Lui *Geosci. Lett.* *(2015) 2:15*
DOI 10.1186/s40562-015-0032-1

Geoscience Letters
a SpringerOpen Journal

RESEARCH LETTER
Open Access

Dipolarization fronts and magnetic flux transport

A. T. Y. Lui*

Abstract

Recent emphasis on dipolarization fronts (DFs) has led to the impression that DFs play a significant role in bringing magnetic flux to the inner magnetosphere during substorms. In this work, we investigate the amount of magnetic flux transport associated with DFs by examining the frozen-in field line condition (FIC) for previously reported DF events. A study of 18 DF cases shows that the FIC does not hold for 17 cases when the ratio of $\left|\left[E_y + (V \times B)_y\right] / (V \times B)_y\right|$ exceeds 0.5, i.e., the mismatch of E_y and $-(V \times B)_y$ exceeds 50 %; this criterion is applied only when the electric field magnitude exceeds 0.5 mV/m to eliminate times of low-level electric fluctuations. Furthermore, the peak magnetic flux transport rate for DFs in which FIC holds is found to be in the range of ~8–42 kWb/s/R_E while the accumulated flux transport within the DF intervals to be ~0.1–2.8 MWb/R_E. Assuming a dawn-dusk dimension of 3 R_E for a DF, the accumulated magnetic flux transport is ~0.3–8 MWb, which amounts to ~0.1–2.2 % of what is needed to account for magnetic flux increase in the near-earth dipolarization during substorms. This result casts doubt on the idea that DFs play a significant role in substorm dipolarization.

Background

Two recently very popular topics in magnetospheric research are fast transient plasma flows, also called bursty bulk flows (BBFs) (e.g., Angelopoulos et al. 1992; Nakamura et al. 2001), and dipolarization fronts (DFs) (e.g., Nakamura et al. 2002; Runov et al. 2009; Schmid et al. 2011). Statistical studies show that BBFs carry significant amount of mass, energy, and magnetic flux earthward (Angelopoulos et al. 1994; Liu et al. 2011).

A statistical examination of BBFs with Geotail observations reveals that BBFs near the neutral sheet are associated with brief B_z component enhancements that bear striking resemblance to DFs (Ohtani et al. 2004). The general pattern of B_z during BBFs is also reproduced well by global magnetohydrodynamics (MHD) simulations (Wiltberger et al. 2015). Therefore, BBFs and DFs are associated phenomena, but their time scales are different. The time scale of BBFs is ~10 min, while that of DFs is ~1–2 min. In spite of the short durations for DFs, their magnetic flux transport is estimated to be just as significant as BBFs. In particular, Liu et al. (2013, 2014) studied the magnetic flux transport by DFs, referring them as dipolarization flux bundles and proposing them as elementary elements for the substorm current wedge.

Magnetotail observations often reveal the presence of multiple particle populations showing significant deviations from a single fluid (Chen et al. 2000; Parks et al. 2001; Parks 2004). Lui et al. (2005) were the first to present quantitative comparison between single-component (MHD) and multi-component (kinetic) approaches on the transport of mass and energy in BBF events. The result shows significant differences between MHD and kinetic approaches in determining transport properties of BBFs, a result that was further verified by later studies (Lui and Hori 2006; Cao et al. 2013). Therefore, the use of single-fluid approach such as dipolarization flux bundles (Liu et al. 2013, 2014) in evaluating transport properties of BBFs is likely to be inappropriate.

There are attempts to label current disruption events (Takahashi et al. 1987; Lui et al. 1988) as groups of DFs without providing evidence for such an assertion (Zhang et al. 2011; Liu et al. 2013). Careful examination of their characteristics shows that DFs and current disruptions have distinct characteristics and associated physical processes, suggesting that they should not be considered as

---

*Correspondence: tony.lui@jhuapl.edu
JHU/APL, Laurel, MD 20723-6099, USA

the same phenomenon (Lui 2014; Yao et al. 2015). In fact, the event analyzed by Zhang et al. (2011) showed the disturbance spreading tailward, which is a feature of current disruptions (Lopez and Lui 1990; Jacquey et al. 1991; Ohtani et al. 1992) and is in contrast to many reported isolated DFs that propagate earthward.

Inherent in the previous studies on magnetic flux transport by BBFs and DFs is the assumption that magnetic flux is carried by plasma flow. This implies the validity of the frozen-in field line condition (FIC) in these structures. In this work, we examine several cases of DFs for the validity of FIC. These cases were based on observations from THEMIS (time history of events and macroscale interactions during substorms) (Angelopoulos 2008). The result shows that the FIC does not hold in most cases. Therefore, whether DFs can be related to magnetic flux transport needs to be investigated carefully. Furthermore, it is estimated that the magnetic flux transport for cases when the FIC holds is insignificant in comparison with what is needed to account for the magnetic flux increase during substorm dipolarization.

