<http://www.diva-portal.org>

This is the published version of a paper published in *Journal of Geophysical Research - Space Physics*.

Citation for the original published paper (version of record):

Hamrin, M., Pitkänen, T., Norqvist, P., Karlsson, T., Nilsson, H. et al. (2014)
Evidence for the braking of flow bursts as they propagate toward the Earth.
Journal of Geophysical Research - Space Physics, 119(11): 9004-9018
<https://doi.org/10.1002/2014JA020285>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:umu:diva-99391>

RESEARCH ARTICLE

10.1002/2014JA020285

Key Points:

- We find indications of plasma deceleration in the region $-20 R_E < X < -15 R_E$
- Compressed magnetic flux tubes in DFs can decelerate incoming flow bursts
- Energy conversion arguments can be used for studying flow braking

Correspondence to:

M. Hamrin,
hamrin@space.umu.se

Citation:

Hamrin, M., et al. (2014), Evidence for the braking of flow bursts as they propagate toward the Earth, *J. Geophys. Res. Space Physics*, 119, 9004–9018, doi:10.1002/2014JA020285.

Received 11 JUN 2014

Accepted 21 OCT 2014

Accepted article online 26 OCT 2014

Published online 20 NOV 2014

Evidence for the braking of flow bursts as they propagate toward the Earth

M. Hamrin¹, T. Pitkänen¹, P. Norqvist¹, T. Karlsson², H. Nilsson³, M. André⁴, S. Buchert⁴, A. Vaivads⁴, O. Marghita⁵, B. Klecker⁶, L. M. Kistler⁷, and I. Dandouras⁸
¹Department of Physics, Umeå University, Umeå, Sweden, ²School Electrical Engineering, KTH, Stockholm, Sweden, ³Swedish Institute of Space Physics, Kiruna, Sweden, ⁴Swedish Institute of Space Physics, Uppsala, Sweden, ⁵Institute for Space Sciences, Bucharest, Romania, ⁶Max-Planck-Institut für extraterrestrische Physik, Garching, Germany, ⁷Space Science Center, University of New Hampshire, Durham, USA, ⁸IRAP-CNRS, Toulouse, France

Abstract In this article we use energy conversion arguments to investigate the possible braking of flow bursts as they propagate toward the Earth. By using $\mathbf{E} \cdot \mathbf{J}$ data ($\mathbf{E}$ and $\mathbf{J}$ are the electric field and the current density) observed by Cluster in the magnetotail plasma sheet, we find indications of a plasma deceleration in the region $-20 R_E < X < -15 R_E$. Our results suggest a braking mechanism where compressed magnetic flux tubes in so-called dipolarization fronts (DFs) can decelerate incoming flow bursts. Our results also show that energy conversion arguments can be used for studying flow braking and that the position of the flow velocity peak with respect to the DF can be used as a single-spacecraft proxy when determining energy conversion properties. Such a single-spacecraft proxy is invaluable whenever multispacecraft data are not available. In a superposed epoch study, we find that a flow burst with the velocity peak behind the DF is likely to decelerate and transfer energy from the particles to the fields. For flow bursts with the peak flow at or ahead of the DF we see no indications of braking, but instead we find an energy transfer from the fields to the particles. From our results we obtain an estimate of the magnitude of the deceleration of the flow bursts, and we find that it is consistent with previous investigations.

1. Introduction

So-called bursty bulk flows (BBFs) are commonly observed in the Earth's magnetotail at $X \gtrsim -20 R_E$ [Baumjohann et al., 1990; Angelopoulos et al., 1994]. BBFs are intervals of highly structured fast flows ($\gtrsim 400$ km/s) with a duration of several minutes. According to the theory of bubbles, BBFs are depleted flux tubes with decreased entropy propagating toward the Earth [Pontius and Wolf, 1990; Chen and Wolf, 1993, 1999; Kim et al., 2010]. BBFs are often associated with substorms, although they are sometimes also observed during more quiet times [Baumjohann et al., 1990, 1999, and they play a major role for the transport of magnetic flux, mass, and energy in the magnetotail plasma sheet [Sergeev, 2004].

BBFs are generally considered to be generated at a magnetic neutral line (X line), where large amounts of stored magnetic energy is released abruptly through the process of magnetotail reconnection [Sergeev, 2004; Sharma et al., 2008]. Often associated with BBFs is a sharp increase in the northward magnetic field component, GSM B_z , a so-called dipolarization front (DF) [Nakamura et al., 2002]. DFs have been observed propagating earthward in the magnetotail plasma sheet, $-30 R_E < X < -5 R_E$ [e.g., Ohtani et al., 2004].

The occurrence rate of BBFs is observed to decrease closer to the Earth. This decrease is believed to be caused by a general flow braking and diversion, in particular, in the near-Earth plasma sheet around $X \lesssim -10 R_E$ [Baumjohann et al., 1990; Shiokawa et al., 1997; McPherron et al., 2011]. BBFs usually do not reach the altitude of the geosynchronous orbit [Ohtani et al., 2006]. However, it is still an open question what happens to the BBFs during their propagation from the X line toward the Earth. Are they continuously decelerated along their way, or is the main deceleration concentrated to the near-Earth plasma sheet where the plasma flows meet the significantly more dipolar geomagnetic field?

Baumjohann et al. [1990] used 8 months of data from the AMPTE/IRM spacecraft to statistically investigate the characteristics of BBFs in the plasma sheet. In their Figure 3 they showed that there is a large decrease in BBF occurrence frequency already in the region $-18 R_E \lesssim X \lesssim -15 R_E$, suggesting a nonnegligible flow braking even rather close to the X line. AMPTE/IRM data were also used by Shiokawa et al. [1997], who

statistically investigated the flow braking in the region $-19 R_E \lesssim X \lesssim -9 R_E$. They showed that the BBF occurrence rate decreases continuously toward the Earth, suggesting a continuous braking mechanism for BBFs. However, *Shiokawa et al.* [1997] also found that flow bursts in the higher-speed range, >600 km/s, penetrate all the way to $\sim 10 R_E$. They therefore propose that such high-speed flows are stopped at the inner edge of the plasma sheet, where the geomagnetic configuration changes from taillike to more dipolar.

A continuous deceleration of flow bursts along their propagation toward Earth has already been suggested in the above statistical investigations [Baumjohann et al., 1990; Shiokawa et al., 1997]; however, what mechanisms are causing this flow braking is not fully understood. For example, it has been suggested that the growth of Kelvin-Helmholtz waves on the boundary of flow channels can be important for flow braking in the magnetotail [Volwerk et al., 2007; Turkakin et al., 2014]. In this article we will instead investigate the possibility that compressed magnetic flux tubes in DFs can constitute local impediments to flow bursts along their earthward propagation. Magnetic field dipolarizations are indeed expected to be important for the flow braking closer to the Earth, $X \lesssim -10 R_E$ [Shiokawa et al., 1997], but here we focus on the region between $X \sim -20 R_E$ and $X \sim -15 R_E$ in a statistical investigation using Cluster data from 2001.

In our investigations we will use energy arguments, and we will analyze the observed power density $\mathbf{E} \cdot \mathbf{J}$, where $\mathbf{E}$ is the electric field and $\mathbf{J}$ the current density. The power density corresponds to the amount of energy (per unit volume and per unit time) converted between its electromagnetic and kinetic forms. When $\mathbf{E} \cdot \mathbf{J} < 0$, energy is transferred from the particles to the fields, and the electromagnetic energy density increases if the Poynting flux can be neglected. This can be verified from the Poynting's theorem. Similarly, energy is transferred from the fields to the particles when $\mathbf{E} \cdot \mathbf{J} > 0$, and electromagnetic energy density decreases. Using the analogy of circuit theory, $\mathbf{E} \cdot \mathbf{J} < 0$ corresponds to generator (or dynamo) processes, while $\mathbf{E} \cdot \mathbf{J} > 0$ corresponds to load processes.

2. Data and Event Selection

In this article we use plasma sheet data from 2001 from the Cluster Ion Spectroscopy experiment (CIS), Electric Field and Wave experiment (EFW), and Fluxgate Magnetometer (FGM) instruments onboard the four-spacecraft Cluster mission [see Escoubet et al., 2001, and references therein].

