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THEMIS observations of the dayside traveling compression region and flows surrounding flux transfer events

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[1] We present multipoint observations of Flux Transfer Events (FTEs) by the THEMIS spacecraft in a string-of-pearls configuration, at the near-equatorial magnetopause. Common characteristics from a number of cases, examined at various local times, are exemplified here by a case study of FTE trains observed in the pre-noon sector, on Aug. 18, 2007. We show that the magneto-pause-normal flow velocity is consistently towards and away from the magnetopause on the inbound and outbound transit of the FTE, on all spacecraft sufficiently away from the magnetopause. The velocity just outside the FTE at the time of closest proximity to the FTE core is opposite to the FTE direction of motion even when the FTE moves in the same direction as the adjacent sheath. The total pressure inside and just outside the FTE is consistently larger than expected from pressure balance at a nominal (unperturbed) magnetopause and therefore the result of local compression by the passing FTE. The multi-spacecraft observation enables the reconstruction of the Dayside Traveling Compression Region (DTCR), whose result is consistent with previous theoretical results. Semi-periodic compressional velocity oscillations were observed and are likely driven by nearby occurrences of FTE trains, implying recurrent reconnection with a similar periodicity. **Citation:** Liu, J., V. Angelopoulos, D. Sibeck, T. Phan, Z. Y. Pu, J. McFadden, K. H. Glassmeier, and H. U. Auster (2008), THEMIS observations of the dayside traveling compression region and flows surrounding flux transfer events, *Geophys. Res. Lett.*, *35*, L17S07, doi:10.1029/2008GL033673.

1. Introduction

[2] Flux Transfer Events [*Russell and Elphic*, 1978] are thought to carry substantial amounts of flux from dayside reconnection to the magnetotail. They occur fairly frequently [*Rijnbeek et al.*, 1982] at the magnetopause and are expected as a result of transient reconnection there [*Fu and Lee*, 1985]. While evidence exists for both continuous reconnection [*Phan et al.*, 2006] and pulsed reconnection [*Lockwood and Smith*, 1992], their relative importance for energy transfer at the magnetopause is not known. FTEs may also participate in energy transfer across the magnetopause by generating boundary layer waves which couple to the inner magnetosphere as field line resonances [*Glassmeier et al.*, 1984], especially given their recurrence rate of 2–5 minutes, which is in the Pc5 frequency band [*Kuo et al.*, 1995]. The relative importance of FTEs to other drivers of global magnetospheric oscillations, such as solar wind dynamic pressure changes [*Sibeck et al.*, 1989], the Kelvin-Helmholtz instability [*Pu and Kivelson*, 1983; *Fujita et al.*, 1996] or time varying reconnection is still unknown. Much of the difficulty in answering such questions is purely observational. With but few spacecraft at disparate locations, it is at best difficult to observe simultaneously nearby upstream solar wind variations and local magnetopause effects, and to discriminate between boundary undulations (waves) and FTEs. Magnetic field modeling and reconstruction of the FTE proper helps (has helped) explain the spiraling component of the field within the FTE proper [*Cowley*, 1982; *Saunders et al.*, 1984; *Sonnerup et al.*, 2004; *Hasegawa et al.*, 2004]. The field and flow line draping expected around the FTE, modeled by *Farrugia et al.* [1987] and *Sibeck and Smith* [1992], suggests that the flow past the FTE can be opposed to the FTE motion, due to the displacement of the ambient magnetospheric plasma by the FTE itself. This flow signature is important to understand and differentiate from reconnection flows at the magnetopause on either side of an FTE. Observed Pressure changes within an FTE are likely due to the development of strong core magnetic fields arising from field-aligned currents flowing along the twisted field lines of the rope [*Kivelson and Khurana*, 1995]. Outside the FTE, however, compressional variations of the field are also expected, due to the local pressure balance at the magnetopause, as affected by the passage of the FTE. This local quasi-static pressure balance leads to a modification of the magnetopause Chapman-Ferraro currents in the vicinity of the FTE. The signature of those local pressure balance currents ought to extend to the neighborhood of the FTE itself, just as the signatures of tailward-moving plasmoid/flux rope extend in the magnetotail lobes, creating traveling compression regions (TCRs) [*Slavin et al.*, 1989]. In this paper we present observations of Dayside TCRs and flow variations associated with them, which are interpreted as signatures of nearby FTEs. The combination of pressure and flow perturbations described leads to a remote signature of FTEs, enabling statistical studies of FTEs and their importance for global magnetospheric coupling, even with single spacecraft several R_E away from the magnetopause.