Methods

The DF events are first examined for the FIC so that the DF intervals can be considered as line preserving, i.e., particles on the same field line will remain so at later times (Newcomb 1958). This is done in this work by comparing the values of E_y component with the values of $-(V \times B)_y$, where E_y is the y-component of the electric field, V is the plasma bulk flow (practically the proton plasma flow since electrons are much lighter than protons), and B is the magnetic field. The comparison is done only when the electric field magnitude exceeds 0.5 mV/m to eliminate times of low-level electric fluctuations. Two criterion levels are used. The strict criterion is when the deviation between these two values differs by more than 50 % of the $(V \times B)_y$ component within the DF interval and the lenient criterion (i.e., giving more favorable statistics for DFs with FIC satisfied) is when it is twice the value. This comparison ratio, $\left|\left[E_y + (V \times B)_y\right] / (V \times B)_y\right|$, will be denoted as CR. For DFs that satisfy the FIC, the magnetic flux transport for DF is evaluated. The use of electron velocity instead of plasma bulk velocity to claim the validity of FIC and the calculation of magnetic flux transport by DFs will be discussed later in "Summary and discussion" section.

Data set

The THEMIS data set used in this study consists of magnetic field measured by the fluxgate magnetometer (FGM) (Auster et al. 2008), plasma velocity based on measurements from the electrostatic analyzer (ESA) (McFadden et al. 2008) covering 5 eV–25 keV and from the solid-state telescope (SST) (Angelopoulos 2008) covering 25 keV to ~1 MeV, and electric field obtained by the electric field instrument (EFI) (Bonnell et al. 2008). Only the y-component of the electric field will be examined and its offset for the events is determined by matching the averaged E_y component with the averaged value of $-(V \times B)_y$ during appropriate quiet time of 5 min prior to DF arrival.

Observations

2009 February 27

The clearest multi-case study of DFs was reported by Runov et al. (2011). One of the DFs has also been reported in Runov et al. (2009), which is on 2009 February 27. This event is shown in Fig. 1. The satellite locations for this event and the others discussed in this work are shown in Table 1. The first column of panels in Fig. 1 shows the 3 s spin-averaged B_z component in GSM coordinates for the four spacecraft P1, P2, P3, and P4. The error bars are calculated based on the standard deviation of the mean (SDM) of the spin-averaged values from measurements at a higher resolution of 0.25 s. The second column shows the V_x component in GSM coordinates based on the combined measurements from ESA to SST. The third column shows the comparison between the measured 3 s spin-averaged E_y component in the *dsl* coordinates (close to GSE) and the value of $-(V \times B)_y$ component also in the dsl coordinates using V and B in the dsl coordinates. The error bars on E_y are derived from the SDM of the spin-averaged values based on measurements at a higher resolution of 0.125 s. The error bars on $-(V \times B)_y$ component are based on the SDM of the magnetic field, since no uncertainties are provided for V. The highlighted time intervals are the enhanced B_z periods within the DFs.

The B_z profiles in Fig. 1 show the general properties of DFs. In these cases, the ambient B_z prior to the DF arrival was quite small, ~2–7 nT. The DFs had sharp B_z enhancements to ~20–22 nT for a duration of ~1–2 min. A magnetic dip ahead of a DF, which is a common feature noted previously, can be seen in P1, P2, and P4. Two of the magnetic dips at P1 and P4 reached negative values. The associated flows were earthward and increased significantly further into the DF intervals. There were small tailward flows prior to DF arrival at P2, P3, and P4. Comparison between E_y and $(V \times B)_y$ shows a general agreement. However, there were short intervals that indicate significant discrepancy between the two parameters. For example, there is a noticeable difference during 0751:26–0751:58 UT at P1 with the CR of 0.5–0.8, during 0752:25–0753:18 UT at P2 with the CR of 0.5–0.7, and during 0754:10–0754:20 UT at P4 with the CR of 0.7–1.4. Therefore, under the strict criterion, DFs at P1, P2, and P4 did not satisfy the FIC; and under the lenient criterion, all DFs satisfied the FIC.