Ion moments from the CIS Composition and Distribution Function analyser (CODIF) and the CIS Hot Ion Analyzer (HIA) sensors are used both for estimating the plasma velocity $\mathbf{V}$ and the electric field, $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$. From CODIF we use the moments for H^+ ions, while HIA does not have mass separation. HIA is operational on spacecraft C1 and C3. CODIF is operational on C1, C3, and C4 but suffers from a high noise level on C3. In this investigation we use HIA data from C1 and C3, and CODIF data only from C4. EFW measures the electric field in the satellite spin plane using probes on wire booms. The full EFW electric field vector is estimated from the assumption $\mathbf{E} \cdot \mathbf{B} = 0$, and any effects from possible parallel electric fields are hence not included in this study. Note that the full vector cannot be obtained from EFW when $\mathbf{B}$ is close to the spin plane, but whenever available, full $\mathbf{E}$ vectors from the EFW instrument are used to confirm the electric field estimates from CIS. We use calibrated data from the Cluster Active Archive (CAA). However, for the EFW E_x data we have made additional calibrations to remove offsets in the Sun-Earth direction.

Magnetic field data from the FGM instrument onboard all four spacecraft are used to obtain the full electrical current density, $\mathbf{J} = \nabla \times \mathbf{B} / \mu_0$ by using the curlometer method [Dunlop et al., 2002]. The size and shape of the Cluster tetrahedron affect the curlometer estimate, and structures much smaller than the characteristic size of the tetrahedron cannot generally be resolved. The tetrahedral configuration during the plasma sheet passages of 2001 was optimal (approximately equilateral).

Since the curlometer current density can be regarded as an average value over the Cluster tetrahedron, we also average the electric field over the available instruments before computing the power density. We average the CIS electric field over C1, C3, and C4. For the EFW estimate we average over 0–4 spacecraft, depending on how many EFW sensors that give reliable estimates. Note that the resulting $\mathbf{E} \cdot \mathbf{J}$ cannot be expected to resolve physics on scales much smaller than the tetrahedron. Calculating the median of the H^+ gyroradius of the individual events, we find that it is ~ 700 km (ranging between 350 km and 1550 km). (Our events have median temperature and magnetic field within the ranges 1–7 keV and 6–28 nT, respectively). The Cluster scale size in the magnetotail was ~ 150 km in 2001, i.e., one or a few H^+ gyroradii for our events. In our investigation we can hence only investigate energy conversion processes on ion scales. To resolve

processes on electron scales, future missions such as Magnetospheric Multiscale (MMS) mission are needed. Note also that the typical H^+ gyroradius is considerably smaller than the cross tail scale size of flow bursts, which is expected to be of the order of 1 or a few R_E [e.g., *Sergeev et al.*, 1996; *Angelopoulos et al.*, 1997; *Nakamura et al.*, 2004, 2005, *Walsh et al.*, 2009].

To obtain a basic understanding of the possible flow-braking mechanisms caused by magnetic field interactions tailward of the inner magnetosphere, we will analyze events whose flow signatures are not too complicated. For the event selection we will therefore focus only on flow signatures with rather smooth and simple character, and with not too high velocities. We will denominate such school book events as solitary. In the rest of the article we will use the term flow burst instead of BBF, since we allow slower flows than the original threshold $\gtrsim 400$ km/s for BBFs [*Angelopoulos et al.*, 1992].

We will classify our events into two types based on the position of the peak of the earthward component of the perpendicular flow velocity, $V_{\perp X}$, with respect to the position of the DF: (i) The flow peak is behind the DF and (ii) the flow peak is at or ahead of the DF. In case (ii) one would expect that the flow burst is passing through (or has passed through) the DF, while in case (i) there is excess kinetic energy in the incoming plasma flows, which can compress flux tubes lying ahead. *Fu et al.* [2011] used a similar classification when investigating Fermi and betatron acceleration of suprathermal electrons within so-called magnetic flux pileup regions (FPRs) behind DFs. They denominated case (i) above as “growing FPR” and case (ii) as “decaying FPR.” According to *Fu et al.* [2011], the plasma flow decelerates because more rapidly moving earthward convecting flux tubes are pushing into slower moving ones, magnetic flux is piling up in localized regions, and kinetic energy is transferred to electromagnetic energy in growing FPRs in case (i). This leads to a compression of the earthward flux tubes and betatron acceleration of the electrons. A decaying FPR in case (ii) corresponds to a possibly later stage when the velocity peak is at/ahead of the DF, and the bulk flow is no longer compressing the flux tubes. *Fu et al.* [2011] instead argue that the flux tubes are expanding, and energy is transferred from the fields to the plasma and that Fermi acceleration dominates inside such a decaying FPR.

The concept of an FPR was introduced by *Khotyaintsev et al.* [2011]. *Liu et al.* [2013] instead used the term dipolarizing flux bundle (DFB) for the same type of region with a more dipolar magnetic field than the background. In this article we will use the denomination FPRs when referring to such regions with piled-up magnetic flux, and we will study the possible flow braking which may occur when flow bursts interact with DFs. While *Fu et al.* [2011] used the position of the GSM V_x flow peak for classifying events into growing and decaying FPRs, we will instead use the earthward component of the perpendicular velocity, $V_{\perp X}$, since we believe that this is more physically correct. We will only focus on solitary FPRs, i.e., events that can be distinctly classified into either case (i) or (ii). However, many FPRs are more complicated. The magnetic field and/or plasma velocity can, for example, exhibit large variations within the FPR, suggesting that such an FPR can be composed of both growing and decaying phases [*Fu et al.*, 2012a]. Such complicated events are not included in our investigation.

There are four main stages in the event selection. The first step is an automatic selection of all strong enough B_z gradients (potential DFs) collectively observed by all four spacecraft in the plasma sheet in 2001. Only the tail region $-20 R_E \leq X \leq -10 R_E$ and $|Y| \leq 12 R_E$ is considered. All events are required to have monotonically increasing B_z signatures with a total gradient $\Delta B_z / \Delta T \geq 0.2$ nT/s. The total change should be $\Delta B_z = B_{z2} - B_{z1} \geq 5$ nT, the top value $B_{z2} \geq 4$ nT, and the total magnetic field $|B|$ should be increased during the event. Moreover, to ensure that the DFs are clearly separable from neighboring magnetic field signatures, we require that there is a small B_z plateau in front of all the DFs. The first event selection step results in ~ 300 DF events. Our search criteria for possible DF events are weaker than those used by *Schmid et al.* [2011] and *Fu et al.* [2012b], and we therefore find considerably more events.

We only want to include solitary FPRs. In the second step we therefore manually keep only events with rather smooth and simple signatures, and with clearly definable start and stop times when observing the magnetic field data, B_z and $|B|$. After this step there remain 43 solitary FPRs. In a third step, we use both B_z and $V_{\perp X}$ data from the four spacecraft to manually classify the events into growing or decaying FPRs depending on whether the $V_{\perp X}$ peak is behind or at/ahead of the DF, i.e., cases (i) and (ii) above. All FPRs which cannot clearly be classified according to this rule are rejected. After this third step there remain 13 growing and 20 decaying FPRs. Finally, we only want to keep events where Cluster probes close to the main channel of the flow bursts. This means that $V_{\perp X}$ should be dominantly positive within the FPRs. In an

Figure 1. The location of the selected events in GSM xyz space. Blue and red correspond to growing FPRs and decaying FPRs, respectively. See the text for details.

automatic routine we only keep events where more than half of the $V_{\perp X}$ samples within an FPR are larger than an a priori chosen noise level threshold (0.1 times the 75th percentile of $V_{\perp X}$). After this final selection step, there remain 16 decaying and 10 growing FPRs in the database. Finally, we manually inspect all selected events to verify that there are no clear signatures of B_y Hall fields or V_x jet reversals together with B_z sign changes associated with X lines propagating over the spacecraft. We therefore conclude that our events are not likely to be closely related to nearby reconnection [see, e.g., Eastwood *et al.*, 2010].

Figure 1 shows the location in GSM xyz space of the 26 selected FPRs. We see that they are rather evenly spread in the region $-20 R_E < X < -15 R_E$ of the plasma sheet probed by Cluster, even though a few events are closely located. Growing FPRs are marked blue, and decaying FPRs are marked red.