2. Datasets and Methodology

[3] THEMIS, launched on February 17, 2007, consists of five identical satellites (probes) equipped with comprehen-

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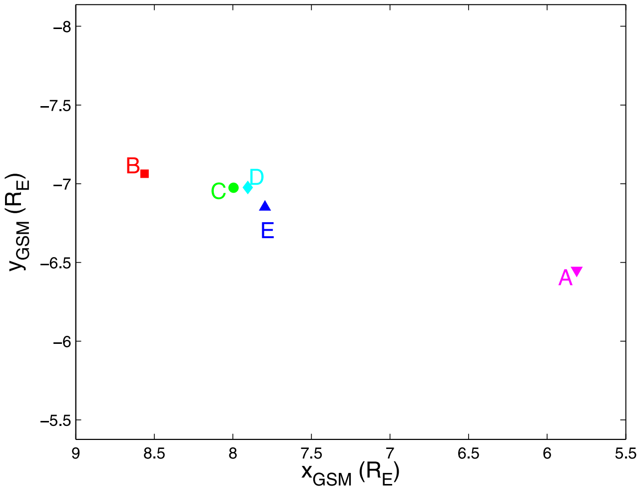


Figure 1. The position of the THEMIS probes at 1010UT, August 18, 2007 in GSM and GSE. The probes were moving away from Earth.

sive particles and fields instrumentation [*Angelopoulos et al.*, 2008]. During the first 7 months of the mission the probes traversed the dusk and dayside magnetosphere in a string-of-pearls configuration in highly elliptical orbits with 14.7 R_E apogee and 16° inclination, coasting en-route to deployment onto their final orbits for their baseline science [*Sibeck and Angelopoulos*, 2008]. The leading and trailing probes along the same orbit were at separations on the order of 1 R_E, while the inner three probes were at separations of 100s of km, an ideal configuration for detailed studies of FTEs.

[4] We used data from the Fluxgate Magnetometer (FGM) instrument [*Auster et al.*, 2008] and the Electro-Static Analyzer (ESA) instrument (J. P. McFadden et al., The THEMIS ESA plasma instrument and in-flight calibration, submitted to *Space Science Reviews*, 2008) on the THEMIS probes. We also used observations from the WIND spacecraft, located at the Earth-Sun Lagrange point. Magnetic Fields Investigation (MFI) magnetometer data [*Lepping et al.*, 1995] and Solar Wind Experiment (SWE) plasma measurements [*Ogilvie et al.*, 1995] from WIND were time-shifted to a judicial point at the subsolar magnetopause, and were used to decide the normal direction of the magnetopause [*Wang et al.*, 2005] using the *Shue et al.* [1998] magnetopause model.

[5] FTE signatures are best shown in the local LMN coordinate of magnetopause [*Russell and Elphic*, 1978], with $\boldsymbol{N}$ normal to the magnetopause pointing to the magnetosheath, $\boldsymbol{L}$ along the projection of the Earth dipole axis onto the magnetopause (positive northward), and $\boldsymbol{M}$ directed dawnward. We transformed THEMIS observation into LMN coordinates [*Wang et al.*, 2005] and picked up FTEs with the following criteria: 1. a recognizable magnetic field B_N bipolar appearing on a relatively quiet background B_N, whose magnitude should be less than 5 nT; 2. a fluctuation duration of between 1 and 5 min. We didn't require an increase in total magnetic strength. We identified 34 events from June 15 to August 31, of which 9 that obey the following criteria were selected: (i) THEMIS was in "fast mode" data collection operations; (ii) a bipolar B_N event was caught with at least one probe at the magnetopause boundary layer; and (iii) fast flows different from the observed or anticipated magnetosheath flow were seen on at least one satellite. The latter criterion was intended for preferential selection of "active" FTE events, i.e., ones likely driven by reconnection on one or both sides. We examined the commonality of the flow and pressure perturbation signatures surrounding them to ascertain that the results presented by means of the following event are consistent with the observations on the others. This paper is not a systematic, statistical study of such signatures; however, our results are supported by observations during more than a handful of "active" FTE crossings.

