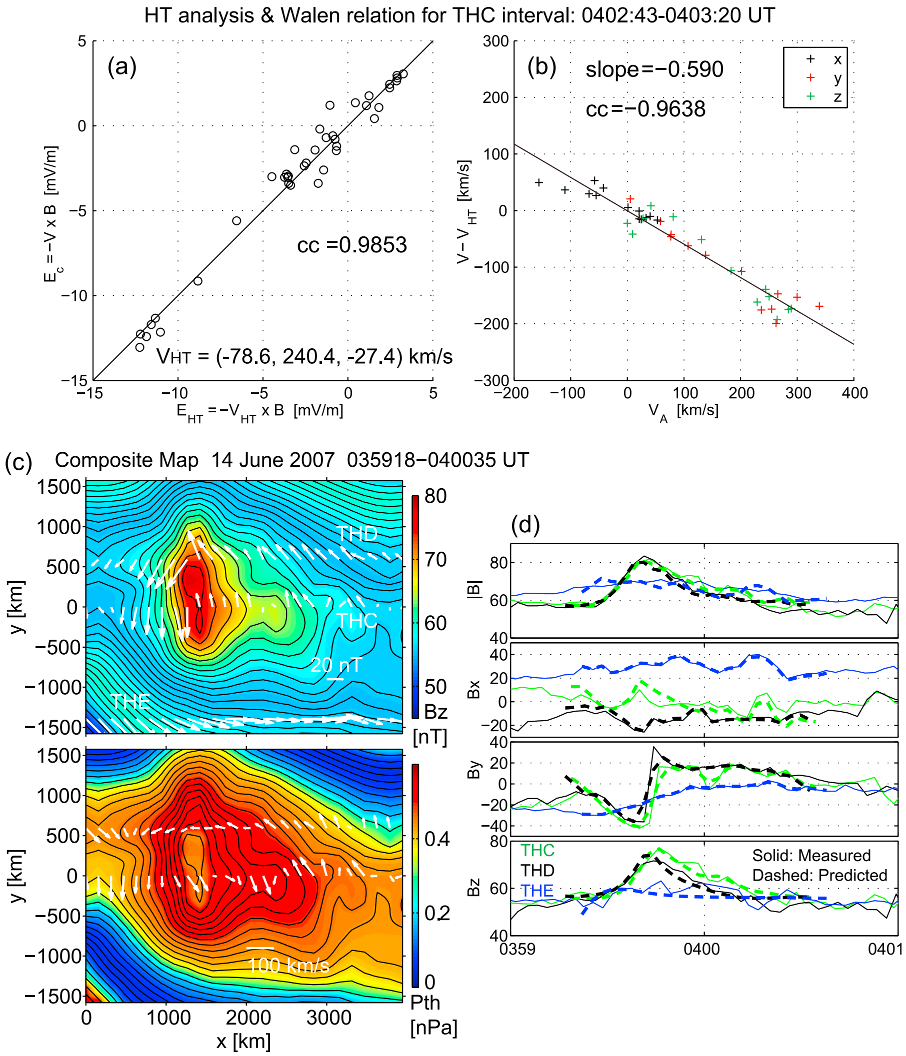

Figure 3. Results from the deHoffmann-Teller (HT) analysis and Walén test for THC interval of magnetopause crossing, 0402:43–0403:20 UT, and those from the GSR method. Scatter plots of three GSM components of (a) the convection electric field versus that based on the HT velocity in the spacecraft-rest frame, and (b) ion velocity in the HT frame versus local Alfvén velocity. (c) 2D maps of the axial magnetic field B_z and plasma pressure reconstructed from THC, THD, and THE data for 0359:18–0400:35 UT, with recovered field lines represented by black lines. The white arrows show the (top) in-plane components of actually measured magnetic field data and (bottom) velocity data transformed into the co-moving HT frame. GSM components of the GSR axes are: x_{GSR} = (0.637, −0.759, 0.136), y_{GSR} = (0.760, 0.589, −0.275), and z_{GSR} = (0.129, 0.279, 0.952), so that in the map the magnetosheath (magnetosphere) is on top (bottom) and the subsolar point (south-dusk side) is to the right (left). (d) Comparison in GSR coordinates between the measured field components and those predicted from the map.

