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The evolution of flux pileup regions in the plasma sheet: Cluster observations

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[1] Bursty bulk flows (BBFs) play an important role for the mass, energy, and magnetic flux transport in the plasma sheet, and the flow pattern in and around a BBF has important consequences for the localized energy conversion between the electromagnetic and plasma mechanical energy forms. The plasma flow signature in and around BBFs is often rather complicated. Return flows and plasma vortices are expected to exist at the flanks of the main flow channel, especially near the inner plasma sheet boundary, but also farther down-tail. A dipolarization front (DF) is often observed at the leading edge of a BBF, and a flux pileup region (FPR) behind the DF. Here we present Cluster data of three FPRs associated with vortex flows observed in the midtail plasma sheet on 15 August 2001. According to the principles of Fu et al. (2011, 2012c), two of the FPRs are considered to be in an early stage of evolution (growing FPRs). The third FPR is in a later stage of evolution (decaying FPR). For the first time, the detailed energy conversion properties during various stages of the FPR evolution have been measured. We show that the later stage FPR has a more complex vortex pattern than the two earlier stage FPRs. The two early stage FPR correspond to generators, \( \mathbf{E} \cdot \mathbf{J} < 0 \), while the later stage FPR only shows weak generator characteristics and is instead dominated by load signatures at the DF, \( \mathbf{E} \cdot \mathbf{J} > 0 \). Moreover, to our knowledge, this is one of the first times BBF-related plasma vortices have been observed to propagate over the spacecraft in the midtail plasma sheet at geocentric distances of about 18RE. Our observations are compared to recent simulation results and previous observations.


1. Introduction

[2] Energy stored in the magnetic field of the Earth’s magnetotail is released through tail reconnection and transported away from the reconnection site as high-speed plasma flows. These high-speed flows is thought to be manifested as bursty bulk flows (BBFs). BBFs are often showing signatures of so-called plasma bubbles [Pontius and Wolf, 1990; Chen and Wolf, 1993, 1999]. As compared to the surrounding plasma, bubbles are depleted flux tubes with reduced entropy and increased earthward propagation velocity. A return plasma flow and/or flow vortices may appear at the flanks of the bubble, twisting the magnetic field and causing field-aligned currents at the flanks forming a local wedge-like current system. Vortices have been observed previously in numerical simulations [e.g., Wiltberger et al., 2000; El-Alaoui et al., 2001; Ashour-Abdalla et al., 2002; Birn et al., 2004; Walker et al., 2006; El-Alaoui et al., 2009, 2010] and by in situ measurements in the plasma sheet [e.g., Kauristie et al., 2000; Keiling et al., 2009; Ohtani et al., 2009; Walsh et al., 2009; Panov et al., 2010; Pitkänen et al., 2011]. There is also increasing evidence in the literature for turbulence playing an important role in the plasma sheet [e.g., Borovsky et al., 1997; Chang, 1999; Klimas et al., 2000; Weygand et al., 2007].

[3] The front edge of an earthward propagating BBF is usually characterized by a sharp increase in the GSM (geocentric solar magnetospheric) \( B_z \) magnetic field component [Nakamura et al., 2002]. Such a dipolarization front (DF) separates the earthward part of the plasma sheet plasma from the low density reconnection jet plasma. DFs have been observed to have a thickness of one to a few ion inertial lengths and to propagate toward the Earth with a velocity...
of a couple of hundred km/s [e.g., Runov et al., 2009, 2011; Schmid et al., 2011; Fu et al., 2012a]. Behind the DF, a flux pileup region (FPR) can often be observed [Fu et al., 2012a].

Previous investigations have shown that BBFs appear for all geomagnetic activity levels, but they are more common during the substorm expansion phase [Angelopoulos et al., 1992, 1994]. BBFs are crucial ingredients in the magnetospheric energy budget. They are believed to play a major role for magnetic flux, mass, and energy transport in the plasma sheet, and they are observed to contribute approximately half of the circulated mass, energy, and magnetic flux in the plasma sheet [Sergeev, 2004]. Hamrin et al. [2011] investigated the relation between BBFs and the energy conversion as probed by the power density \(E \cdot J\), obtained from spacecraft observations of the electric field \(E\) and the current density \(J\). They found that localized energy conversion regions (ECRs) can manifest themselves both as concentrated load regions (CLRs) and as concentrated generator regions (CGRs). In loads, the plasma is accelerated by magnetic pressure and tension, and energy is transferred from the fields to the particles. In generators, on the other hand, the particles are losing energy to the electromagnetic fields.

Hamrin et al. [2012] found that a majority of the loads and generators are correlated with BBFs. Using Cluster data from 2001, 2002, and 2004, they showed that the GSM \(V_x\) component often gives a dominant contribution to the total plasma flow velocity when ECRs are observed, even though there are several ECRs where the \(V_x\) and/or \(V_z\) contribution cannot be neglected. There is a clear correlation between ECRs and BBFs, but there is still not a general consensus on which regions in and around a BBF correspond to loads and generators [Hamrin et al., 2011].

The plasma flow in and around a BBF flow channel is rather complicated. Flow vortices appear at the flanks of the bubble, twisting the magnetic field, and causing a downward (upward) field-aligned current at the dawnside (duskside) flank, and forming a local wedge-like current system [e.g., Chen and Wolf, 1993, 1999; Sergeev et al., 1996; Birn and Hesse, 1996; Birn et al., 1999, 2004; Snevik et al., 2007; Zhang et al., 2009]. It may be suggested that vorticity in the magnetotail is controlled by a combination of earthward pressure gradients and ionospheric Pedersen conductance [Ashour-Abdalla et al., 2002; Walker et al., 2006; El-Alaoui et al., 2009].

According to numerical simulations, the plasma flow near a BBF evolves into a more complicated vortex pattern at later times. Using a 3-D MHD simulation of magnetotail reconnection, Birn et al. [2004] investigated the propagation and evolution of bubbles in the magnetotail. During the early evolution, pressure balance is reestablished through compression of the flux tube. The subsequent evolution is characterized by an earthward propagation of the bubble. Figure 14 of Birn et al. [2004] shows the development of the plasma flow velocity component \(V_x\) with time. At later times, tailward plasma flows are observed in relation to the earthward moving bubble, indicating a plasma return flow or a vortex-like behavior. Figure 18 presents a snapshot of the vortex flow pattern at \(t = 15\) (in simulation time units).