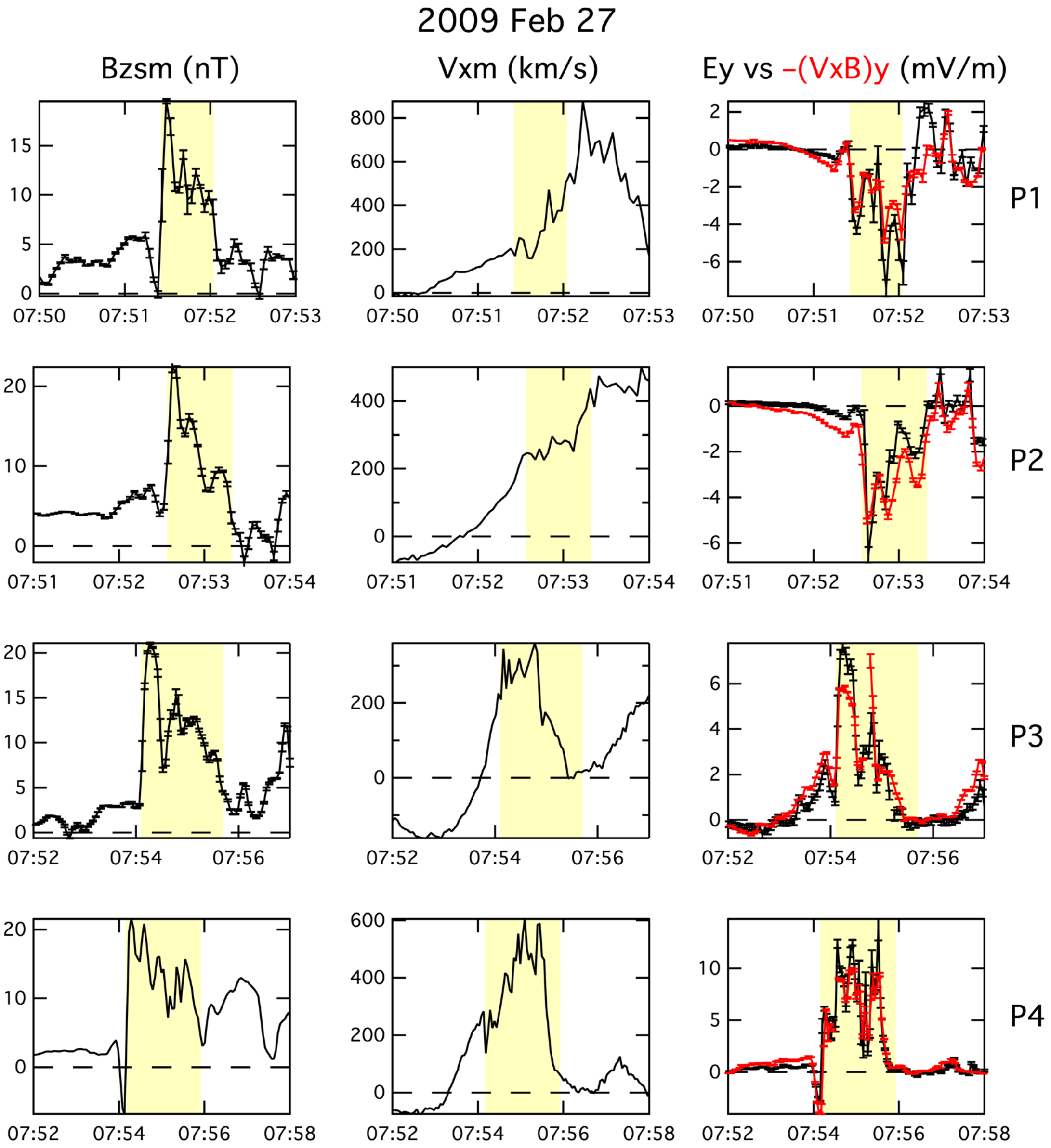

Fig. 1 The B_z component, plasma bulk flow, and comparison between E_y and $-(V \times B)_y$ for four THEMIS satellites on 2009 February 27. The parameters E_y and $-(V \times B)_y$ are in dsl (close to GSE) coordinates

2009 March 5

The event on 2009 March 5 is shown in Fig. 2 with observations from four satellites P2, P3, P5, and P4. For this day, the B_z component prior to the DF arrival was quite different among the satellites, ranging from ~3 to ~10 nT, so was the peak B_z detected within the DF intervals, ranging from ~12 to ~30 nT. Magnetic dips ahead of DFs were relatively small and did not reach negative values for all four satellites. Similar to the previous event, only earthward flows were seen within the DF interval at all satellites. However, this event also shows some significant tailward flows immediately after the DF interval for P5 and P4. Most importantly, for all four satellites, this event shows significant departures between E_y and $-(V \times B)_y$ within the DF intervals. Some significant departure also existed even after the DF interval at P2, P3, and P4. The CRs for DFs at P2, P3, P5, and P4 are 0.7–10.6, 1.6–3.0, 0.9–2.6, and 0.7–2.5, respectively. In other words, the FIC did not hold for all these cases even under the lenient criterion.

Table 1 Spacecraft locations of dipolarization front events

Date	Spacecraft	Xgsm	Ygsm	Zgsm
2009 Feb 27	P1	−20.1	−0.6	−1.5
	P2	−16.7	−1.6	−2.2
	P3	−11.1	−2.7	−2.1
	P4	−11.1	−1.8	−2.4
2009 Mar 5	P2	−17.9	1.4	−1.6
	P3	−10.3	1.5	−1.7
	P5	−9.1	2.4	−2.3
	P4	−9.2	2.4	−1.5
2009 Mar 9	P2	−14.3	−0.8	−1.2
	P4	−11.4	−1.2	−1.6
	P3	−11.1	−2.1	−1.3
2009 Mar 15	P5	−11.5	−0.2	−2.3
	P4	−11.5	−0.2	−1.3
	P3	−11.3	−1.1	−1.0
2009 Mar 19	P4	−11.5	0.6	−1.1
2009 Mar 31	P3	−11.2	1.2	−0.1
	P2	−11.1	1.5	0.0
	P4	−11.3	2.2	−0.4

2009 March 15

Figure 3 shows the event on 2009 March 15. The three satellites are P5, P4, and P3. For this day, the B_z component prior to the DF arrival was quite high before the magnetic dip ahead of the DFs, ranging from ~12 to ~14 nT, so were the peak B_z within the DFs from ~17 to 23 nT. All three satellites detected tailward plasma flow during the DF intervals. Comparison between E_y and $-(V \times B)_y$ shows major departures of these two parameters for all three satellites, indicating a breakdown of the FIC. The CRs for DFs at P5, P4, and P3 are 0.8–6.2, 0.6–3.2, and 2.5–3.2, respectively. Therefore, all these cases did not satisfy the FIC under the lenient criterion.