3. Theoretical Motivation

Below we schematically discuss three types of FPRs. The FPR geometry in the equatorial plane is presented in Figure 2a. Figures 2b–2g show the properties of the FPR as a function of x . The magnetic field is along z , it increases sharply at the front (the DF in region A between x_1 and x_2) and decreases at the rear end (between x_2 and x_3) as shown in Figure 2b. Note that the FPR region behind the DF is m times longer than the DF. In this slab geometry, the current density is $J_y = -\partial B_z / \partial x / \mu_0$. We assume that the magnetic field strength behind the FPR equals its background value. In this configuration, J_y in A is m times stronger than (and oppositely directed to) J_y in B as shown in Figure 2d. In Figure 2c we show three different models of the plasma flow velocity. In case I the entire FPR (A+B) is moving as a unity, while the surrounding plasma is at rest. In cases II and III, either part of the front or the rear region is moving. Case III corresponds to a growing FPR, where tailward flux tubes are running into earthward ones. Case II, on the other hand, corresponds to a decaying FPR. Case I corresponds to an FPR, which is neither accelerating nor decelerating. Figure 2e shows the resulting electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$ for models I–III assuming ideal MHD.

In Figure 2f we show the power density as it would be observed by a spacecraft moving relatively to the FPR along the x direction. It is obtained by multiplying J_y with E_y for the three velocity models. Due to the stronger magnetic field gradient at the front of the FPR, the load $|\mathbf{E} \cdot \mathbf{J}|$ at the front is larger than the generator $|\mathbf{E} \cdot \mathbf{J}|$ at the rear end. This is consistent with previous observations showing that loads in general are stronger than generators in the plasma sheet [Hamrin *et al.*, 2011].

Figure 2. (a–g) Properties of three schematic types of FPRs as a function of x . Case II is decaying (load) and III is growing (generator). Case I corresponds to an FPR which is neither accelerating, nor decelerating. See the text for more details.

Hamrin *et al.* [2013] investigated two growing FPRs and one decaying FPR. They showed that both the front load and the rear end generator signatures must be taken into account when determining the total energy conversion of an FPR. We hence need to integrate the power density over the entire FPR to determine if the net $\mathbf{E} \cdot \mathbf{J} < 0$ and if it is likely that the plasma flow is decelerating while transferring energy to the fields. Figure 2g shows the integral of the power density, $W(x) = \int_{x_1}^x \mathbf{E} \cdot \mathbf{J} dx'$. It is straightforward to show that the total energy change over the FPR $\int_{x_1}^{x_3} \mathbf{E} \cdot \mathbf{J} dx = \int_{\text{FPR}} \mathbf{E} \cdot \mathbf{J} dx = 0$ for case I (the red curve is zero when the spacecraft exits the FPR at x_3). Moreover, the total energy change for a decaying FPR (case II) is $\int_{\text{FPR}} \mathbf{E} \cdot \mathbf{J} dx > 0$, and for a growing FPR (case III) is $\int_{\text{FPR}} \mathbf{E} \cdot \mathbf{J} dx < 0$. For a nonuniformly moving solitary FPR, there will either be a net energy transfer from the fields to the particles (II, load processes), or from the particles to the fields (III, generator processes). In case III we see that the plasma flow is decelerated as bulk flow energy is transferred into magnetic energy. Note that cases I–III above are very simplified, both in the geometrical configuration and in the magnetic field and plasma flow signatures. For example, it is not unlikely that the velocity and magnetic field show substantial variations within the FPR, implying that the FPR consists of several growing and decaying phases. The flow burst velocity may also not be fully aligned with GSM x . Moreover, B_z behind the FPR ($x > x_3$) may sometimes be slightly elevated when compared to the undisturbed value ahead of the DF. This will give a positive contribution to W for all cases I–III.

In this article we will use Cluster data to estimate $W(x)$ and the net energy transfer $W(\text{FPR}) = \int_{\text{FPR}} \mathbf{E} \cdot \mathbf{J} dx$ of the FPRs, and we will investigate the possible deceleration of flow bursts caused by an interaction with the DFs. In practice it is difficult to obtain these integrals from in situ data. The magnetic field and velocity data are often very complicated, and the spacecraft are generally not probing the entire FPR well. However, the integral along the spacecraft path $W(t) = \int_0^t \mathbf{E} \cdot \mathbf{J} V_{\perp} dt$ can be used as a proxy for the energy change if the spacecraft orbit is optimal, i.e., if the satellites evenly probe both ends of the FPR near the

central part of the flow burst channel. Here we will use a statistical approach when estimating $W(t)$ of FPRs, and we will argue that the integral, on the average, will be correctly estimated if the statistical data set is large enough. By analyzing details of the energy change function $W(t)$ and its variation with t (along the spacecraft path), we will be able to determine if it is likely that energy is transferred from the particles to the fields or in the opposite direction. In the case of a decelerating flow burst, the energy function will have a local maximum and show a clearly negative slope toward the rear end, and there will be a net energy transfer from the particles to the fields ($W(\text{FPR}) < 0$), similar to the behavior of case III in Figure 2. If the energy function is approximately monotonically increasing, energy will instead be transferred from the fields to the particles. This corresponds to case II in Figure 2.

4. Observations

In Figure 3 we show two typical FPRs, A and B, from 24 July and 8 October 2001, respectively. From Figures 3a and 3b we see that all four spacecraft observe similar magnetic field signatures with increased B_z and increased $|B|$ (only shown for C3) within the FPRs. The FPRs are highlighted in yellow, and they have rather distinct start and stop times. From Figure 3c we see that the FPRs are dominated by $V_x > 0$, even though there are also some variations in V_y and V_z . The black curve in Figure 3c corresponds to the earthward component of the velocity perpendicular to the average magnetic field, $V_{\perp X}$, which is very similar to V_x . Note that this $V_{\perp X}$ is used for the classification into growing or decaying FPRs according to the description in section 2.

For clarity we have replotted B_z (yellow) and $V_{\perp X}$ (black) for C3 in Figure 3d. We see that the $V_{\perp X}$ peak of FPR-A is approximately colocated with the DF ($\sim 17:31:50$ UT). FPR-A is consequently classified as decaying. For FPR-B we have another situation since the $V_{\perp X}$ peak ($\sim 14:15:53$) is behind the DF ($\sim 14:15:10$), and FPR-B is hence growing. Note that we only show B_z and $V_{\perp X}$ for C3 in Figure 3d, but that data from all available spacecraft are used for the classification of growing and decaying FPRs.

In Figure 3e we show the components of the electric field obtained from different instruments. The solid lines correspond to the CIS-HIA and CIS-CODIF estimates ($-\mathbf{V} \times \mathbf{B}$), while the dashed lines show the electric field measured by EFW. We see that the CIS and EFW estimates agree rather well on the average, even though there are some dissimilarities, for example, near the DF of FPR-A. One possibility is that this discrepancy is caused by the magnetic field not being fully frozen into the plasma [Sun *et al.*, 2014].

In Figure 3f we present the current density data. The solid lines are the components of the curlometer current density, while the dashed magenta line is the approximate J_y component obtained with the single-spacecraft method according to $\mu_0 J_y = \partial B_z / \partial x \sim \Delta B_z / (V_{\perp X} \Delta t)$, where we have used the magnetic field and earthward perpendicular flow velocity from C3. This is a very simple approximation of J_y , and we do not expect it to be equally correct throughout the entire FPR, since the magnetic field and the flow velocity vary substantially. The single-spacecraft method is expected to work well when a spacecraft is crossing a distinct current sheet, as at the DF. In such regions, the single-spacecraft method is usually better than the curlometer in resolving small-scale current density structures, but it is not appropriate for determining the full current density vector of more general current density structures. It also gives large errors when $V_{\perp X}$ is close to zero (see, for example, the rear end of FPR-A). The single-spacecraft estimate can still be used for double checking the y component of the curlometer current, at least in parts of the FPR. From Figure 3f we see that the curlometer current shows more smooth variations than the single-spacecraft current and that the curlometer peak at the DF is slightly shifted with respect to the single-spacecraft peak. These differences between the curlometer method and the single-spacecraft method are expected [Hamrin *et al.*, 2008]. A deviation between the Curlometer J_y and the single-spacecraft estimate can of course also be caused by $V_{\perp X}$ not being entirely perpendicular to the current sheet at the DF. However, we find that the single-spacecraft result do not contradict the curlometer result, and we conclude that it is justified to use the curlometer method when estimating the larger-scale currents of the FPRs.