Another example of the time evolution of a vortex flow pattern can be found in Birn et al. [2011]. They studied the fate of earthward BBFs generated by reconnection using a 3-D MHD simulation code. According to Birn et al. [2011, Figure 5], for a BBF in an early stage of the simulation, there are two rather well-defined plasma flow vortices surrounding the BBF flow channel, also in the region where Cluster would be probing. However, the flow pattern around a later stage BBF is more complex. Note that simulation units are used in the figure. The simulation box of Birn et al. [2011] covers a region between 0 and \(-60\) in the \(x\) direction, and this corresponds to a range of real GSM positions between \(X_\text{GSM} = -7.8R_E\) and \(X_\text{GSM} = -100R_E\). This means that Figure 5 in practice covers the region between \(-7.8R_E\) and \(-23R_E\). It should also be noted that the vortices in Birn et al. [2011] are said to be associated with the rebound of the Earthward flows, i.e., at the inner boundary of the plasma sheet where the increased dipole magnetic field acts as an obstacle to the plasma flow. In this article we discuss the interaction of plasma flows with DFs. Such DFs are localized and transient dipolarizations with an increased magnetic field elevation angle, and they can act as an obstacle to a plasma flow and cause vortices in a similar manner as in Birn et al. [2011]. This makes the simulation of Birn et al. [2011] useful for comparing with our Cluster data observed at \(-18R_E\). Wilberger et al. [2000] also investigated the time evolution of BBF-related plasma flow patterns in a MHD simulation setup to capture the evolution of the 10 December 1996, substorm. Their Plates 2 and 3 show the plasma flow pattern at various stages of the simulation. From Wilberger et al. [2000] it can be seen that the flow pattern becomes more complex at later stages of the simulation, and this is consistent with the results from Birn et al. [2011].

Fu et al. [2011] and Fu et al. [2012c] used Cluster data to investigate the evolution of DFs. They showed that betatron acceleration dominates inside a growing (early stage of evolution) FPR, and that Fermi acceleration dominates inside a decaying (later stage of evolution) FPR. A growing FPR is associated with the BBF peak velocity being observed behind the DF [Fu et al., 2011]. In such a case, the leading part of the FPR moves slower than the rear part of the FPR, and tailward flux tubes are running into the earthward flux tubes. This leads to a compression of the flux tubes, which subsequently causes betatron acceleration of the electrons. For a decaying FPR, the BBF peak is just ahead of (or collocated with) the DF, and Fu et al. [2011] suggest that the flux tubes expand.

In this article we use Cluster data to investigate the flow pattern, the energy conversion, and the time evolution of three FPRs observed on 15 August 2001, in the midtail plasma sheet (\(-18R_E\)). Two of the FPRs are growing, and one is decaying, according to the classification of Fu et al. [2011].

### 2. Instrumentation

The Cluster mission consists of four identical spacecraft, C1–C4, which in 2001 flew in a tetrahedral formation. The spin period is 4 s. For a discussion of the Cluster mission and instruments, see Escoubet et al. [2001], and references therein. In this article we use data from the CIS, EFW, and FGM instruments. Geocentric solar magnetospheric (GSM) coordinates are used throughout the article.

The plasma velocity (assuming \(H^+\) ions) are estimated from the CIS sensors HIA and CODIF. CODIF is operational on C1, C3, and C4, and HIA on C1 and C3.

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Figure 1
However, since CODIF on C3 suffers from a higher noise level due to a degraded particle detection efficiency, only HIA data are used from C3. Spacecraft C3 and C4 are rather closely separated in GSM $xy$ space during our event, and they observe approximately the same plasma environment. In the following we use data only from C1 and C3 to investigate the plasma flow.

[13] We use plasma density data and electric field data from the EFW instrument. EFW is operational onboard all four spacecraft. It measures the field components in the satellite spin plane (approximately the GSM $xy$ plane), and the third component is estimated by using the assumption that $\mathbf{E} \cdot \mathbf{B} = 0$. Estimates of the electric field is also obtained from ion moments obtained by CIS, assuming that the $\mathbf{E} \times \mathbf{B}$ drift is dominant.

[14] The full current density vector, $\mathbf{J}$, is calculated from the FGM magnetic field according to $\nabla \times \mathbf{B}/\mu_0$ (neglecting the displacement current) by using the curlometer method [Robert et al., 1998; Dunlop et al., 2002]. There is no strict error estimate for the current density when using the curlometer method. However, $|\nabla \cdot \mathbf{B}|/|\nabla \times \mathbf{B}|$ can be used as a qualitative error estimate [Paschmann and Schwartz, 2000]. A one-to-one correspondence between $|\nabla \cdot \mathbf{B}|/|\nabla \times \mathbf{B}|$ and the actual error in the estimated current density is not expected. In theory, this quantity should be identically zero, but in practice it can vary substantially due to, e.g., small-scale variations in the magnetic field and measurement errors. During our events, $|\nabla \cdot \mathbf{B}|/|\nabla \times \mathbf{B}|$ is considerably smaller than 50%, and we expect that the curlometer current density gives accurate enough values. The size and shape of the Cluster tetrahedron affect the curlometer estimate, and current density structures smaller than the characteristic size of the tetrahedron cannot generally be resolved with the curlometer. For our events on 15 August 2001, the Cluster tetrahedron was optimal (approximately equilateral tetrahedron) with small elongation and planarity of 0.0012 and 0.0060, respectively. The scale size of the tetrahedron was $\sim 1400$ km. With a H$^+$ temperature of about 5 keV during the interval of interest, the Cluster scale size is of the order of the H$^+$ gyroradius.

3. Observations

3.1. Event Overview

[15] Cluster entered the plasma sheet from the north at about 01:40 UT on 15 August 2001. Between about 08:00 and 10:00, Cluster was located in the magnetotail at about GSM $[-18, -5.5, 0.5]R_E$, and the spacecraft observed an extended region of BBFs with associated DFs and FPRs (see Figure 1). In this article we will focus on three of these FPRs: 08:22 (FPR-1a), 08:26 (FPR-1b), and 09:43 (FPR-2). Some of the BBFs observed between 08:20 and 08:40 on 15 August 2001, have also been investigated by Hwang et al. [2011] and by Pang et al. [2012]. However, we choose not to study all of the events from the previous investigations, but only those which show the clearest data signatures. The selected events are hence most easily interpreted. Note that in this article, for simplicity, we refer to the plasma flow regions associated with FPRs as BBFs, although according to the original definition of Angelopoulos et al. [1994], they may qualify better as flow bursts (FBs). Note also that in one case the velocity is well below the original threshold of 400 km/s.