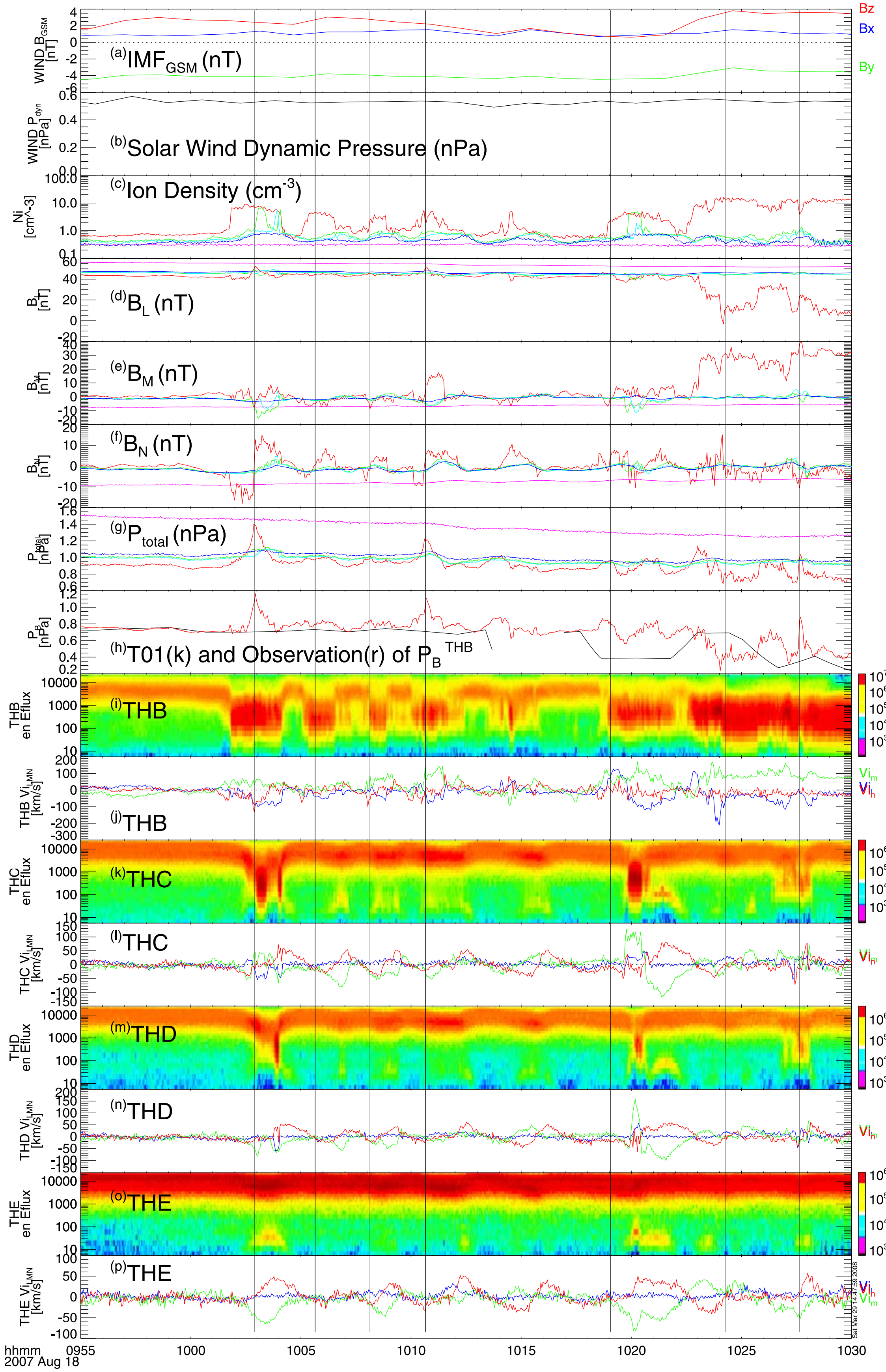
[6] The event presented occurred on August 18, 2007 between 0950 and 1030 UT. The probes were in an outbound orbit, near the nominal model magnetopause (Figure 1 and Table 1). TH-B led furthest away from Earth, TH-A trailed closest to Earth, while TH-C, -D and -E were in between the other two, in that order of decreasing distance. The probes were at around 1010MLT. The sheath magnetic field was southward, while the IMF was northward according to WIND.