Figures 3g and 3h show the power density and the energy function $W(t) = \int_0^t \mathbf{E} \cdot \mathbf{J}_{\perp X} dt$ along the spacecraft path, using available electric field data from CIS (solid lines) and EFW (dashed lines) onboard the different satellites. Note that we in this case have calculated $\mathbf{E} \cdot \mathbf{J}$ by multiplying the curlometer current with the local electric field measurements from various spacecraft. This is done to show that there may be differences between the satellites' electric field estimates, but still the general trend of the resulting $W(t)$ curve is

Figure 3. Typical (A) decaying and (B) growing FPR. For both FPRs, (a) FGM B_z from C1–C4; (b) B from C3; (c) HIA $\mathbf{V}$ from C3; the black line corresponds to the earthward component of the perpendicular velocity, $V_{\perp X}$; (d) B_z (yellow) and $V_{\perp X}$ (black) from C3; (e) $\mathbf{E}$ obtained from CIS (solid lines) and EFW (dashed); (f) curlometer current density (solid lines) and the single-spacecraft estimate of J_y for C3 (dashed magenta line); (g) power density obtained by multiplying $\mathbf{J}$ with $\mathbf{E}$ from CIS-HIA on C1 and C3 (black and green solid lines), from CIS-CODIF on C4 (blue solid line), and from spacecraft with available EFW data (dashed lines); and (h) $W(t) = \int_0^t \mathbf{E} \cdot \mathbf{J} dt$. The GSM coordinate system is used.

topologically the same. The difference in $\mathbf{E} \cdot \mathbf{J}$ between the spacecraft can in fact be used to obtain a scale size estimate of the regions [Hamrin et al., 2009].

For FPR-A, we see in Figure 3A:g that the positive power density at the front dominates over the negative power density at the rear end. We hence conclude that FPR-A should be classified as a load. The conclusion can be verified from Figure 3A:h, where we see that the estimated net energy change is clearly positive, $W(\text{FPR}) > 0$. Using CIS or EFW in the $W(\text{FPR})$ calculation gives slightly different results, but both instruments agree on the sign of the power density, and hence on the general conclusion that FPR-A is a load. FPR-A is therefore associated with energy conversion from the fields to the particles. Either there is no deceleration at all of the flow burst, or load processes dominate over any possible generator processes.

The energy conversion characteristics of FPR-B are different as can be seen when analyzing Figures 3B:g and 3B:h. Now the rear end generator signature is comparable to (or even larger than) the front load in Figure 3B:g. As can be seen in Figure 3B:h, the energy function $W(t)$ has a negative slope at the rear end. The net energy change of the FPR (observed after $\sim 14:16:00$ UT) is hence negative, $W(\text{FPR}) < 0$, and energy is transferred from the particles to the fields. One possible interpretation is that the incoming flow burst is braking as it runs into the flux tubes ahead, which act as a local impediment to the flow. Note that there is a slightly increased B_z value behind FPR-B. According to the discussion in section 3, this adds an additional positive contribution to W , i.e., weakens the generator signatures.

Figure 4 presents the result from our statistical investigation of solitary FPRs observed by Cluster in the plasma sheet in 2001. The data are normalized along the horizontal axis so that every FPR extends between 0 and 1. The panels contain a superposed epoch analysis of B_z (Figures 4a and 4b), $V_{\perp X}$ (Figures 4c and 4d), and $W(t) = \int_0^t \mathbf{E} \cdot \mathbf{J} V_{\perp X} dt$ using either CIS (Figures 4e and 4f) or EFW (Figures 4g and 4h) data. The result for decaying and growing FPRs is presented in the left and right columns, respectively. The magnetic field data in the two top panels are shifted so that $B_z = 0$ at $t = 0$ for all events. The thick lines correspond to the median values, and the thin lines to the 10th

and 90th percentiles of the FPRs included in the statistics. Before calculating the medians and percentiles, note that we have computed B_z , $V_{\perp X}$, and $W(t)$ as averages over all available instruments for each FPR. B_z is averaged over four spacecraft and $V_{\perp X}$ over three spacecraft. $W(t)$ for each FPR is of course inherently an average over the Cluster tetrahedron, since it is obtained by multiplying the curlometer current with the average electric field (see section 2).

By comparing the average velocity $V_{\perp X}$ with the average B_z in Figures 4a–4d, the typical behavior of growing and decaying FPRs can be observed. For a growing FPR, the $V_{\perp X}$ peak is located behind the DF, and for a decaying FPR, the $V_{\perp X}$ peak is colocated or just ahead of the DF. It is also interesting to note that both $V_{\perp X}$ and B_z are larger during a growing FPR than during a decaying FPR. Moreover, the B_z slope of a growing FPR is slightly steeper. These observations may be expected since a decaying FPR should relax its electromagnetic energy, while a growing FPR still is building up due to the excess kinetic energy in the incoming plasma flow.

From Figures 4e–4h we note a distinct difference of the topology of the energy change function $W(t)$ of growing and decaying FPRs. On the average (thick solid curve), the energy function is continuously increasing for a decaying FPR. For a growing FPR, on the other hand, the median energy function exhibits a local maximum within the FPR, after which the power density decreases toward negative values at the rear end. A little more than 90% of the growing FPRs show a net energy change $W(\text{FPR}) < 0$ according to our observations, but a few events show small but positive W . However, the dominating picture is that the net energy change is positive (negative) for a decaying (growing) FPR. A growing FPR should therefore be associated with dominant generator processes, i.e., an overall energy transfer from the particles to the fields. It is likely that the observed generator character of the growing FPRs in Figure 4 (right column) is caused by the braking of the incoming flow bursts, which decelerate as they interact with the DFs ahead. As for the decaying FPRs (Figure 4, left column), we see no clear signature of the flow bursts being decelerated. This suggests that the DF can no longer cause any visible flow braking when the flow peak is colocated with the DF or has passed through the DF. Our results hence show indications of a deceleration of the flow bursts in the region $-20 R_E < X - 15 R_E$. The flow braking can, however, only be observed for growing FPRs, i.e., FPRs where the flow burst is running into compressed flux tubes (DFs) earthward of the flow peaks. The median value of the net energy transfer of a growing FPR is $\sim -5 \mu\text{W}/\text{m}^2$ (see Figure 4), but individual events can deviate quite much from this.

In Figure 5 we present the average electric field and the average current density from the superposed epoch study. Data corresponding to decaying and growing FPRs are presented to the left and to the right, respectively. The electric field is given in the spacecraft coordinate system (Despun System Inverted, DSI) and the current density in the GSM system. The thick solid lines in Figures 5a and 5b correspond to CIS estimate obtained as a median of the electric field measurements observed by all available spacecraft (HIA on C1 and C3, and CODIF on C4). The thin dashed lines show the difference between the CIS estimate and the electric field measured by EFW ($\Delta E = E(\text{CIS}) - E(\text{EFW})$). Note that we in Figures 5a and 5b use the spacecraft coordinate system instead of GSM for the electric field measurements. The spacecraft coordinate system is the primary system for EFW, and detailed comparisons between the instruments should therefore be done in this system. GSM and the spacecraft system are, however, rather close (only differing a few degrees). GSM is the physically relevant system, and it is therefore used in general in this article. As can be seen from Figures 5a and 5b, the median electric field from CIS and EFW correlate rather well, even though there are some deviations. One possible cause for the slight discrepancy is that the frozen-in condition is not fully valid throughout the entire FPRs, and that the CIS estimate ($-\mathbf{V} \times \mathbf{B}$) may not be completely correct. Measuring errors can also be involved. However, on the average we believe that CIS rather well captures the electric field within the FPRs.