[16] The geomagnetic activity was very low (Kp$\sim$1) during the time of interest on 15 August 2001. The foot points of Cluster were close to the Churchill-line CARISMA geomagnetic stations, and the BBFs were accompanied by weak enhancements in the $AE$ index [Pang et al., 2012], associated with auroral activity as observed by the FUV instrument on IMAGE [Hwang et al., 2011]. According to Pang et al. [2012], the BBFs were detected during substorm recovery. The magnetosphere-ionosphere coupling between the observed BBFs and ionospheric auroral activity confirms that the correct frame of reference to be used for analyzing energy conversion issues should be stationary with respect to the Earth, e.g., GSM (see Marghitu et al. [2006] for a discussion).

[17] Using timing analysis of how the four spacecraft encounter the sharp B$_z$ increase associated with the DFs, we can obtain an estimate of the velocity and the orientation of the DFs. For DF-1a and DF-1b, we obtain $V_{DF-1a} \approx 161 \cdot [0.97, -0.23, -0.11]$ km/s and $V_{DF-1b} \approx 179 \cdot [0.88, -0.40, -0.27]$ km/s, respectively. Hence, the DFs are moving with a velocity $\lesssim 200$ km/s dominantly in the GSM $x$ direction, and with a smaller velocity component in the GSM $-y$ and $-z$ directions. DF-2 is moving considerably slower and with significant velocity components in all $xyz$ space, $V_{DF-2} \approx 75 \cdot [0.52, 0.80, 0.29]$ km/s. The DF-1a, DF-1b, and DF-2 orientations can be verified by using minimum variance analysis (MVA). Estimating the front orientation using MVA on each separate spacecraft, and then averaging over the spacecraft, we obtain a mean orientation of DF-1a, DF-1b, and DF-2 as $[0.91, -0.41, 0.017]$, $[0.90, -0.37, -0.25]$, and $[0.14, 0.87, 0.48]$. Our results are consistent with those of Hwang et al. [2011] and Pang et al. [2012].

3.2. FPR Stage of Evolution

[18] Fu et al. [2011] and Fu et al. [2012c] define the stage of evolution (growing or decaying) of an FPR from the position of the peak of the plasma flow V with respect to the DF as observed from the sharp gradient in the $B_z$ data. A growing FPR is associated with a flow velocity peak being observed behind the DF. For a decaying FPR, the velocity peak is just ahead of (or colocated with) the DF. According to this classification, FPR-1a and FPR-2 are included in the statistical database compiled by Fu et al., [2012c] as growing and decaying, respectively. FPR-1b is not included in the database, probably due to effects from the automatic event selection of Fu et al. [2012c]. However, according to the criterion above, FPR-1b should be growing.
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Following the line of Fu et al. [2011], the Type-I and Type-II bubbles discussed by Pang et al. [2012] should correspond to decaying (late stage) and growing (early stage) FPRs, respectively. However, note that we in this article discuss the evolution of FPRs, while Pang et al. [2012] discuss the evolution of bubbles. The difference between a bubble and an FPR is elaborated in Walsh et al. [2009]. Their Figure 15 shows a cartoon of a bubble and the surrounding regions. The region of flux and plasma pileup in front of the bubble (yellow) should be interpreted as the FPR, while the bubble is the depleted flux tube (gray), and it is observed behind. Note that the cartoon of Walsh et al. [2009] is very simplified. In simulations like those presented in Wilberget al. [2000] and Birn et al. [2011], there are also more complicated vortex patterns. Moreover, note that the pileup is located in front of the bubble in the cartoon, but that the region of \( B_z \) pileup and density depletion may well overlap in measured data as in our three events. Below we show that the evolutionary stage of an FPR can be investigated by analyzing the flow pattern and the observed power density \( E \cdot B \). as well as by the method discussed by Fu et al. [2011] and Fu et al. [2012c]. A growing FPR is characterized by the local braking of the bulk flow velocity, and the decreased kinetic energy is transferred to the fields. This should correspond to a generator region, \( E \cdot J < 0 \). In a decaying FPR, the fields may be losing energy to the particles instead. Such an FPR should therefore not show any significant generator signatures, but possibly load signatures, \( E \cdot J > 0 \).

3.3. Events FPR-1a and FPR-1b

Figure 2 is a zoom into FPR-1a and FPR-1b. Figures 2a, 2b, and 2c show C3 data of the GSM \( B_z \) component from high resolution FGM data, the plasma density estimated from the EFW spacecraft potential, and the GSM \( V_x \) and \( V_y \) components of the plasma flow. The thick lines in Figure 2c show the \( x \) and \( y \) velocity components smoothed with a 20 s running average. The FPRs start at the sharp increase in \( B_z \) and ends when \( B_z \) has declined toward approximately undisturbed values. The two FPRs 1a and 1b are highlighted in yellow in Figure 2, and the DFs are indicated with the vertical magenta lines. From the top three panels we see that the FPRs are colocated with a distinct dip in the plasma density, and a peak in \( V_y \). This is consistent with plasma bubble theory for the BBFs [Chen and Wolf, 1993, 1999]. Data from C1 are very similar to data from C3 and are therefore not shown.

From Figure 2c, we see oscillations of \( V_y \) around a central value of about \(-40 \) km/s for both FPR-1a and FPR-1b. Below we show that a possible interpretation of the velocity data is that plasma vortices are drifting past the spacecraft. The sinusoidal variation is most evident for FPR-1b, while FPR-1a shows more internal structure (e.g., the individual smaller peaks at about 08:25:00, 08:25:45, and 08:27:00).