3. Observations

[7] Several quantities from all five probes are shown in Figure 2. As evidenced by the density and ion spectrogram of TH-B, that probe was in the magnetosphere at the beginning of the interval (ion density ∼0.8/cc, 10 keV peak ion energy), but by the end of the interval, at 1029UT, it had traversed into the high-density, lower-energy magnetosheath plasma (high ion density, 10 keV peak ion energy). Temporary transitions into the magnetopause boundary layer, a mixture of magnetospheric and magnetosheath plasma, occurred at ∼1003, 1006, 1008:30, 1011, 1014:30 and 1020 UT. A more permanent transition into the layer occurred at 1029UT, at which point TH-B exited into the magnetosheath proper as evidenced by the reduction in the flux of 10keV energy particles at that time. The magnetic field on TH-B (Figure 2f) shows a series of bipolar signatures on B_N, accompanied by correlated bipolar or more complex signatures on B_M. B_L, near the direction of the internal field, as well as increases for some of these events, while the total field (not shown) shows temporary maxima for all of them. The above signatures are characteristic of FTEs. The vertical lines in Figure 2 indicate times of FTEs on TH-B. The FTEs were encountered from the magnetospheric side of the current layers prior to 1023 UT and from the magnetosheath side after 1023UT. The flow direction within the FTEs (Figure 2j) is predominantly dawnward (with a few exceptions of north-south excursions). V_M is comparable

Table 1. The Position of the THEMIS Probes at 1010UT, August 18, 2007 in GSM and GSE

Probe	(x,y,z) in GSM (RE)	(x,y,z) in GSE (RE)
THA	5.812, −6.45,1.012	6.516, −6.276, −2.484
THB	8.562, −7.064,0.434	9.088, −6.374, −3.225
THC	7.996, −6.975,0.559	8.599, −6.384, −3.086
THD	7.905, −6.976,0.598	8.474, −6.41, −3.055
THE	7.796, −6.852,0.546	8.377, −6.28, −3.044


(a)IMF GSM (nT)
WIND B GSM [nT]
Bz
Bx
By
(b)Solar Wind Dynamic Pressure (nPa)
WIND P dyn [nPa]
(c)Ion Density (cm-3)
Ni [cm^-3]
(d)B L (nT)
(e)B M (nT)
(f)B N (nT)
(g)P total (nPa)
(h)T01(k) and Observation(r) of P B THB
(i)THB
THB en Eflux
(j)THB
THB Vi LMN [km/s]
(k)THC
THC en Eflux
(l)THC
THC Vi LMN [km/s]
(m)THD
THD en Eflux
(n)THD
THD Vi LMN [km/s]
(o)THE
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(p)THE
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2007 Aug 18
0955
1000
1005
1010
1015
1020
1025
1030

Figure 2

to (but at times stronger than) the sheath flow, which is seen to be ∼100 km/s at this end of the interval.

[8] The total pressure (including thermal and ram pressure normal to the nominal magnetopause) is shown in Figure 2g. It indicates peaks that exceed the average pressure profile that starts at 0.9 nPa at the beginning of the interval and ends at 0.8 nPa at the end of the interval. These transient pressure increases indicate local pressure changes within the FTEs. We used the *Tsyganenko* [2001] model (T01) to predict the dynamic pressure within the magnetosphere at the time, using instantaneous solar wind measurements. Matching the WIND data with the field signatures at the sheath after the event, we found that the time lag between WIND and THEMIS is ∼57 minutes and applied that to the data. We also adjusted the solar wind dynamic pressure to ensure a magnetopause crossing on TH-B at 10:23UT in the model. The T01 model magnetic pressure at the location of TH-B is shown in Figure 2h. It is evident that the pressure fluctuations observed at TH-B are unrelated to solar wind variations and are due to local pressure enhancements within the observed FTEs.

[9] TH-C, the second closest to Earth, was in the magnetosphere proper, except three times: around 1003UT, 1020UT and 1027:30UT. At those times, the probe exited to the boundary, as evidenced by TH-C's density and ion spectrogram (Figure 2). The magnetic field and total pressure increases, suggest these are transient crossings of FTEs. The total pressure (like the density) on TH-C at those times is comparable to that on TH-B signifying the increased pressure within the FTE proper. The velocity variations at those times are predominantly bipolar in V_N, (towards and away from the satellite, indicating approach and retreat of the FTE) with a predominantly duskward component within the FTE proper (indicating the predominant FTE motion in the same general direction as in the adjacent magnetosheath). Density variations on TH-C during the remainder of the interval (e.g., 1007, 1009, 1011, 1015:30, 1022, 1024) were due to cold (100 eV) magnetospheric particles (as evidenced in the ion spectrogram) and not due to magnetosheath encounters. These are likely cold plasmaspheric plumes, which are accelerated into the energy range of the ESA instrument when the flow is significant (above ∼10 km/s) but are otherwise present for significant times in the dayside magnetosphere [*McFadden et al.*, 2008]. Their contribution to the plasma pressure is very small.