In Figures 5c and 5d we show the curlometer current density (thick solid lines) and the ΔJ_y difference between the Curlometer estimate and the single spacecraft estimate (thin dashed red lines, median over spacecraft C1, C3, and C4). We see that the curlometer and the single-spacecraft method agree rather well on the current density signatures near the DF. This is a region where the single-spacecraft method is expected to work well. The single-spacecraft method is usually better than the curlometer in resolving the small-scale current density signatures, but we see that the general current density profile is also obtained with the curlometer. Note that the single-spacecraft method is less applicable outside the DF. The single-spacecraft method is also very sensitive to small values of the plasma flow velocity, which causes the

Figure 4. Superposed epoch analysis of (left) decaying and (right) growing FPRs observed by Cluster in 2001. The FPRs are normalized to $0 \leq t \leq 1$. (a–d) B_z and V_{Lx} . (e–h) $W(t) = \int_0^t \mathbf{E} \cdot \mathbf{J} dt$ obtained by using $\mathbf{E}$ data from CIS and EFW, respectively. The thick lines correspond to the median, and the thin lines to the 10th and 90th percentiles.

current density estimate to diverge (typically in the rear end of the FPR and sometimes in front of the DF). Deviations between the estimates obtained with the curlometer and the single-spacecraft method can also be attributed to V_{Lx} not being entirely perpendicular to the DF. In the regions where the single-spacecraft method is expected to work, however, we note that it confirms the curlometer result. We therefore argue that the curlometer is valid to use in our investigations.

In general, from Figure 5 we see that the dominating components are E_y and J_y for many FPRs, but individual events can show a different behavior. According to the simplified model presented in Figure 2, the FPR moves solely along the x direction, and $W(\text{FPR}) < 0$ requires substantial regions of $J_y < 0$ and $E_y > 0$. However, in a more general case when the FPR velocity is not fully aligned with x , velocity components in the yz plane will also contribute to the negative sign of $W(\text{FPR})$. As can be seen from Figures 5b and 5d, this is generally the case for our observed FPRs.

Figure 5. Superposed epoch analysis of the electric field and current density. (top) Electric field components obtained from CIS (solid thick lines) and the difference $\Delta E = E(\text{CIS}) - E(\text{EFW})$ between the CIS and EFW measurements (dashed lines). (bottom) Curlometer current components (solid thick lines) and the ΔJ , difference between the curlometer estimate and the single spacecraft estimate (dashed lines). In Figures 5a and 5b we use the spacecraft coordinate system since it is the primary coordinate system for the EFW measurements. In Figures 5c and 5d we use the GSM system.

5. Discussion

As we have shown in this article, it is likely that flow bursts are decelerated as they run into DFs, compressing flux tubes lying ahead. However, the decelerating capacity decreases as the $V_{\perp X}$ peak approaches (and finally possibly passes through) the DF. One may therefore make the interpretation that growing FPRs are in an early stage of evolution and that decaying FPRs are in a later stage. The evolution of FPRs was investigated by Hamrin *et al.* [2013], who used energy conversion properties to investigate the stage of evolution of two growing and one decaying FPR observed by Cluster in the plasma sheet. They showed that the early stage FPRs were dominated by generator signatures, $\mathbf{E} \cdot \mathbf{J} < 0$, and that the later stage FPRs was dominated by load signatures, $\mathbf{E} \cdot \mathbf{J} > 0$. If there exists a continuous braking of flow bursts as they propagate toward the Earth, one would therefore expect that the corresponding FPRs transform from being more growing-like farther downtail, to becoming more decaying-like closer to the Earth. This assumption was supported by an investigation by Ohtani *et al.* [2004] who used Geotail data from October 1993 to July 2001 to study bulk flows in the plasma sheet. In their Figures 5a and 5b, they show the average $V_{\perp X}$ velocity and B_z profiles at various downtail distances within the region $-31 R_E < X < -5 R_E$. It is interesting to note that the results of Ohtani *et al.* [2004] indeed show that the distance between the velocity peak and the DF decreases as the flow bursts approach the Earth. In the most earthward bin, $-10 R_E < X < -5 R_E$, the average $V_{\perp X}$ peak is in fact approximately colocated with the average DF. Since FPRs seem to change from growing to decaying during their earthward propagation, the results of Ohtani *et al.* [2004] hence suggest an evolution of the FPRs as they propagate toward the Earth. However, this cannot be verified from our data since we do not cover such a large X range as Ohtani *et al.* [2004]. Moreover, due to the Cluster orbit, more earthward measurements are obtained closer to the flanks, and this also complicates the interpretation.

From Figures 4e–4h we see that the exact value of the integrated power density is dependent on how the electric field is measured. The magnitude of the net energy change is somewhat smaller when using the EFW electric field than when using the estimate from CIS. One possibility is that the frozen-in condition is not fully satisfied within parts of the FPRs (e.g., at the sharp B_z gradients of the DFs) and that the CIS estimate

$(-\mathbf{V} \times \mathbf{B})$ therefore is not totally correct. Another possibility for generator signatures is that they are more difficult to resolve since they are often weaker than load signatures [Hamrin *et al.*, 2011], and the relative error is therefore larger when measuring generator processes than when measuring load processes. However, the discrepancy is not very large in Figure 4, and both instruments agree completely on the different topology of $W(t) = \int_0^t \mathbf{E} \cdot \mathbf{J} V_{\perp X} dt$ for decaying and growing FPRs: For decaying FPRs, the $W(t)$ curve is approximately monotonically increasing, while it has a local maximum for growing FPRs. We hence suggest that topology differences between $W(t)$ for growing and decaying FPRs can be used for resolving dominant energy conversion processes and that energy conversion arguments can be used for investigating possible flow-braking mechanisms.

Note that we have used the curlometer method for estimating the current density in this article. We can therefore only study energy conversion processes on spatial scales determined by the size of the Cluster tetrahedron, i.e., on ion scales. However, energy conversion processes on smaller scales are also important for the physics of FPRs. Angelopoulos *et al.* [2013] used data from the THEMIS (Time History of Events and Macroscale Interactions during Substorms) mission to investigate DF energy conversion on both electron and ion (MHD) scales. By comparing the cumulative power conversion of $J_y E_y$ with its MHD approximation in their Figure 3e, they show that the general load character of DFs is observed also on ion scales, even though the magnitude of the cumulative sum can be different, presumably due to nonideal terms in the Ohm's law. The future MMS mission will enable investigation of the energy conversion on electron scales, and it will show how much of the small-scale physics can be observed on larger scales.

$\mathbf{E} \cdot \mathbf{J}$ corresponds to the amount of energy (per unit volume and unit time) converted between its electromagnetic and kinetic forms. As can be seen from Poynting's theorem, energy is transferred locally from the particles to the field if $\mathbf{E} \cdot \mathbf{J} < 0$, and the electromagnetic energy density increases if energy is not transported away as Poynting flux. An increased electromagnetic energy density can manifest itself as, e.g., compressed magnetic field lines. If $\mathbf{E} \cdot \mathbf{J} > 0$, energy is instead transferred from the fields to the particles, which gain energy in the form of bulk flow energy and/or thermal energy.

To check the reliability of our results, we estimate the possible deceleration of growing FPRs and compare with what has been presented in the literature. Let us simplify by assuming that an FPR is an entity, which moves over the spacecraft with an average velocity v_0 . We assume that the mass of the FPR is a constant $M = nm_p A v_0 \Delta t$, where n is the average number density, m_p the proton mass (we neglect any oxygen), A is the cross section of the FPR, and Δt is the time for the FPR to pass the spacecraft. The energy change per unit time and unit area is therefore

$$W = \frac{1}{A} \frac{d}{dt} \frac{Mv^2}{2} \bigg|_0 = \frac{Mav_0}{A} = nm_p a v_0^2 \Delta t, \quad (1)$$

where a is the acceleration ($a < 0$ for a decelerating FPR). The quantity in equation (1) should be compared to $W(\text{FPR})$ obtained from our Cluster observations.