Other cases

The other DF cases have also been examined and the associated plots are given in the Additional file. Additional file 1: Fig. S1 shows cases for 2009 March 9 event and Additional file 1: Fig. S2 shows cases for 2009 March 19 and March 31 events. For 2009 March 9 event, CRs for P2, P4, and P3 are 1.0–1.3, 0.7–1.1, and 0.7–0.9, respectively. For 2009 March 31, CRs for P3, P2, and P4 are 0.5–2.6, 0.6–0.8, and 1.5–3.5, respectively. For 2009 March 19, CR for P4 is 0.8–0.9. Therefore, under the strict criterion, all seven DFs did not satisfy the FIC whereas under the lenient criterion, the FIC is invalid for only two DFs. Overall, there are 18 cases that can be investigated with reliable measurements. Out of these, FIC was not satisfied for 9 of them under the lenient criterion and for 17 of them under the strict criterion. This small sample indicates that FIC is invalid for ~50 and ~94 % of DFs under the lenient and strict criterion, respectively.

Magnetic flux transport rate and accummulated flux transport

For the cases in which the FIC holds for at least the lenient criterion, one can then proceed to investigate the transport of magnetic flux Φ by DFs. The transport rate $\mathrm{d}\Phi/\mathrm{d}t$ and the accumulated flux transport Φ during the DF interval are given in Fig. 4 for the event on 2009 February 27. The peak magnetic flux transport rate was not steady and fluctuated within the range 35–42 kWb/s/R_E while the accumulated magnetic flux transport within the DF intervals was in the range of 0.7–2.8 MWb/R_E. Similar plots for the other events are shown in Additional file 1: Figs. S3, S4. The peak magnetic flux transport rate for these other cases varied from ~8 to 42 kWb/s/R_E, while the accumulated magnetic flux transport within the DF intervals ranged from 0.1 to 0.8 MWb/R_E. For a DF with 3 R_E wide in the dawn-dusk direction, the range of accumulated magnetic flux transport is ~0.3–8 MWb.

Summary and discussion

We have investigated quantitatively the validity of the FIC for 18 cases of DFs using the measurements from THEMIS and events published by Runov et al. (2011). The FIC is evaluated by comparing the y-component of the in situ electric field with that of the product $-V \times B$ in *dsl* (close to GSE) coordinates. The result shows that out of 18 cases, the FIC is invalid for 9 cases under the lenient criterion of CR greater than 2 and for 17 cases under the strict criterion of CR greater than 0.5. Therefore, most DFs did not satisfy the FIC. The dominance of DFs not satisfying the FIC is probably due to the large inertia of protons, such that their flow cannot change fast enough to match the rapid fluctuations of electric field encountered in DFs.

For cases that satisfy the FIC, the magnetic flux transport rate and the total accumulated magnetic flux within the dipolarization front intervals are evaluated. The peak magnetic flux transport rate is found to be in the range of ~8–42 kWb/s/R_E, while the accumulated magnetic flux transport is in the range of 0.1–2.8 MWb/R_E.

The magnetic flux needed for dipolarization in the near-earth region during substorms has been estimated by Angelopoulos et al. (1994). The amount needed is ~0.36 GWb. This estimate is derived by judging the amount of magnetic flux transport from dayside magnetic reconnection during the substorm growth phase.