In Figure 3a, we show the plasma velocity observed by Cluster C1 (black) and C3 (green) for BBF-1a. The smoothed data from Figure 2c have been used in Figure 3. The DF extension is indicated by the two parallel lines, and the spacecraft separation is presented to scale. The relative motion of Cluster C1 and C3 in relation to the velocity of the DF is also shown. From Figure 3a it is clear that the plasma flow is deflected first toward \(-y\), then toward \(+y\),

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Figure 2. FPR-1a and FPR-1b. (a) GSM \( B_z \) for C3. (b) Plasma density as estimated from EFW on C3. (c) GSM \( V_x \) and \( V_y \) from C3. The thick lines show the smoothed velocity components (running averages with a window size of 20 s). (d) Vorticity computed from FGM, CIS, and EFW data. (e) Power density based on electric field estimates from CIS (black) and EFW (red). (f) Divergence of the Poynting flux using EFW for the electric field. (g) \( J \times B \) force obtained from high resolution FGM data. The FPRs are highlighted in yellow and the DFs are indicated by the vertical magenta lines.

19 FPR-1a and FPR-1b and four other FPRs from 15 August 2001, are investigated in Hwang et al. [2011] and in Pang et al. [2012]. Hwang et al. [2011] studied the \( B_z \) and \( B_y \) fluctuations observed behind the DFs, and discussed the possible generation of field-aligned currents that may power auroral brightening. Pang et al. [2012] argued that the BBFs can be classified into two types: Type-I and Type-II bubbles. Type-I bubbles are similar to those studied by Sergeev et al. [1996] and by Walsh et al. [2009]. The trailing parts of Type-II bubbles are running into the leading parts, making the trailing parts decelerate.

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and finally toward $-y$ again. During the entire interval, the flow in the $x$ direction was varying but positive. We argue that a possible interpretation is that C1 and C3 are observing plasma vortices propagating over the spacecraft. The exact value of the propagation velocity is not known, but assuming that the vortices are moving with a drift velocity of the order of the DF velocity ($161 \cdot [0.97, -0.23, -0.11]$ km/s) as presented in section 3.1, this drift velocity should be subtracted from the observed plasma velocity in Figure 3a to resolve the true flow vortices. This has been done in Figure 3b. A possible vortex structure is indicated by the half-circle, and a possible BBF main channel by the straight arrow. It should be noted that it is reasonable to expect that the velocity vectors in front of the DF should not be transformed to the coordinate system moving with the DF velocity. However, for simplicity, the entire interval 08:20:00–08:24:30 has been transformed in Figure 3b.

[24] In this article we discuss the time evolution of FPRs. It is therefore useful to compare our observations with simulation results where the time evolution of the plasma flow and pileup is analyzed. Simulations put the measured data into a broader perspective and help in the interpretation of the observed data. An example of a vortex flow pattern surrounding a BBF can be found in Birn et al. [2004, Figure 18]. Normalization units of $4R_E$ (the half-width of plasma sheet or current sheet) are used in the MHD simulation. This means that Figure 18 displays a snapshot of the Earthward propagating BBF when it is located within approximately $20R_E < X_{GSM} < 32R_E$. Birn et al. [2004, Figure 14] also show the evolution of $V_z$ with time. Tailward return flows are developed after a while, and one can expect that the flow evolves into a more complicated pattern with time. A 2-D example (in the $xy$ plane) of the possible time evolution of the plasma vortices surrounding a BBF can be found in Birn et al. [2011, Figure 5]. Figures 5a and 5b show the flow pattern at simulation times $t = 132$ and $t = 142$ (1220 s and 1420 s) within a region $-7.8R_E < X_{GSM} < 23R_E$. We see that the main flow channel of an early stage BBF (early in the simulation) is surrounded by two vortices, similar to our cartoon in Figure 3b which is based on Cluster data obtained at about $-18R_E$.

[25] To further investigate the properties of the flow, we present the vorticity $\nabla \times \mathbf{V}$ in Figure 2d. For the velocity data we use HIA on C1 and C3, and CODIF on C4. Since there is no operational CIS instrument on C2, for this satellite we use EFW and FGM data and approximate the plasma flow velocity with $\mathbf{E} \times \mathbf{B}/B^2$. Since EFW and CIS give consistent result on all other spacecraft, we believe that $\mathbf{E} \times \mathbf{B}/B^2$ gives a correct estimate of the velocity at the position of C2. Note that the third EFW electric field component cannot be obtained when the background magnetic field is close to the satellite spin plane. This explains the data gaps in the panel. From Figure 2d we see that especially the $x$ and $z$ components of $\nabla \times \mathbf{V}$ show considerable variation during FPR-1a. However, in this article we only focus on the plasma flow in the GSM $xy$ plane, and the $z$ component of $\nabla \times \mathbf{V}$ measures the vorticity in this plane. We see that the $z$ component is clearly positive during the latter parts of FPR-1a, about 08:22–08:23:30. This corresponds to an anticlockwise rotation of the plasma, and it is consistent with the sketched plasma motion in Figure 3b. Note that the vorticity only measures the local motion of the plasma, and Cluster only observes a small part of the possible vortex flow region. Hence, we cannot claim that the plasma flow moves in closed circles (only a half-circle is therefore depicted in Figure 3b). It might also be that the plasma bulk flow is just performing a meandering motion as it passes the spacecraft.

[26] The vortex pattern of FPR-1b (not shown) is similar to the one presented in Figure 3b. However, there are additional small-scale variations in the $V_x$ and $V_y$ data in Figure 2c. The extra complexity of the flow pattern of FPR-1b can also be seen in the vorticity presented in Figure 2d. A possible interpretation is that FPR-1b also corresponds to a vortex (with some extra internal structure) propagating over the spacecraft.

[27] As discussed in section 3.2, Fu et al. [2011] predict that FPR-1a and FPR-1b are growing. Following the line of Hamrin et al. [2011], these FPRs should therefore on the average correspond to generators where particle energy is transferred into electromagnetic energy. Figure 2e shows the power density $\mathbf{E} \cdot \mathbf{J}$ obtained using two different estimates of the electric field. The black curve is obtained by using $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$ from CIS ion moments and the red curve by...
The magnetic field is oriented close to the satellite spin plane, and magnetic field. Note that there are data gaps whenever the filtered magnetic field has been subtracted from the total and are used for the calculations. The background (low-pass filtered) magnetic field has been subtracted from the total all satellites (CIS is operational only on C1, C3, and C4), and are used for the calculations. The background (low-pass filtered) magnetic field has been subtracted from the total magnetic field. Note that there are data gaps whenever the magnetic field is oriented close to the satellite spin plane, and the full electric field vector cannot be obtained from EFW.