If we neglect any energy transfer due to Poynting flux, and if we neglect heating or energization of particles, we can obtain a simple estimate of the possible deceleration of growing FPRs observed in our investigation. According to our result in Figure 4, there exist growing FPRs with $W(\text{FPR}) \sim -5 \mu\text{W}/\text{m}^2$. The median time extent of our FPRs (not shown) is 170 s (with 25th and 75th percentiles of 110 s and 210 s), and the median density (assuming protons) is 0.25 cm^{-3} (with 25th and 75th percentiles of 0.15 cm^{-3} and 0.42 cm^{-3}). For a simple estimate, let us assume typical values $n \sim 0.2 \text{ cm}^{-3}$, $v_0 = 200 \text{ km/s}$ (see Figure 4), and $\Delta t \sim 20 \text{ s}$. $W \sim -5 \mu\text{W}/\text{m}^2$ hence corresponds to $a \sim -2 \text{ km/s}^2$. The characteristic size of the Cluster tetrahedron for our events is 1500 km. Using $a = -2 \text{ km/s}^2$, an FPR with initial velocity of 200 km/s would decrease its velocity to about 185 km/s between two spacecraft. This is unfortunately practically impossible to resolve with the Cluster observations in our investigation. Even for Cluster data from the tail season of 2002, when the interspacecraft distance was $\sim 4000 \text{ km}$, it will most likely be impossible to observe any velocity decrease (if not an extremely clean and well-behaved event is found).

Ohtani *et al.* [2004] used 290 tail flow events observed by Geotail in the region $-31 R_E < X < -5 R_E$. From the superposed epoch investigation presented in their Figure 5, we see that the average plasma flow velocity decreases from about 240 km/s to about 160 km/s over $\sim 21 R_E$. Assuming a uniform deceleration, we obtain $a \sim -0.13 \text{ km/s}^2$ for these Geotail events. The deceleration obtained from our data is more than 10 times larger than the value derived from the results of Ohtani *et al.* [2004]. One possible cause for our

overestimation is that flow burst in practice may not have the same deceleration all along their propagation toward the Earth. This is consistent with the fact that not all of the observed FPRs in our investigation appear to be decelerating, but instead more than half of them are decaying and have $W(\text{FPR}) > 0$, and some of the growing FPRs indeed have $W(\text{FPR}) \gtrsim 0$. Moreover, it is also likely that the braking capacity of piled-up magnetic flux decreases if a flow burst changes from being quasi-perpendicular to becoming quasi-parallel. It should also be noted that we have selected a certain type of events in our investigation. Only clean flow bursts associated with a distinct magnetic flux pile-up are selected (see section 2). However, in the event selection of *Ohtani et al.* [2004], there was, for example, no criteria on the magnetic field for a flow burst to be included in the database. It is hence likely that the events of *Ohtani et al.* [2004] better correspond to typical earthward propagating flow bursts, while we have selected events which are more suitable when investigating details of the energy transfer.

It should be noted that most of our events have velocities $\lesssim 400$ km/s, but that there exist much faster flow bursts in the plasma sheet [e.g., *Juusola et al.*, 2011]. *Runov et al.* [2009] used THEMIS data to investigate the earthward propagation of a dipolarization front. Inspecting their Figure 2, we find that the front decelerates from ~ 1000 km/s to ~ 500 km/s over about $3.4 R_E$ (between THEMIS probe P1 and P2). Again assuming a constant deceleration, this results in $a \sim -17$ km/s², the magnitude of which is approximately 10 times larger than our estimate. However, the event discussed by *Runov et al.* [2009] corresponds to much faster flow burst velocities than those treated in our investigation, and it is likely that faster flow burst are associated with stronger decelerations.

Using equation (1), as a consistency check we can also compute the corresponding energy conversion which we would obtain for $a \sim -0.13$ km/s² [*Ohtani et al.*, 2004] and $a \sim -17$ km/s² [*Runov et al.*, 2009]. For the *Ohtani et al.* [2004] case we use $n \sim 0.3$ cm⁻³, $v_0 = 200$ km/s, and $\Delta t \sim 200$ s (typical values from their Figure 5) and we find $W(\text{FPR}) \sim -0.5$ μ W/m². For the *Runov et al.* [2009] case we use 0.15 cm⁻³, $v_0 = 750$ km/s, and $\Delta t \sim 40$ (from their Figure 2) and we find $W(\text{FPR}) \sim -100$ μ W/m². Our result from Figure 4, $W(\text{FPR}) \sim -5$ μ W/m², is hence within the range obtained from the previous investigations: The magnitude is larger than the general case from the large statistical investigation of *Ohtani et al.* [2004] but smaller than the more extreme case of *Runov et al.* [2009]. Our results hence nicely fit in the interval limited by the results of *Ohtani et al.* [2004] and *Runov et al.* [2009]. We therefore argue that our results are consistent.

However, there are many processes which may be relevant for the energy transfer between the fields and the particles, especially near and around DFs, where wave-particle interactions are expected to be important [e.g., *Fu et al.*, 2011; *Khotyaintsev et al.*, 2011; *Hwang et al.*, 2014]. As we discuss here, energy can be locally stored in a pileup of the magnetic field, which is frozen in the plasma [*Fu et al.*, 2012b; *Liu et al.*, 2014]. Moreover, bulk kinetic energy may be lost to the growth of waves [e.g., *Viberg et al.*, 2014; *Volwerk et al.*, 2007; *Turkakin et al.*, 2014]. Particles may also gain energy in acceleration processes, for example, near DFs [e.g., *Ukhorskiy et al.*, 2013; *Zhou et al.*, 2010, 2011, 2014; *Artemyev et al.*, 2012; *Birn et al.*, 2013] or as the ambient plasma is accelerated away from the earthward propagating flow burst (plasma bubble) [*Li et al.*, 2011; *Hamrin et al.*, 2013]. One can also speculate if the load character of decaying FPRs can be related to changes in the magnetic topology as DFs propagate toward the Earth. Reconnected field lines are likely to have some degree of tangled topology, meaning that the north-south magnetic field lines are not correctly connected to their exact geoconjunction counterparts. *Ergun et al.* [2009] argue that double layers observed within BBF events can operate in detangling these field lines. Such a detangling process might also contribute to a positive value of the power density.

In this article we have assumed that the deceleration of the plasma bulk flow is the main cause for the integrated power density being negative for growing FPRs. We have neglected any effects caused by the energy transfer due to Poynting flux and any effects caused by heating or energization of particles. Instead we have only discussed energy changes in the bulk plasma flow and in compressed magnetic field lines. It is outside the scope of the present investigation to include other effects. However, the MMS mission will be very useful for extended investigations including, e.g., effects due to changes in the plasma temperature.

To simplify our data analysis, in this article, we have focused on rather simple, smooth, and solitary FPRs of school book character. Since no other energy conversion mechanisms have been included in our calculations, one can argue that our value of $a \sim -2$ km/s corresponds to a maximum magnitude of the deceleration for such simple events of school book type. However, we know that there exist more complicated events in the tail than what is included in our database. For example, there exist events consisting of both

growing and decaying phases [Fu *et al.*, 2012a] and events with higher velocity peaks. For example, the event studied by Runov *et al.* [2009] had a velocity peak of ~ 1000 km/s, while our events have a median peak of ~ 200 km/s as indicated in Figure 4. We can hence not say that $a \sim -2$ km/s corresponds to a maximum value of the deceleration for a general BBF in the magnetotail at Cluster distances.

This limits the number of events available for a statistical investigation. In the plasma sheet data observed by Cluster in 2001, we only find 26 such solitary events. Including Cluster data from more years would of course increase the database, but it would also introduce new problems in interpreting the data since the Cluster tetrahedron varies considerably over the years, and this influences the curlometer estimate of the current density. We have therefore limited our analysis to the few events observed in 2001. Even though our investigation is based on quite few events of very simple character, we still argue that our result is very important. It shows that energy conversion arguments can be used for studying flow braking and that the position of the $V_{\perp X}$ peak with respect to the position of the B_z gradient of the DF can be used as a single-spacecraft proxy when determining the energy conversion properties (and the evolutionary stage) of FPRs. Such a single-spacecraft proxy is invaluable whenever it is impossible to compute the full power density $\mathbf{E} \cdot \mathbf{J}$, for example, when multispacecraft data are not available, or when the multispacecraft tetrahedron is badly configured.

6. Conclusions

In this article we have used energy conversion arguments to show that there are indications of a plasma flow-braking mechanism in the plasma sheet in the region $-20 R_E < X - 15 R_E$. This is considerably tailward of the inner boundary of the plasma sheet ($\sim 10 R_E$), where the flow braking is expected to be substantial. Our results suggest a mechanism where compressed magnetic flux tubes in DFs can constitute a local impediment to the earthward propagating flow bursts.