[10] TH-D saw similar signatures as TH-C, except its crossings of the three FTEs were more transient. TH-E did not traverse any of the FTEs, as evidenced in its ion spectrogram in Figure 2. Density variations on TH-E were due to cold ions as evidenced by its ion spectrogram, due to local velocity fluctuations. Pressure variations on TH-E were mostly due to magnetic field variations (compressional oscillations on that satellite), which also correlate very well with those seen on TH-B. During the times of the three FTEs that were barely crossed on TH-D (and presumably just missed on TH-E), velocity fluctuations on TH-E in V_N were (like on TH-C) bipolar, but mostly in the duskward direction in the V_M component, i.e. opposite the sheath flow, and opposite the general FTE motion as determined by TH-E and TH-D measurements.

[11] TH-A, also in the magnetosphere proper, detected slower oscillatory flows in V_N, which correlated with those in TH-E. TH-A also observed bipolar signatures in B_N, in good correlation with the other satellites, but with much lower amplitude. This is interpreted as a reduction in the compressional signal amplitude further away from the source, i.e., the currents associated with the local compression of the magnetopause due to the passage of the FTE.

4. Discussion and Conclusions

[12] In the interval studied, TH-B, in an outbound transit of the magnetopause, observed several FTEs. The FTEs were encountered in the early part of the interval from the magnetosphere side of the current layer out, and in the late part of the interval from the magnetosheath part of the current layer in. Probes TH-C and TH-D encountered three of the FTEs from the magnetopause out, and saw remote signatures of the remaining FTEs from the magnetosphere proper. TH-E and TH-A saw remote signatures of most of the FTEs: flow variability in V_N consistent with the nearby passage of the FTE structure i.e., towards and away the magnetopause, and pressure variations consistent with a compression of the nearby plasma due to the passage of the FTEs.

[13] We can elucidate further the properties of the plasma surrounding the FTEs by examining the pressure perturbations and velocity perturbations around the 1003UT FTE on all five spacecrafts. By timing the observations of the peak pressure we obtain a time delay of t_{BD} = 30s and t_{DE} = 10s between TH-B and -D (separated by 0.5 R_E along the magnetopause boundary) and TH-D and E (separated by 0.1 R_E along the same direction). We thus confirm that the DTCR associated with this FTE was moving roughly in the direction of the magnetosheath flow with a speed ∼100 km/s.

[14] By recording the magnetic and flow field variations around the FTE at various spacecraft it is possible to place them in context of the particle flux and total pressure

Figure 2. (a, b) Solar wind condition obtained by WIND. (c–g) Plots are arranged in five probes per quantity. Quantities are shown in Red, Green, Ciel, Blue and Magenta respectively for TH-B, C, D, E, and A. Magnetic field data are shown in LMN coordinates, which is obtained by Coplanarity Theorem [*Paschmann and Schwartz*, 2000]: $\boldsymbol{n} = \pm \boldsymbol{B_{in}} \times \boldsymbol{B_{out}}/|\boldsymbol{B_{in}} \times \boldsymbol{B_{out}}|$ (pointing out of magnetosphere), $\boldsymbol{m} = \boldsymbol{n} \times \boldsymbol{B_{in}}/|\boldsymbol{n} \times \boldsymbol{B_{in}}|$, $\boldsymbol{l} = \boldsymbol{m} \times \boldsymbol{n}$; where $\boldsymbol{B_{in}}$ and $\boldsymbol{B_{out}}$ are the magnetic field observation in magnetosphere and in magnetosheath by THB, separately. The total pressure is computed as the sum of magnetic, plasma (ion plus electron) and ram pressure (from the V_N component of the flow). (h) Comparison of THB observation and T01 prediction of magnetic pressure. (i–p) Plots are arranged in two plots per probe. The probe data are arranged from the furthest out (Figure 2i) to the closest in at the bottom. Top plot (each probe): Ion energy flux spectrogram ($eV/cm^2 \cdot s \cdot sr \cdot eV$) from the ESA instrument; bottom plot (each probe): Ion flow velocity in LMN coordinates (L, M, N are shown in Blue, Green, Red). The vertical lines shows possible FTEs.