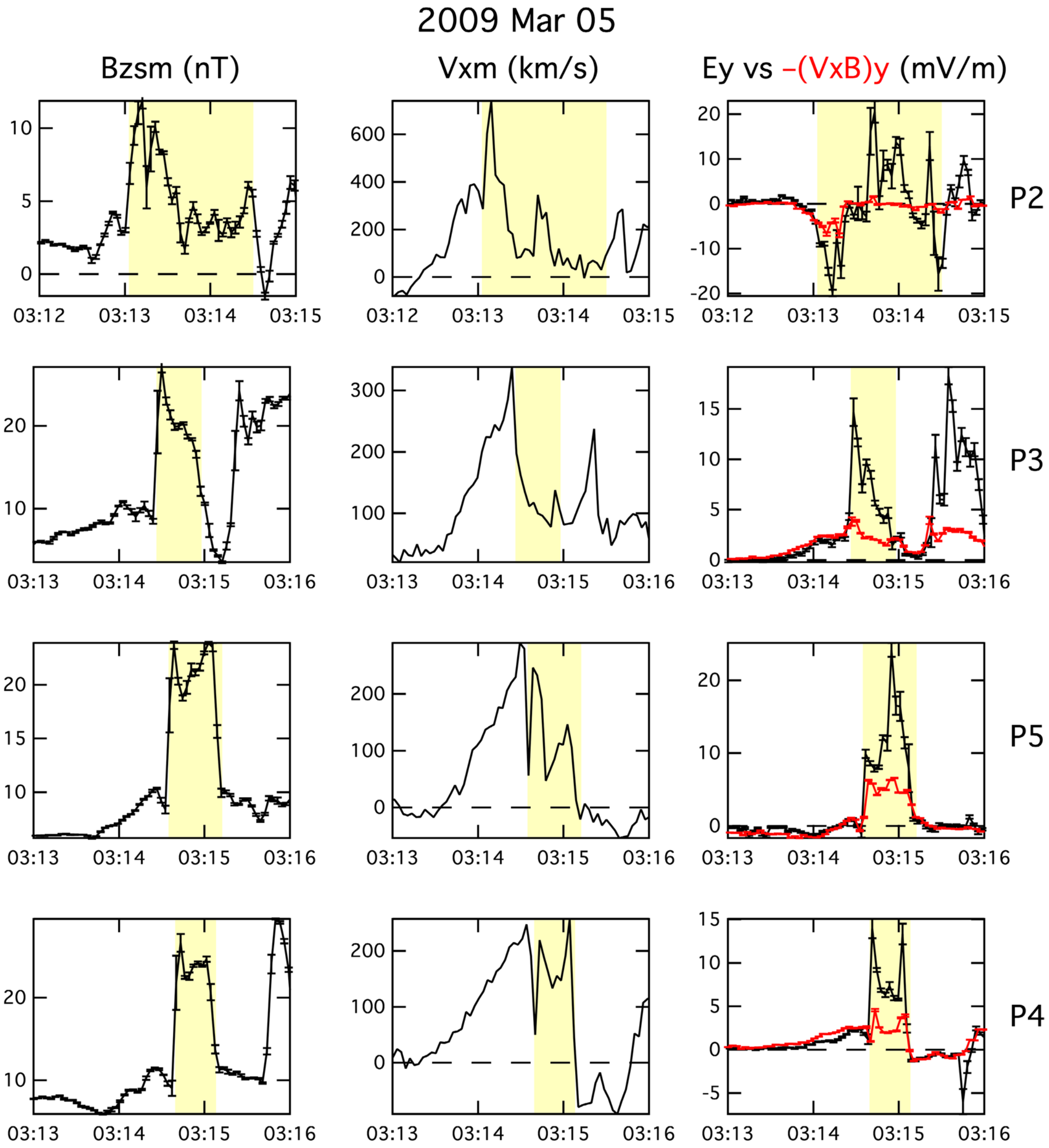

Fig. 2 The B_z component, plasma bulk flow, and comparison between E_y and $-(V \times B)_y$ for four THEMIS satellites on 2009 March 5

Table 5 in that article stated 0.385 GWb for a "typical" substorm. A slightly larger estimate of ~0.5–1 GWb was later given by Angelopoulos et al. (2013). With these estimates, the range of accumulated magnetic flux transport amounts to ~0.1–2.2 % per DF for the 0.385 GWB and ~0.09–0.84 % per DF for the 1 GWB. In other words, it would take at the minimum ~50 DFs to provide the magnetic flux needed for a typical substorm. Therefore, the magnetic flux transport provided by DFs is insignificant in accounting for the magnetic flux needed for substorm dipolarization. This conclusion is consistent with the estimate made in the study by Yao et al. (2015).

Attempts have been made previously to justify magnetic flux transport of DFs by claiming that electrons are still magnetized and the transport can be estimated using the $E \times B$ drift of electrons (Angelopoulos et al. 2013; Liu et al. 2013). However, in order to justify line preserving under this condition with electron flow V_e, it is necessary to demonstrate that $E + V_e \times B = 0$ for all three components of this vector equation, not just one component.