From Figure 2f we see that \( \mathbf{V} \cdot \mathbf{S} > 0 \) when \( \mathbf{E} \cdot \mathbf{J} < 0 \), i.e., there is a Poynting flux away from this region. This is consistent with the region being a generator of electromagnetic energy.

Figure 2g shows the \( xyz \) components of the \( \mathbf{J} \times \mathbf{B} \) force where high resolution FGM data have been used. The current density is estimated by the curlometer method, and \( \mathbf{B} \) is averaged over all spacecraft before computing the cross product. Near both DF-1a and DF-1b, there is a strong component of the \( \mathbf{J} \times \mathbf{B} \) force in the \( +z \) direction (with small components also in \( y \) and \( z \)). Note that this \( \mathbf{J} \times \mathbf{B} \) force is earthward and approximately parallel to the normal of the DF in Figure 3b. We suggest that the \( \mathbf{J} \times \mathbf{B} \) force operates to expel (accelerate) the ambient plasma away from the FPR, i.e., it maintains the density dip in the plasma bubble. It is therefore reasonable to conclude that the small positive peaks of \( \mathbf{E} \cdot \mathbf{J} \) in Figure 2e at the DFs indeed capture true load behavior. It should be noted that the net force on the plasma element is \( \mathbf{J} \times \mathbf{B} - \mathbf{V} \mathbf{P} \). However, an exact value of the \( \mathbf{V} \mathbf{P} \) force is difficult to obtain from Cluster due to the lack of measurements of \( \mathbf{P} \) from all spacecraft and due to uncertainties in the absolute flux calibration of the instruments between the spacecraft. However, preliminary investigations (not shown) using C1 and C4 indicate that the \( \mathbf{V} \mathbf{P} \) force is in the \( -x \) direction and smaller than \( |\mathbf{J} \times \mathbf{B}| \), i.e., opposite to the \( \mathbf{J} \times \mathbf{B} \) force, and consistent with the sharp decrease of the plasma density at the DFs (see Figure 2b).

Around 08:23:30 and 08:26:30 in Figure 2g, the dominating \( \mathbf{J} \times \mathbf{B} \) force is along \( +y \). (Around 08:23:30 and 08:26:30, there is also a significant force component in the \( z \) direction, but it is outside the scope of the present investigation to study the effects of this component.) This \( y \) force is in the opposite sense as compared to the plasma flow, \( V_y < 0 \). In this region the plasma element is decelerating, and particle energy is transferred into electromagnetic energy. This is confirmed by Figure 2e and 2f which show \( \mathbf{E} \cdot \mathbf{J} < 0 \) and \( \mathbf{V} \cdot \mathbf{S} > 0 \), i.e., generator signatures.

The weak load signature at the front of the FPR and the dominating generator at the rear end are indicated in Figure 3b by the red dashed line and the blue solid line. However, note that \( (\mathbf{J} \times \mathbf{B}) \cdot \mathbf{V} = \mathbf{E} \cdot \mathbf{J} \) when we use \( \mathbf{E} = -\mathbf{V} \times \mathbf{B} \). Hence, Figures 2e and 2g are complementary, but \( \mathbf{J} \times \mathbf{B} \) captures the 3D behavior of the interaction between the plasma element and the magnetic field, while \( \mathbf{E} \cdot \mathbf{J} \) only resolves the resulting load or generator behavior.

3.4. Event FPR-2

Figure 4 is a zoom into FPR-2. The panels are the same as in Figure 2. From Figures 4a and 4b, we see that the DF and the density drop are less well defined as compared to FPR-1a and FPR-1b. There is a sharp decrease in the plasma density just after 09:42. The density then increases until 09:43:30, and after that a new but weaker density dip is observed. The \( B_z \) first decreases rapidly after the DF until 09:43:30 when it increases again and levels out at a slightly increased value. Around 09:47, both \( B_z \) and the density appear to have reached approximately the background level. Where FPR-2 exactly ends (e.g., \( \sim 09:43:30 \) or \( \sim 09:47 \)) is, however, difficult to determine. Here we have chosen to include the entire plasma density dip between 09:42 and about 09:47 in FPR-2 (the yellow region highlighted in Figure 4).
[34] From Figure 4c we see that the bulk flow is rather complicated. No clear BBF main channel can be observed. Another possibility is that Cluster misses the main channel and only probes outer parts of the flow region. The plasma flow in Figure 4c shows variations of approximately equal magnitudes in both $V_x$ and $V_y$. A sinusoidal variation in the velocity panel is less evident as compared to $V_y$ in Figure 2c. However, both $V_x$ and $V_y$ show both positive and negative excursions. This makes it reasonable to assume that DF-2 also is related to vortices propagating over the spacecraft.

[35] In Figure 5a, we present the plasma velocity observed by Cluster C1 (black) and C3 (green) for FPR-2. The thickness of the DF (indicated with the two parallel lines) and the distance between C1 and C3 are pictured to scale. Note that DF-2 extends over ~15 s, while DF-1a and DF-1b extend over ~5 s (compare the $B_z$ increase in Figures 4a and 2a). From Figure 5a, it is difficult to resolve any clear vortex flow pattern. However, remember that Cluster probes the midtail plasma sheet at about 18$R_E$. At these distances, it is reasonable to assume that any possible vortices propagate toward the Earth together with the DF. According to section 3.1, DF-2 moves with $V_{DF-2} \approx 75 \cdot [0.52, 0.80, 0.29]$ km/s. In Figure 5b, we have subtracted this velocity from the observed plasma velocity in Figure 5a to resolve the vortex pattern, and we see that the plasma flow organizes into a much more structured pattern. Two possible vortices are indicated by the arrows. As observed from Figure 4c, there is no clear high-speed BBF channel observed together with FPR-2.

[36] According to Figure 4d, the $z$ component of the vorticity changes sign during the event. In the first part of the FPR, it is positive (approximately 09:42:15–09:44), in the middle, negative (09:44–09:45:30), and in the rear part, it is positive again (09:45:30–09:47). Comparing with the sketch in Figure 5b, we see that the two latter regions correspond to the indicated flows: first, clockwise (negative vorticity) at 09:44–09:45:30 and then anticlockwise (positive vorticity) at 09:45:30–09:47. As for the positive vorticity during 09:44–09:45:30, the velocity vectors in Figure 5b are more difficult to interpret as a larger-scale vortex flow. However, it should be noticed that the vorticity only measures the local motion of the plasma.