the south-dusk side of the probes at that time. During the interval 0401–0403 UT after the FTE, in contrast, the two probes detected a high-speed southward and duskward jet. Figure 3b shows that the Walén relation [*Sonnerup et al.*, 1987] is fairly well satisfied for the magnetopause crossing at ~0403 UT by THC: velocity change across the boundary was roughly Alfvénic. This indicates that the boundary was a rotational discontinuity (RD) and thus the jet was a consequence of reconnection. The duskward and southward components of the deHoffmann-Teller (HT) velocity and negative Walén slope are both consistent with an X-line being on the north-dawn side of THC at the crossing time.

[7] At about the time of the FTE, THC and THD both observed a flow reversal from northward to southward. One may be inclined to interpret this reversal as an X-line traversal from its northern to southern side, i.e., the signature of a northward motion of the X-line. This is not the case, however, for this particular event; a prominent flux rope rather than X-line existed right at the reversal and in fact was moving away from the subsolar point. THD, slightly closer to the subsolar point than THC, indeed saw the B_x reversal in the FTE core slightly earlier (Figure 2g).

[8] Figure 3c shows 2D maps of the FTE structure recovered by Grad-Shafranov reconstruction (GSR) technique extended for multi-spacecraft applications [*Hasegawa et al.*, 2005]. The ion and/or magnetic field data from THC, THD, and THE are used (THB at y_{GSR} = 4683 km was too far to be included in the current version of the method). The resulting

HT velocity, taken as the moving velocity of the FTE, is (−46, 11, −103) km/s in GSM. The correlation coefficient for the HT analysis (as shown in Figure 3a) is not high (0.817), possibly indicating still ongoing time evolution of the structure. The Walén slope for the GSR interval is small (0.164); inertia effects from field-aligned flow were weak so that the GSR method may be applied. Figure 3d shows that the field map is successfully produced because the recovered magnetic field variations agree well with those actually measured, with the correlation coefficient of 0.991 between three GSR components of the measured field and those predicted from the map along the paths of THC, THD, and THE [*Hasegawa et al.*, 2005]. We thus believe that the structural properties seen in the map are mostly reliable (see also *Hasegawa et al.* [2007] for applications to a 3D evolving structure in simulation), although the technique assumes that the structure is in principle 2D and magnetohydrostatic. However, we do not rely on the topological property of the recovered field to infer if single or multiple X-lines were involved. This is because if the structure has some three-dimensionality, the GSR method may lead to closed field loops in the 2D map even when there is in fact only single X-line [*Hasegawa et al.*, 2007].

[9] In the map, the probes were sliding from left to right, so that the northward and dawnward flow preceding the FTE was located to the left while the southward and duskward flow following the FTE was to the right. It is thus concluded that the two oppositely-directed flows were generally converging toward the FTE and originated from two separate X-lines, one on the south-dusk side and another on the subsolar side of the FTE. Before 0355 UT, THC and THD actually saw southward flows probably associated with the south-dusk side X-line (Figure 2e). The recovered FTE structure is indeed suggestive of collision of the two jets; the cross-section of the flux rope is elongated at its core in the magnetopause normal (approximately y_{GSR} axis) rather than tangential direction, and the axial field GSR B_z is highly enhanced at the center of the flux rope, most likely compressed by the oppositely-directed flows along the magnetopause. Moreover, the FTE speed along the magnetopause, represented by the x_{GSR} component of the HT velocity, 52 km/s, is much lower than the magnetosheath Alfvén speed 244 km/s, computed using the density 20 cm^{-3} and field intensity 50 nT. This slow FTE motion also is incompatible with models of single X-line reconnection which would sweep away an associated FTE at the Alfvén speed.