In our statistical investigation we have shown that FPRs with the $V_{\perp X}$ peak located tailward of the DFs (growing FPRs according to Fu *et al.* [2011]) on the average are associated with a negative power density when integrating over the entire FPR, i.e., associated with a net energy transfer from the particles to the fields. This energy transfer may well correspond to a braking of the incoming flow bursts.

The integrated power density is on the other hand positive for decaying FPRs, where the $V_{\perp X}$ peak is observed at or ahead of the DFs. This implies a net energy transfer from the fields to the particles, and no significant braking is observed. For decaying FPRs it is likely that the DFs no longer can act as a significant impediment to the plasma flow since the $V_{\perp X}$ peak has passed (or is passing) the DF.

A typical value of the net energy change of growing FPRs is $W(\text{FPR}) \sim -5 \mu\text{W}/\text{m}^2$, but individual events can deviate quite much from this. Using some simplifying approximations, this energy transfer corresponds to a deceleration of ~ -2 km/s, which is in principle impossible to observe for most Cluster configurations. The magnitude of the deceleration is larger than the value derived from the results of Ohtani *et al.* [2004] (~ -0.13 km/s²) but smaller than the value derived from Runov *et al.* [2009] (~ -17 km/s²). We hence conclude that our results are consistent.

In this article, we have hence shown that the observed $W(\text{FPR})$ for growing FPRs may well match the order of magnitude of the expected deceleration of flow bursts. In practice, some fraction of energy may of course be transformed between other forms than bulk flow energy and the magnetic energy in compressed magnetic flux. However, our results show that the deceleration of flow burst may well contribute significantly to the energy balance.

Our results show that energy conversion arguments can be used for studying flow braking and that the position of the flow peak with respect to the DF can be used as a single-spacecraft proxy when determining the energy conversion properties. Such a single-spacecraft proxy is invaluable whenever multispacecraft data are not available.

References

- Angelopoulos, V., W. Baumjohann, C. Kennel, F. Coroniti, M. Kivelson, R. Pellat, R. Walker, H. Luhr, and G. Paschmann (1992), Bursty bulk flows in the inner central plasma sheet, *J. Geophys. Res.*, **97**(A4), 4027–4039, doi:10.1029/91JA02701.
- Angelopoulos, V., C. Kennel, F. Coroniti, R. Pellat, M. Kivelson, R. Walker, C. Russell, W. Baumjohann, W. Feldman, and J. Gosling (1994), Statistical characteristics of bursty bulk flow events, *J. Geophys. Res.*, **99**(A11), 21,257–21,280, doi:10.1029/94JA01263.

Acknowledgments

We thank the FGM, CIS, and EFW teams and the Cluster Active Archive, CAA, (now Cluster Science Archive, CSA, <http://www.cosmos.esa.int/web/csa>) for providing well-calibrated Cluster magnetic field, electric field, and velocity moments data. M.H. and T.P. acknowledge support by the grant from the Swedish National Space Board, project 78/11AB, and O.M. acknowledges support by the M-ICAR grant of the Romanian National Authority for Scientific Research, CNCS-UEFISCDI, project PN-II-ID-PCE-2011-3-1013. We thank K. Rönmark, H. Fu, and V. Angelopoulos for fruitful discussions.

Larry Kepko thanks the reviewers for their assistance in evaluating this paper.

- Angelopoulos, V., et al. (1997), Magnetotail flow bursts: Association to global magnetospheric circulation, relationship to ionospheric activity and direct evidence for localization, *Geophys. Res. Lett.*, **24**(18), 2271–2274.
- Angelopoulos, V., A. Runov, X. Z. Zhou, D. L. Turner, S. A. Kiehas, S. S. Li, and I. Shinohara (2013), Electromagnetic energy conversion at reconnection fronts, *Science*, **341**(6153), 1478–1482, doi:10.1126/science.1236992.
- Artemyev, A. V., V. N. Lutsenko, and A. A. Petrukovich (2012), Ion resonance acceleration by dipolarization fronts: Analytic theory and spacecraft observation, *Ann. Geophys.*, **30**, 317–324, doi:10.5194/angeo-30-317-2012.
- Baumjohann, W., G. Paschmann, and H. Luhr (1990), Characteristics of high-speed ion flows in the plasma sheet, *J. Geophys. Res.*, **95**(A4), 3801–3809.
- Baumjohann, W., M. Hesse, S. Kokubun, T. Mukai, T. Nagai, and A. A. Petrukovich (1999), Substorm dipolarization and recovery, *J. Geophys. Res.*, **104**, 24,995–25,000, doi:10.1029/1999JA900282.
- Birn, J., M. Hesse, R. Nakamura, and S. Zaharia (2013), Particle acceleration in dipolarization events, *J. Geophys. Res. Space Physics*, **118**, 1960–1971, doi:10.1002/jgra.50132.
- Chen, C., and R. Wolf (1993), Interpretation of high-speed flows in the plasma sheet, *J. Geophys. Res.*, **98**(A12), 21,409–21,419, doi:10.1029/93JA02080.
- Chen, C., and R. Wolf (1999), Theory of thin-filament motion in Earth's magnetotail and its application to bursty bulk flows, *J. Geophys. Res.*, **104**(A7), 14,613–14,626, doi:10.1029/1999JA900005.
- Dunlop, M. W., A. Balogh, K. H. Glassmeier, and P. Robert (2002), Four-point Cluster application of magnetic field analysis tools: The curlometer, *J. Geophys. Res.*, **107**(A11), 1385, doi:10.1029/2001JA005088.
- Eastwood, J. P., T. D. Phan, M. Oieroset, and M. A. Shay (2010), Average properties of the magnetic reconnection ion diffusion region in the Earth's magnetotail: The 2001–2005 Cluster observations and comparison with simulations, *J. Geophys. Res.*, **115**, A08215, doi:10.1029/2009JA014962.
- Ergun, R. E., et al. (2009), Observations of double layers in Earth's plasma sheet, *Phys. Rev. Lett.*, **102**(15), 155002, doi:10.1103/PhysRevLett.102.155002.
- Escoubet, C. P., M. Fehringer, and M. Goldstein (2001), The Cluster mission—Introduction, *Ann. Geophys.*, **19**(10–12), 1197–1200.
- Fu, H. S., Y. V. Khotyaintsev, M. Andre, and A. Vaivads (2011), Fermi and betatron acceleration of suprathermal electrons behind dipolarization fronts, *Geophys. Res. Lett.*, **38**, L16104, doi:10.1029/2011GL048528.
- Fu, H. S., Y. V. Khotyaintsev, A. Vaivads, M. André, V. A. Sergeev, S. Y. Huang, E. A. A. Kronberg, and P. W. Daly (2012a), Pitch angle distribution of suprathermal electrons behind dipolarization fronts: A statistical overview, *J. Geophys. Res.*, **117**, A12221, doi:10.1029/2012JA018141.
- Fu, H. S., Y. V. Khotyaintsev, A. Vaivads, M. Andre, and S. Y. Huang (2012b), Occurrence rate of earthward-propagating dipolarization fronts, *Geophys. Res. Lett.*, **39**, L10101, doi:10.1029/2012GL051784.
- Hamrin, M., K. Ronnmark, N. Borlin, J. Vedin, and A. Vaivads (2008), GALS—Gradient analysis by least squares, *Ann. Geophys.*, **26**(11), 3491–3499.
- Hamrin, M., P. Norqvist, O. Marghitu, A. Vaivads, B. Klecker, L. M. Kistler, and I. Dandouras (2009), Scale size and life time of energy conversion regions observed by Cluster in the plasma sheet, *Ann. Geophys.*, **27**(11), 4147–4155.
- Hamrin, M., O. Marghitu, P. Norqvist, S. Buchert, M. Andre, B. Klecker, L. M. Kistler, and I. Dandouras (2011), Energy conversion regions as observed by Cluster in the plasma sheet, *J. Geophys. Res.*, **116**, A00K08, doi:10.1029/2010JA016383.
- Hamrin, M., et al. (2013), The evolution of flux pileup regions in the plasma sheet: Cluster observations, *J. Geophys. Res. Space Phys.*, **118**, 6279–6290, doi:10.1002/jgra.50603.
- Hwang, K.-J., M. L. Goldstein, A. F. -Viñas, D. Schriver, and M. Ashour-Abdalla (2014), Wave-particle interactions during a dipolarization front event, *J. Geophys. Res. Space Physics*, **119**, 2484–2493, doi:10.1002/2013JA019259.
- Juusola, L., N. Ostgaard, and E. Tanskanen (2011), Statistics of plasma sheet convection, *J. Geophys. Res.*, **116**, A08201, doi:10.1029/2011JA016479.
- Khotyaintsev, Y. V., C. M. Cully, A. Vaivads, M. Andre, and C. J. Owen (2011), Plasma jet braking: Energy dissipation and nonadiabatic electrons, *Phys. Rev. Lett.*, **106**(16), 165,001, doi:10.1103/PhysRevLett.106.165001.
- Kim, H.-S., D.-Y. Lee, S.-I. Ohtani, E.-S. Lee, and B.-H. Ahn (2010), Some statistical properties of flow bursts in the magnetotail, *J. Geophys. Res.*, **115**, A12229, doi:10.1029/2009JA015173.
- Li, S. S., V. Angelopoulos, A. Runov, X. Z. Zhou, J. McFadden, D. Larson, J. Bonnell, and U. Auster (2011), On the force balance around dipolarization fronts within bursty bulk flows, *J. Geophys. Res.*, **116**, A00I35, doi:10.1029/2010JA015884.
- Liu, J., V. Angelopoulos, A. Runov, and X. Z. Zhou (2013), On the current sheets surrounding dipolarizing flux bundles in the magnetotail: The case for wedgelets, *J. Geophys. Res. Space Physics*, **118**, 2000–2020, doi:10.1002/jgra.50092.
- Liu, J., V. Angelopoulos, X.-Z. Zhou, and A. Runov (2014), Magnetic flux transport by dipolarizing flux bundles, *J. Geophys. Res. Space Physics*, **119**, 909–926, doi:10.1002/2013JA019395.
- McPherron, R. L., T. S. Hsu, J. Kissinger, X. Chu, and V. Angelopoulos (2011), Characteristics of plasma flows at the inner edge of the plasma sheet, *J. Geophys. Res.*, **116**, A00I33, doi:10.1029/2010JA015923.
- Nakamura, R., et al. (2002), Motion of the dipolarization front during a flow burst event observed by Cluster, *Geophys. Res. Lett.*, **29**(20), 1942, doi:10.1029/2002GL015763.
- Nakamura, R., et al. (2004), Spatial scale of high-speed flows in the plasma sheet observed by Cluster, *Geophys. Res. Lett.*, **31**, L09804, doi:10.1029/2004GL019558.
- Nakamura, R., et al. (2005), Localized fast flow disturbance observed in the plasma sheet and in the ionosphere, *Ann. Geophys.*, **23**(2), 553–566.
- Ohtani, S., M. Shay, and T. Mukai (2004), Temporal structure of the fast convective flow in the plasma sheet: Comparison between observations and two-fluid simulations, *J. Geophys. Res.*, **109**, A03210, doi:10.1029/2003JA010002.
- Ohtani, S., H. J. Singer, and T. Mukai (2006), Effects of the fast plasma sheet flow on the geosynchronous magnetic configuration: Geotail and GOES coordinated study, *J. Geophys. Res.*, **111**, A01204, doi:10.1029/2005JA011383.
- Pontius, D., and R. Wolf (1990), Transient flux tubes in the terrestrial magnetosphere, *Geophys. Res. Lett.*, **17**(1), 49–52, doi:10.1029/GL017i001p00049.
- Runov, A., V. Angelopoulos, M. I. Sitnov, V. A. Sergeev, J. Bonnell, J. P. McFadden, D. Larson, K. H. Glassmeier, and U. Auster (2009), THEMIS observations of an earthward-propagating dipolarization front, *Geophys. Res. Lett.*, **36**, doi:10.1029/2009GL038980.
- Schmid, D., M. Volwerk, R. Nakamura, W. Baumjohann, and M. Heyn (2011), A statistical and event study of magnetotail dipolarization fronts, *Ann. Geophys.*, **29**(9), 1537–1547, doi:10.5194/angeo-29-1537-2011.
- Sergeev, V. (2004), Bursty bulk flows and their ionospheric footprints, in *Multiscale Processes in the Earth's Magnetosphere: From Interball to Cluster*, *Nato Science Series, Series II: Mathematics, Physics and Chemistry*, vol. 178, edited by J. A. Sauvaud and Z. Nemecek,