[37] According to section 3.2 and Fu et al. [2011], FPR-2 is classified as decaying, i.e., it should be in a later stage of evolution. Birn et al. [2011, Figures 5a and 5b] show the flow pattern around a BBF at an early and at a late stage of the MHD simulation. As shown in section 3.1, the early stage FPR-1a and FPR-1b observed by Cluster are related to a rather simple flow pattern with two vortices surrounding the central BBF channel. A later stage BBF, on the other hand, has a more complicated flow pattern as can be seen from Figure 5b in Birn et al. [2011, Figures 5b. Also, Wilberger et al. [2000] show the evolution of plasma flows in a tail MHD simulation. A more complex flow pattern with several vortices of different sizes and directions of rotation can be observed at later stages in this simulation. In the Birn et al. [2011] simulation, the main BBF channel becomes narrower at later times in the simulation. Our observational data resemble the flow pattern of Figure 5b in Birn et al. [2011] where one can see two distinct vortices with reversed flow direction (as compared to the flow direction of the narrow BBF channel). However, Cluster only probes part of the flow region, and it is difficult to make any conclusion about the global flow pattern, but we note that our observational data qualitatively agree with the simulations of both Birn et al. [2011] and Wilberger et al. [2000] with a considerably more complex flow pattern at later stages. We therefore suggest that FPR-2 is in a later stage of its evolution.

[38] From Figure 4g, we see that FPR-2 also has a $\mathbf{J} \times \mathbf{B}$ force directed approximately along the normal of the DF in Figure 5b. This is similar to the observations of FPR-1a and FPR-1b in section 3.3. The force at DF-2 hence acts to expel (accelerate) the ambient plasma away from the FPR and to maintain the density dip in the plasma bubble. A consistent load signature of $\mathbf{E} \cdot \mathbf{J} > 0$ and $\nabla \cdot \mathbf{S} < 0$ is observed at DF-2 (see Figures 4e and 4f). Note that the $\mathbf{J} \times \mathbf{B}$ force of DF-2 is of the order of 20 nA/m$^3$, which is about half the value of the $\mathbf{J} \times \mathbf{B}$ force of DF-1a and DF-1b. A weaker $\mathbf{J} \times \mathbf{B}$ force at DF-2 is, however, reasonable since FPR-2 is related to much weaker plasma flows (~100 km/s) than FPR-1a and FPR-1b (~600 km/s). Consequently, the load $\mathbf{E} \cdot \mathbf{J}$ signatures of DF-1a and DF-1b are stronger (2.5–5 pW/m$^3$) than that of DF-2 (1–2 pW/m$^3$).
[39] At the rear end of FPR-2, there is a $\mathbf{J} \times \mathbf{B}$ force mainly in the $-y$ direction, and with smaller variations in $x$ and $z$. This force is in the opposite direction compared to the weak plasma flow observed at the rear end of FPR-2. It hence decelerates the remaining BBF flow of this late stage FPR, and we observe a consistent signature of $\mathbf{E} \cdot \mathbf{J} < 0$ and $\mathbf{V} \cdot \mathbf{S} > 0$ in this region. However, this generator signature is much weaker than the load signature observed at the DF. In Figure 5b we indicate the regions of positive and negative power densities with the red and blue lines, respectively.

[40] A growing FPR, e.g., FPR-1a and FPR-1b, should be dominated by a deceleration of the plasma bulk flow, and hence correspond to a generator. A decaying FPR such as FPR-2, on the other hand, should not show any significant generator signatures, but may well instead be dominated by load signatures. In Figure 4e, we indeed see that the dominating behavior in the power density data of FPR-2 is $\mathbf{E} \cdot \mathbf{J} > 0$ at the DF. There are also some weaker generator signatures, $\mathbf{E} \cdot \mathbf{J} < 0$, at the rear end of the event. However, the magnitude $|\mathbf{E} \cdot \mathbf{J}|$ in the generator region is less than half of the $|\mathbf{E} \cdot \mathbf{J}|$ in the load region at the DF. Comparing with DF-1a and DF-1b, we see the opposite behavior: The generators’ $|\mathbf{E} \cdot \mathbf{J}|$ at the rear ends of FPR-1a and FPR-1b are more than twice as strong as the load $|\mathbf{E} \cdot \mathbf{J}|$ at the DFs.

4. Summary and Discussion

[41] In this article we have investigated the evolutionary stage of three FPRs observed by Cluster in the midtail plasma sheet at about $18R_E$ on 15 August 2001. We have shown that a possible interpretation of the observed flow pattern is that flow vortices propagate over the spacecraft. Plasma vortices and tailward return flows have previously been observed [e.g., Kauristie et al., 2000; Keiling et al., 2009; Ohtani et al., 2009; Walsh et al., 2009; Panov et al., 2010; Pitkänen et al., 2011]. Such plasma flow signatures have often been observed rather close to the inner boundary of the plasma sheet. Plasma velocity shear ahead of bubbles and near a DF have previously also been observed at midtail distances (18–20R_E) [Sergeev et al., 1996; Nakamura et al., 2005]. However, to our knowledge, this is one of the first times plasma vortices have been resolved in larger BBF regions (inside FPRs and behind DFs), and observed to propagate over the spacecraft, at midtail geocentric distances. It should be noted that Pang et al. [2012] also investigated FPR-1a and FPR-1b. They say that it is unlikely that the plasma flows at the trailing parts of the bubbles are part of the flow shear layer ahead of the bubbles. Instead they argue that trailing parts of plasma bubble go around the main bubble as they catch up and collide with the leading parts. However, it should be mentioned that Pang et al. [2012] mainly focus on the $V_y$ flows, while we investigate the flow pattern in the $xy$ plane.