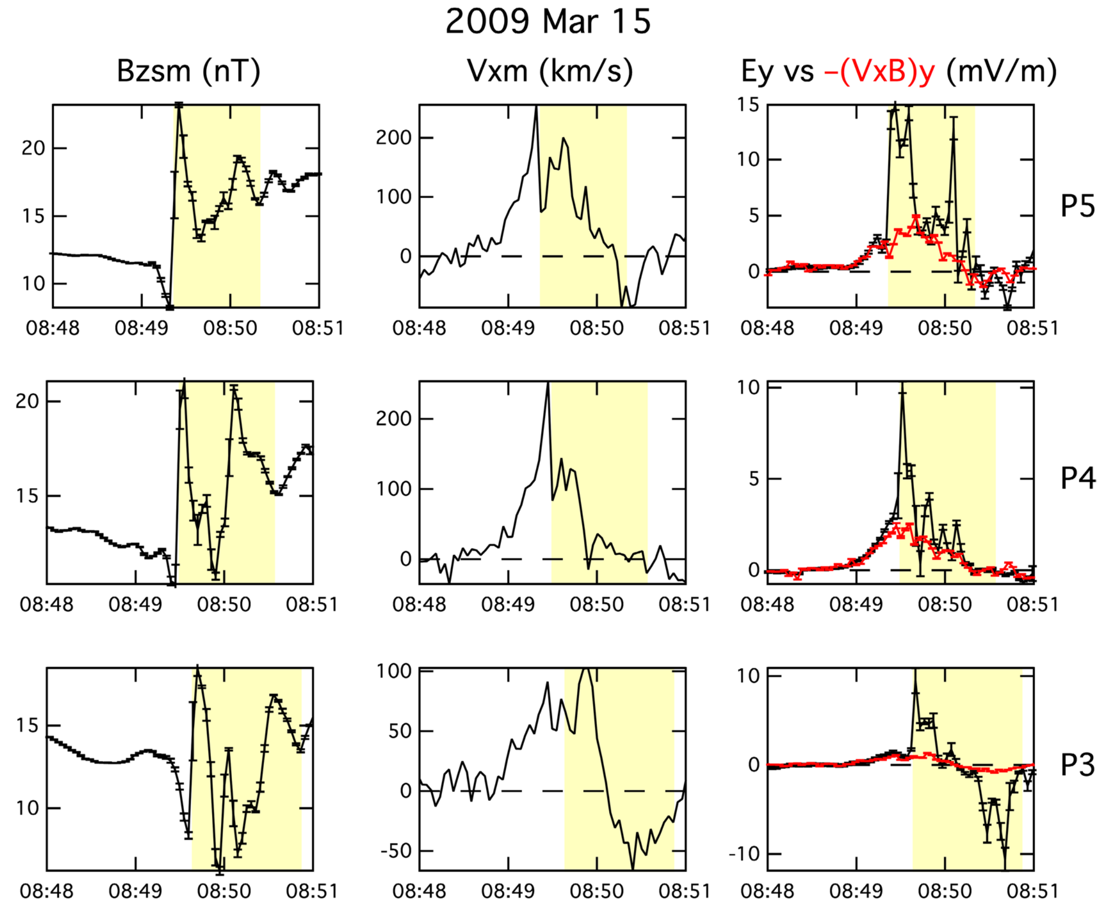

Fig. 3 The B_z component, plasma bulk flow, and comparison between E_y and $-(V \times B)_y$ for three THEMIS satellites on 2009 March 15

This check was not performed by these previous publications. Therefore, it is questionable whether the use of electron motion to compute magnetic flux transport is justified, especially when almost all DFs do not satisfy the strict criterion for the FIC.

In a related matter, Angelopoulos et al. (2013) calculated the energy conversion for these DFs using J_y E_y, where J_y denotes the y-component of the current density. The value of J_y was estimated using $(\partial B_z/\partial t)/V_{xe}$ where V_{xe} is the x-component of the electron flow. This method implicitly assumes line preserving property as well, which was not demonstrated in the work. A proper way to evaluate the current density to estimate the electromagnetic energy conversion is using a tetrahedron configuration like cluster. This was done by Lui et al. (2007) who evaluated all the terms in the generalized Ohm's law during current disruption activity unconnected with magnetic reconnection.

Conclusion

DFs are interesting features in the magnetotail and may transport magnetic flux to the inner magnetosphere. However, the FIC that allows magnetic flux being transported by plasma motion does not hold for many DFs. Even though a small sample of DFs is examined here, the result indicates that the FIC does not hold for a majority of DFs. Therefore, it is necessary to isolate only those cases for which the FIC holds to evaluate the magnetic flux transport. For DFs that satisfy the FIC, the peak magnetic flux transport rate is found to be in the range of 8–42 kWb/s/R_E, while the accumulated magnetic flux transport during the DF intervals is in the range of 0.1–2.8 MWb/R_E. Adopting a width of 3 R_E extent for each DF that satisfies the FIC, it would require 50–1000 of them to account for the magnetic flux needed for near-earth dipolarization in a typical substorm. In other