- pp. 289–306, Springer, Dordrecht, Netherlands. Nato Sci Affairs Div, Nato Advanced Research Workshop on Multiscale Processes in the Earth's Magnetosphere - From Interball to Cluster, Charles Univ, Prague, Czech Republic, 09–12 SEP, 2003.
- Sergeev, V., V. Angelopoulos, J. Gosling, C. Cattell, and C. Russell (1996), Detection of localized, plasma-depleted flux tubes or bubbles in the midtail plasma sheet, *J. Geophys. Res.*, *101*(A5), 10,817–10,826.
- Sharma, A. S., et al. (2008), Transient and localized processes in the magnetotail: A review, *Ann. Geophys.*, *26*, 955–1006, doi:10.5194/angeo-26-955-2008.
- Shiokawa, K., W. Baumjohann, and G. Haerendel (1997), Braking of high-speed flows in the near-Earth tail, *Geophys. Res. Lett.*, *24*(10), 1179–1182.
- Sun, W.-J., S. Fu, G. K. Parks, Z. Pu, Q.-G. Zong, J. Liu, Z. Yao, H. Fu, and Q. Shi (2014), Electric fields associated with dipolarization fronts, *J. Geophys. Res. Space Physics*, *119*, 5272–5278, doi:10.1002/2014JA020045.
- Turkakin, H., I. R. Mann, and R. Rankin (2014), Kelvin-Helmholtz unstable magnetotail flow channels: Deceleration and radiation of MHD waves, *Geophys. Res. Lett.*, *41*, 3691–3697, doi:10.1002/2014GL060450.
- Ukhorskiy, A. Y., M. I. Sitnov, V. G. Merkin, and A. V. Artemyev (2013), Rapid acceleration of protons upstream of earthward propagating dipolarization fronts, *J. Geophys. Res. Space Physics*, *118*, 4952–4962, doi:10.1002/jgra.50452.
- Viberg, H., Y. V. Khotyaintsev, A. Vaivads, M. André, H. S. Fu, and N. Cornilleau-Wehrlin (2014), Whistler mode waves at magnetotail dipolarization fronts, *J. Geophys. Res. Space Physics*, *119*, 2605–2611, doi:10.1002/2014JA019892.
- Volwerk, M., K.-H. Glassmeier, R. Nakamura, T. Takada, W. Baumjohann, B. Klecker, H. Reme, T. L. Zhang, E. Lucek, and C. M. Carr (2007), Flow burst-induced Kelvin-Helmholtz waves in the terrestrial magnetotail, *Geophys. Res. Lett.*, *34*, L10102, doi:10.1029/2007GL029459.
- Walsh, A. P., et al. (2009), Cluster and double star multipoint observations of a plasma bubble, *Ann. Geophys.*, *27*(2), 725–743.
- Zhou, X.-Z., V. Angelopoulos, V. A. Sergeev, and A. Runov (2010), Accelerated ions ahead of earthward propagating dipolarization fronts, *J. Geophys. Res.*, *115*, A00I03, doi:10.1029/2010JA015481.
- Zhou, X. Z., V. Angelopoulos, V. A. Sergeev, and A. Runov (2011), On the nature of precursor flows upstream of advancing dipolarization fronts, *J. Geophys. Res.*, *116*, A03222, doi:10.1029/2010JA016165.
- Zhou, X.-Z., V. Angelopoulos, J. Liu, A. Runov, and S.-S. Li (2014), On the origin of pressure and magnetic perturbations ahead of dipolarization fronts, *J. Geophys. Res. Space Physics*, *119*, 211–220, doi:10.1002/2013JA019394.