[42] By using Cluster data and comparing our observations with simulation results [Birn et al., 2011], we have shown that the evolutionary stage of our FPRs can be analyzed from at least three perspectives: (i) The complexity of the flow pattern around the FPR. (ii) The position of the plasma velocity peak as compared to the DF position observed in the $B_z$ data [Fu et al., 2011]. (iii) The sign of the power density, $\mathbf{E} \cdot \mathbf{J}$ (or the $\mathbf{J} \times \mathbf{B}$ force and the plasma velocity $\mathbf{V}$). Below we discuss these three perspectives briefly.

[43] 1. Comparing with the MHD simulation of Birn et al. [2011, Figure 5], we have shown that the stage of evolution of an FPR can be related to the complexity of the flow pattern. An FPR in its early stage of evolution shows a simpler flow pattern than a later stage FPR. For an early stage FPR, such as FPR-1a and FPR-1b presented in Figure 3b in this article, the vortex flow is rather simple. A later stage FPR, such as FPR-2 in Figure 5b, shows a more complex flow pattern with several vortices. FPR-2 also lacks a distinct main high-speed BBF flow channel. However, it should be noted that the BBF in the simulation of Birn et al. [2011] is observed near the stopping region at the inner boundary of the plasma sheet. Our Cluster data, on the other hand, are obtained in the midtail plasma sheet where the vortices are expected to have a drift motion past the spacecraft. This drift velocity is subtracted from the observed plasma flow when producing Figures 3b and 5b.

[44] 2. The evolutionary stage of an FPR can also be analyzed from the position of the plasma flow peak as compared to the DF as discussed in section 3.2 and by Fu et al. [2011]. For a growing FPR (early stage of evolution), the peak in $\mathbf{V}$ is behind the DF. A decaying FPR (late stage of evolution), on the other hand, has its flow peak collocated or just in front of the DF. According to this classification, FPR-1a and FPR-1b are growing, and FPR-2 is decaying. Fu et al. [2011] argue that a growing FPR corresponds to tailward flux tubes, which are running into and compressing earthward flux tubes. The compression of the flux tubes of FPR-1a and FPR-1b is verified by Pang et al. [2012] who analyzed a set of BBFs observed on 15 August 2001. They claim that FPR-1a and FPR-1b are so-called Type-II bubbles. For a decaying FPR, Fu et al. [2011] suggest that the flux tubes expand.

[45] 3. Energy conversion issues can also be used for analyzing the stage of evolution of an FPR. For a growing FPR, the tailward plasma element has excess kinetic energy. The particles are decelerated as they run into the earthward flux tubes, and energy is transferred from the particles to the electromagnetic fields. An early stage or growing FPR should therefore correspond to a generator, $\mathbf{E} \cdot \mathbf{J} < 0$. At a later stage, the bulk flow velocity has decreased and the main BBF channel is less pronounced. In this case energy may be transferred back to the particles from the fields. A later stage or decaying FPR should therefore show no dominant generator signatures, but possibly load signatures instead, $\mathbf{E} \cdot \mathbf{J} > 0$.

[46] As pointed out by Fu et al. [2012c], the plasma flow velocity often varies inside an FPR, and the FPR could therefore include both growing and decaying phases. Hence, the power density can also vary considerably inside the FPR. In this article we have focused on the most dominating load or generator signatures within the FPRs. By using the three different perspectives discussed above, we have shown that an early stage FPR corresponds to a generator, $\mathbf{E} \cdot \mathbf{J} < 0$. A later stage FPR, on the other hand, only shows weak generator characteristics and is dominated by load signatures at the DF, $\mathbf{E} \cdot \mathbf{J} > 0$.

[47] More thorough investigations are, however, needed before we can claim that growing FPRs in general correspond to generators in the plasma sheet. In this article we
have chosen to investigate only three FPRs from 15 August 2001. More events are, however, discussed in both Hwang et al. [2011] and Pang et al. [2012]. Preliminary investigations indicate that the other events also may support our conclusion, but the data are more complicated and difficult to analyze.

[48] The generator and load signatures can be verified either by analyzing the $\mathbf{J} \times \mathbf{B}$ force direction as compared to the plasma flow, or by analyzing the divergence of the Poynting flux. It should be noted that the net force on the plasma element is $\mathbf{J} \times \mathbf{B} - \nabla \mathbf{P}$. However, an exact value of $\nabla \mathbf{P}$ is difficult to obtain, but preliminary investigations (not shown) indicate that it is observed in a consistent direction. The force balance near a DF has previously been analyzed by Li et al. [2011]. However, they used a magnetic field model when estimating the current density for calculating $\mathbf{J} \times \mathbf{B}$. In this article, on the other hand, we have been using observed data and the curlometer method for estimating $\mathbf{J}$.

[49] We have shown that the $B_z$ gradient of the DF of all three FPRs corresponds to load regions ($\mathbf{E} \cdot \mathbf{J} > 0$) where there is a $\mathbf{J} \times \mathbf{B}$ force parallel with the observed plasma velocity. We conclude that this force acts to expel (accelerate) the ambient plasma away from the FPR to maintain the density dip of the plasma bubble. This is consistent with the observations of Li et al. [2011], who argue that the net force $\mathbf{J} \times \mathbf{B} - \nabla \mathbf{P}$ causes an acceleration of the local plasma ahead of the earthward propagating DF. However, it should be noted that the load signature at the DF is rather narrow, and that the detailed structure of $\mathbf{E}$ and $\mathbf{J}$ may not be fully resolved. The resolution of the CIS and EFW $\mathbf{E}$ is 4 s, and $\mathbf{J}$ is estimated from multispacecraft measurements of $\mathbf{B}$. Indeed, Fu et al. [2012b] argue that $\mathbf{E}$ and $\mathbf{J}$ at the DF are perpendicular at subproton scales. However, $\mathbf{E}$ was obtained in a frame of reference moving with the DF in Fu et al. [2012b].

[50] There is also a $\mathbf{J} \times \mathbf{B}$ force antiparallel with the plasma flow at the rear ends of all three FPRs analyzed in this article. This force decelerates the plasma velocity of the BBF. The rear ends of the FPRs can hence be interpreted as generator regions ($\mathbf{E} \cdot \mathbf{J} < 0$). The generator signatures are dominated in FPR-1a and FPR-1b, while the load signatures are dominating in FPR-2.