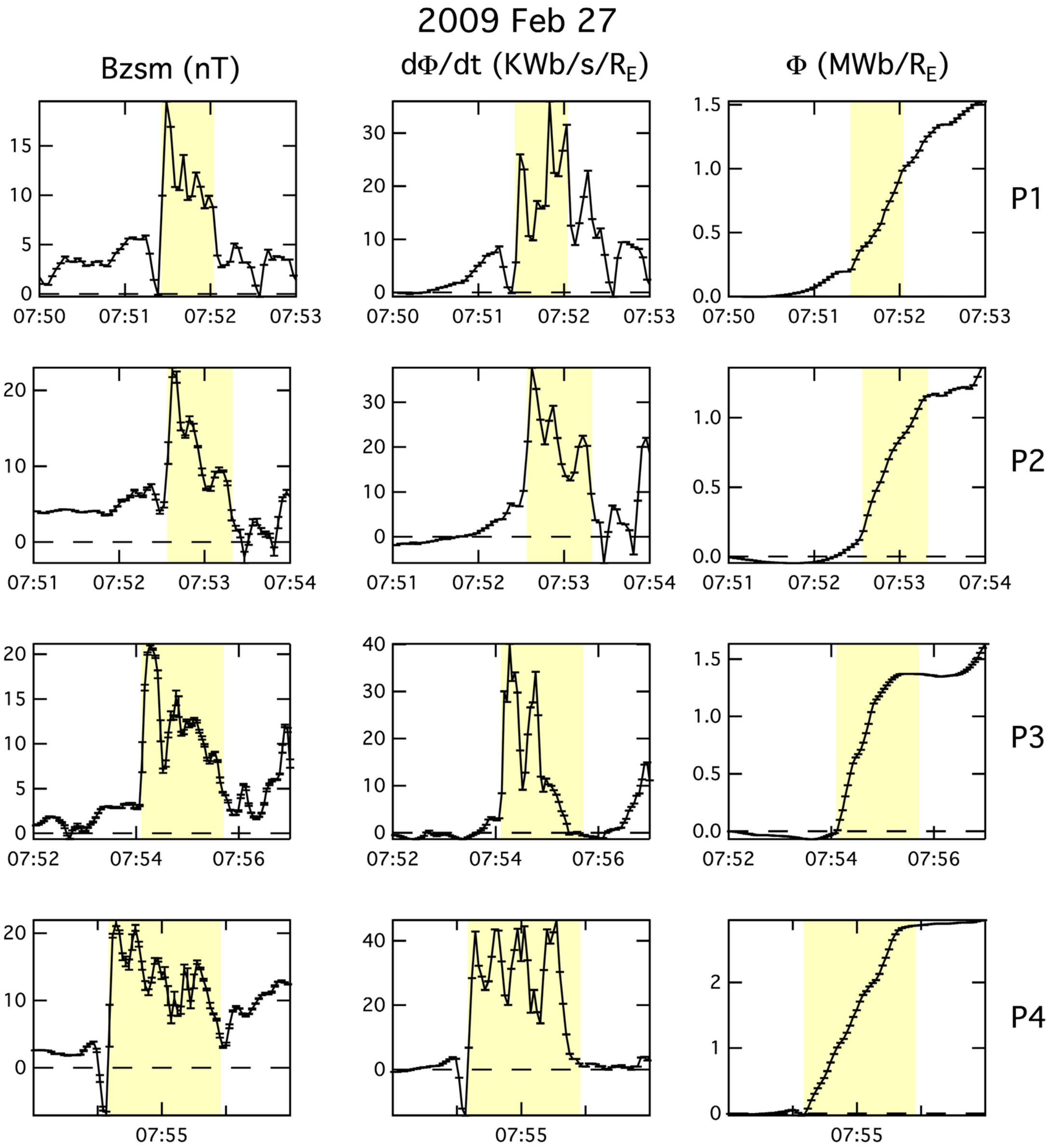

Fig. 4 The B_z component, the magnetic flux transport rate, and the accumulated magnetic flux transport for four THEMIS satellites on 2009 February 27

words, contribution of magnetic flux transport from DFs is negligible for substorms.

Additional file

Additional file 1: Figure S1. The B_z component, plasma bulk flow, and comparison of E_y with $-(V \times B)_y$ in dsl (close to GSE) coordinates for four THEMIS satellites on 2009 March 9. **Figure S2.** The B_z component, plasma bulk flow, and comparison of E_y with $-(V \times B)_y$ for THEMIS satellites on 2009 March 31 and March 9. **Figure S3.** The B_z component, the magnetic flux transport rate, and the accumulated magnetic flux transport for four THEMIS satellites on 2009 March 9. **Figure S4.** The B_z component, the magnetic flux transport rate, and the accumulated magnetic flux transport for four THEMIS satellites on 2009 March 19 and 31.

Acknowledgements
This work was supported by the NSF Grants AGS-1250634 and the NASA grants NNX15AJ48G to The Johns Hopkins University Applied Physics Laboratory, and by NAS5-02099 for THEMIS mission support. We acknowledge NASA contract NAS5-02099 and V. Angelopoulos for use of data from the THEMIS mission through AIDA at Institute of Space Science, National Central University in Taiwan, C. W. Carlson and J. P. McFadden for use of ESA data, D. Larson and R. P. Lin for use of SST data, J. W. Bonnell for use of EFI data, K-H. Glassmeier, U. Auster and W. Baumjohann for use of FGM data provided under the lead of the Technical University of Braunschweig and with financial support through the German Ministry for Economy and Technology and the German Center for Aviation and Space (DLR) under contract 50 OC 0302.

Competing interests
The author declares that he has no competing interests.