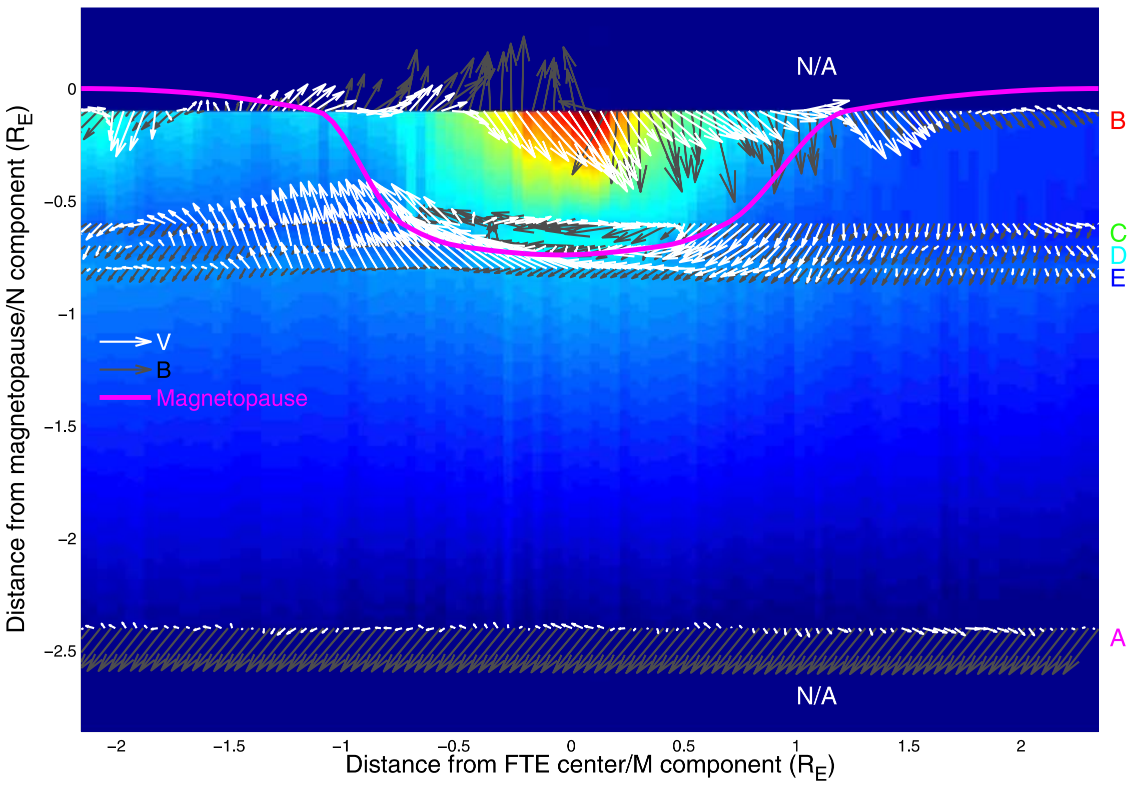

Figure 3. Reconstruction of FTE signatures observed around 1003 UT on multiple THEMIS satellites, on the M−N plane of the LMN coordinate system. Color are ln ΔP with blue the smallest and red the largest, obtained by linear interpolation of the observation of the five probes. Both magnetic field and velocity are smoothed every three points. The magenta line represents the particle flux boundary of the FTE, obtained by cubic interpolation.

variations and construct a sketch of these quantities in a cross-section of the FTE. This is done in Figure 3.

[15] Figure 3 indicates that the FTE perturbs nearby magnetosphere like an obstacle moving through an otherwise stationary plasma. Near the magnetopause, the plasma ahead and behind the FTE is accelerated in the direction of the FTE motion. Further away from the magnetopause the flow is diverted away from the magnetopause before the FTE arrival and towards the magnetopause after the FTE passage. A $\sim$180° rotation of magnetic field across the center of the FTE indicates a rope-like structure [*Russell and Elphic*, 1978] of it. The magnetospheric field is draped around the FTE during its passage near the FTE. Further away, the field direction is unaffected, but flow variations are still evident. Specifically, the flow is opposite the FTE motion and comparable in speed, as the flow is diverted around the moving obstacle (FTE). This reconstruction result is very similar to the prediction of the FTE vicinity model of *Farrugia et al.* [1987].

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