[51] We have confirmed the load and generator behavior by using Cluster measurements of the Poynting flux $\mathbf{S}$. For the generator regions of the FPRs, we have shown that $\nabla \cdot \mathbf{S} > 0$, i.e., Poynting flux is consistently flowing out of the regions. Similarly, for the loads, we have shown that $\nabla \cdot \mathbf{S} < 0$ and that Poynting flux is flowing into the regions. Writing the divergence of the Poynting flux as

$$\frac{\partial}{\partial t} \frac{B^2}{2\mu_0} = -\nabla \cdot \mathbf{S} - \mathbf{E} \cdot \mathbf{J},$$

we see that $\nabla \cdot \mathbf{S} > 0$ ($< 0$) whenever $\mathbf{E} \cdot \mathbf{J} < 0$ ($> 0$) if $\partial(B^2/2\mu_0)/\partial t$ is small enough. For our events FPR-1a, FPR-1b, and FPR-2 we find that $\nabla \cdot \mathbf{S}$ and $\mathbf{E} \cdot \mathbf{J}$ generally are of similar magnitude but different signs (see Figures 2 and 4). Poynting flux flowing out of generators (or into loads) hence dominates over the local changes in the magnetic field energy density. On the average, one would expect that the magnetic field energy increases when an FPR is growing, and decreases when an FPR is decaying. However, an accurate value of $\partial(B^2/2\mu_0)/\partial t$ is difficult to obtain since $\partial(B^2/2\mu_0)/\partial t$ is much smaller than the terms on the right-hand side of equation (1), and it is sensitive to errors in $\mathbf{V} \cdot \mathbf{S}$ and $\mathbf{E} \cdot \mathbf{J}$. Investigating the variation of $\partial(B^2/2\mu_0)/\partial t$ during FPR-1a, FPR-1b, and FPR-2 (not shown), we find that there are indications of $\partial(B^2/2\mu_0)/\partial t$ on the average being slightly positive within regions of $\mathbf{E} \cdot \mathbf{J} > 0$ and varying between positive and negative values within regions of $\mathbf{E} \cdot \mathbf{J} < 0$. However, due to uncertainties in the computation of $\partial(B^2/2\mu_0)/\partial t$, it is difficult to draw any definitive conclusions.

[52] In our events, the generator signatures are related to vortical flow patterns. We note that generator regions are expected to exist as part of vortical or shear flow regions [e.g., Birn and Hesse, 1996; Birn et al., 1999; Birn and Hesse, 2005; Pang et al., 2012]. Such flow patterns are usually associated with the buildup of field-aligned currents. The generator regions in Birn and Hesse [2005] are generally observed toward the flanks and off the equatorial plane, near edges of earthward flow regions. This is consistent with our observed generators associated with FPR-1a and FPR-1b, which are observed at $B_{GSM} \approx -18R_E$ and $B_{GSM} \approx 0.5R_E$. Birn and Hesse [2005] also note that the generated energy is converted into Poynting flux, $\nabla \cdot \mathbf{S} > 0$, with corresponding to an approximate balance of the two terms on the right-hand side of Poynting’s theorem in equation (1). This is consistent with our result that $\partial(B^2/2\mu_0)/\partial t$ is small during our events. Pang et al. [2012] also address the issue of the field-aligned current system (FAC) generation, and they investigate why the observed FACs are located at the trailing part of the Type-II bubbles. According to our interpretation of the data, the trailing regions are characterized by vortical flows (see Figures 3b and 5b). The observed FAC systems may hence well be caused by vortical flows that twists flux tubes according to Birn and Hesse [2005].

[53] FPRs develop when BBFs propagate toward the Earth, piling up magnetic flux at the front. BBFs are believed to play a major role for magnetic flux, mass, and energy transport in the plasma sheet [e.g., Angelopoulos et al., 1992, 1994, 1999; Sergeev et al., 1996; Scholze et al., 2001]. In the literature there are many reports of the relation between BBFs and auroral phenomena at the ionospheric end of the M-I coupling system, e.g., auroral expansions, localized brightenings, and auroral streamers [e.g., Fairfield et al., 1999; Lyons et al., 1999; Ieda et al., 2001; Sergeev et al., 2001; Nakamura et al., 2001a, 2001b, 2005; Miyashita et al., 2003; Forsyth et al., 2008; Pithan et al., 2011]. In this article we have analyzed the stage of evolution of the three FPRs and shown that two of them are growing and one is decaying. It is outside the scope of the present article to determine the importance of the individual FPRs for any possible auroral activity in the conjugate ionosphere. However, previous investigations show that the BBFs observed on 15 August 2001, are associated with auroral activity [Hwang et al., 2011; Pang et al., 2012].

[54] Earthward moving BBFs are dominantly observed earthward of $\sim -20R_E$ [e.g., Baumjohann et al., 1990]. They are reported to occur $< 15\%$ of the time in the plasma sheet at geocentric distances of $16-22R_E$ [Angelopoulos et al., 1999]. According to, e.g., Baumjohann et al. [1990] and Shiokawa et al. [1997], the occurrence rate decreases toward the Earth due to flow breaking. We may expect that BBFs, which propagate with low velocities in the midtail will not
reach the inner boundary of the plasma sheet since they will be quickly decelerated. The inner boundary of the plasma sheet is believed to be an important region, e.g., for hosting auroral generators. For example, the large substorm current wedge is expected to be caused by the braking and diversion of earthward directed flows closer to the inner boundary, resulting in the generation of electromagnetic power, which eventually can power the aurora [Wygant et al., 2000].

We may expect that the time evolution (stage) of FPRs is intimately related to the ultimate fate of the bulk flow in the plasma sheet. A growing FPR observed in the midtail should have a higher probability of reaching the inner boundary of a plasma sheet than a decaying FPR. The growing FPR is pushed by the high-speed flow, so it can arrive at the inner plasma sheet more easily than a decaying FPR which has a decreasing velocity. However, future investigations are needed to confirm this assumption. More studies are also needed for resolving the detailed energy conversion behavior and time evolution of FPRs. One intriguing question concerns the deceleration of BBFs and the formation of complex flow patterns around decaying FPRs. Our data presented in Figure 5b indicate that there is some vortex formation also in front of the DF. Whether or not this is caused by the FPR itself, or by other flows in the surrounding plasma, is impossible to determine in this article. However, future event studies should be performed to analyze this. Moreover, statistical investigations should be conducted to determine the general behavior of the flow pattern surrounding both growing and decaying FPRs.

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