Received: 6 November 2015 Accepted: 1 December 2015

References

Angelopoulos V. The THEMIS mission. Space Sci Rev. 2008;141:453–76. doi:10.1007/s11214-008-9336-1.
Angelopoulos V, et al. Bursty bulk flow in the inner central plasma sheet. J Geophys Res. 1992;97:4027–39.
Angelopoulos V, et al. Statistical characteristics of bursty bulk flow events. J Geophys Res. 1994;99:21257–80.
Angelopoulos V, et al. Electromagnetic energy conversion at reconnection fronts. Science. 2013;341:1478–82.
Auster HU, et al. The THEMIS fluxgate magnetometer. Space Sci Rev. 2008;141:235–64.
Bonnell JW, et al. The electric field instrument (EFI) for THEMIS. Space Sci Rev. 2008;141:303–41. doi:10.1007/s11214-008-9469-2.
Chen LJ, et al. Kinetic properties of bursty bulk flow events. Geophys Res Lett. 2000;27:1847–50.
Cao J, et al. Kinetic analysis of the energy transport of bursty bulk flows in the plasma sheet. J Geophys Res. 2013. doi:10.1029/2012JA018351.
Jacquey C, Sauvaud JA, Dandouras J. Location and propagation of the magnetotail current disruption during substorm expansion: analysis and simulation of an ISEE multi-onset event. Geophys Res Lett. 1991;18:389–92.
Liu J, et al. Superposed epoch analysis of magnetotail flux transport observed by THEMIS. J Geophy Res. 2011;116:A00I29. doi:10.1029/2010JA015886.
Liu J, et al. On the current sheets surrounding dipolarizing flux bundles in the magnetotail: the case for wedgelets. J Geophy Res Space Phys. 2013;118:2000–20. doi:10.1002/2013JA019395.
Liu J, et al. Magnetic flux transport by dipolarizing flux bundles. J Geophy Res Space Phys. 2014;119:909–26. doi:10.1002/jgra.50092.
Lopez RE, Lui ATY. A multisatellite case study of the expansion of a substorm current wedge in the near-earth magnetotail. J Geophys Res. 1990;95:8009–18.
Lui ATY. Evidence for two types of dipolarization in the earth's magnetotail. J Atmos Solar Terr Phys. 2014;115:17–24.
Lui ATY, et al. A case study of magnetotail current sheet disruption and diversion. Geophys Res Lett. 1988;15:721–4.
Lui ATY, et al. Plasma transport from multi-component approach. Geophys Res Lett. 2005;32:L06101. doi:10.1029/2004GL021891.
Lui ATY, Hori T. Phase space density analysis of energy transport in the earth's magnetotail. Space Sci Rev. 2006;122(1–4):69–80.
Lui ATY, et al. Breakdown of the frozen-in condition in the earth's magnetotail. J Geophys Res. 2007;112:A04215. doi:10.1029/2006JA012000.
McFadden JP, et al. The THEMIS ESA plasma instrument and in-flight calibration. Space Sci Rev. 2008;141(1–4):277–302. doi:10.1007/s11214-008-9440-2.
Nakamura R, et al. Earthward flow bursts, auroral streamers, and small expansions. J Geophys Res. 2001;106(10):791.
Nakamura R, et al. Motion of the dipolarization front during a flow burst event observed by cluster. Geophys Res Lett. 2002;29(20):1–3. doi:10.1029/2002GL015763.
Newcomb WA. Motion of magnetic lines of force. Ann Phys. 1958;3:347–85.
Ohtani S, Takahashi K, Russell CT. Radial expansion of the tail current disruption during substorms: a new approach to substorm onset region. J Geophys Res. 1992;97:3129–36.
Ohtani SI, Shay MA, Mukai T. Temporal structure of the fast convective flow in the plasma sheet: comparison between observations and two-fluid simulation. J Geophys Res. 2004;109:A03210. doi:10.1029/2003JA010002.
Parks GK, et al. Kinetic characterization of plasma sheet dynamics. Space Sci Rev. 2001;95:237–55.
Parks GK. Why space physics need to go beyond the MHD box. Space Sci Rev. 2004;113:97–125.
Runov A, et al. THEMIS observations of an earthward-propagating dipolarization front. Geophys Res Lett. 2009;36:L14106. doi:10.1029/2009GL038980.
Runov A, et al. A THEMIS multicase study of dipolarization fronts in the magnetotail plasma sheet. J Geophys Res. 2011;116:A05216. doi:10.1029/2010JA016316.
Schmid D, et al. A statistical and event study of magnetotail dipolarization fronts. Ann Geophys. 2011;29:1537–47.
Takahashi K, et al. Disruption of the magnetotail current sheet observed by AMPTE/CCE. Geophys Res Lett. 1987;14:1019–22.
Wiltberger M, et al. High-resolution global magnetohydrodynamic simulation of bursty bulk flows. J Geophys Res Space Phys. 2015;120:4555–66. doi:10.1002/2015JA021080.
Yao ZH, et al. A physical explanation for the magnetic decrease ahead of dipolarization fronts. Ann Geophys. 2015;33:1301–9.
Zhang XJ, et al. Current carriers near dipolarization fronts in the magnetotail: a THEMIS event study. J Geophys Res. 2011;116:A00I20. doi:10.1029/2010JA015885.