[10] Particle signatures of reconnection on both south-dusk and subsolar sides of the FTE were identified from THB observations in the magnetosheath. Figures 2k and 2m show that exactly at the time of the THB FTE, THB detected anti-field-aligned (subsolar-ward) fluxes of both ions and electrons with energies ≥1 keV, the signatures of the magnetosheath boundary layer (MSBL) [*Fuselier*, 1995]. They are believed to originate from the magnetosphere or be generated by reconnection-associated energization of the magnetosheath populations; in either case, their streaming direction indicates that the field lines there were reconnected on the south-dusk side of THB. Figure 2l shows that almost at the same time, field-aligned fluxes of heated magnetosheath electrons were observed; the field lines were reconnected on the subsolar side as well (Figure 1c). Similar bidirectional MSBL electrons, but as a signature of high-latitude reconnection in both hemispheres, have been reported, e.g., by *Onsager et al.* [2001]. The intensity of the field-aligned fluxes was weaker at their start and end than that of the anti-field-aligned fluxes (Figure 2m), suggesting that the subsolar X-line became active later than the south-dusk side X-line, or a smaller amount of magnetic flux was reconnected at the subsolar X-line than at the south-dusk side X-line. In addition, Figure 2j shows that far fewer field-aligned energetic ions, corresponding to the subsolar-side ion MSBL, were found (slight energization of magnetosheath ions is probably due to adiabatic compression by the FTE bulge). This feature also implies that the subsolar X-line got activated relatively recently, namely, later than the south-dusk side X-line. The coincidence of the MSBL and FTE encounters is explained by the reconnected MSBL field lines being pushed toward THB by the bulge of the moving FTE. The magnetotail equivalent of these signatures has been observed in association with traveling compression regions [*Owen et al.*, 2005].

3. Discussion

[11] Figure 1c summarizes our observation of the FTE and surrounding regions. The flux rope axis, represented by the invariant z_{GSR} axis (Figure 3), is mostly in the north-south direction with a modest east-west component, and is compatible with the X-line orientation expected for the dominantly duskward IMF. Despite that THB was at y_{GSR} = 4683 km, it also saw an appreciable FTE-associated magnetic perturbation on the magnetosheath side; thus the FTE bulge size normal to the magnetopause was about 1 R_E. A lower bound of the distance between the two associated X-lines can be estimated from 52 km/s (HT velocity along the magnetopause, i.e., x_{GSR} axis) times ~6 min (interval from the start ~0357 UT of the northward jet to the end ~0403 UT of the southward jet) to be ~3 R_E.

[12] The event occurred near solstice when the dipole axis was tilted sunward in the northern hemisphere, exactly the conditions simulated by *Raeder* [2006, 2009]. While the observed bidirectional MSBL electrons, converging flows, and FTE shape and speed may all be compatible with any multiple X-line reconnection models, there are the signatures that point to Raeder's model as the process of FTE generation and evolution for this particular event: the FTE encounter in, and motion into, the winter (in this case, southern) hemisphere and later activation of the subsolar than south-dusk side X-line. Therefore, although from a single event, the present multi-spacecraft analysis shows the first clear support for what Raeder calls "sequential multiple X-line reconnection" (SMXR) as an FTE generation mechanism.

[13] Raeder's simulations predict that SMXR may occur preferentially for large dipole tilts, while small tilt intervals may be dominated by single X-line reconnection. If this is the case, we speculate that the transfer of solar wind energy to the magnetosphere through open magnetic flux transport into the tail may be less efficient for larger dipole tilt (Figures 1a and 1b). This possibly reduced energy transfer under large dipole tilts may be responsible for part of the semiannual variation of geomagnetic activity, in addition to the Russell-McPherron effect [*Russell and McPherron*, 1973]. Future simulation studies are necessary to understand if and how the energy transfer is controlled by the dipole tilt

as well as other factors such as IMF B_x, while observational studies need to statistically reveal occurrence patterns and the topology of FTEs as a function of dipole tilt.

[14] **Acknowledgments.** The authors thank the International Space Science Institute for the opportunity to discuss and exchange ideas in its facilities in Bern, Switzerland, and acknowledge THEMIS contract NAS5-02099 and TUBS support by DLR.

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