

JGR Space Physics

RESEARCH ARTICLE

10.1029/2020JA028978

Special Section:

Cluster 20th anniversary: results from the first 3D mission

Key Points:

- Tailward flows around BBFs (TWABs) can frequently be observed. They have high |V| and plasma properties similar to bursty bulk flows (BBFs) compared to the general tailward flows
- It is more common to observe a TWAB succeeding than preceding a BBF. However, there is no distinctive difference between them
- TWABs are likely the "freshly" rebounded BBFs. They may represent the early stage of the evolution of tailward flows in the plasma sheet

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Chong, G. S., De Spiegeleer, A., Hamrin, M., Pitkänen, T., Gunell, H., & Aizawa, S. (2021). Tailward flows in the vicinity of fast earthward flows. *Journal of Geophysical Research: Space Physics*, *126*, e2020JA028978. https://doi. org/10.1029/2020JA028978

Received 27 NOV 2020 Accepted 10 MAR 2021

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Tailward Flows in the Vicinity of Fast Earthward Flows

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Abstract The occurrence of tailward flows in the magnetotail plasma sheet is closely linked to the dynamics of earthward bursty bulk flows (BBFs). Tailward flows that are observed in the vicinity of these BBFs (or TWABs – Tailward flows around BBFs) may hold unique information on its origin. In this study, we conduct a statistical survey on TWABs by using data from the Cluster mission. We find that TWABs are observed in the vicinity of ~75% of the BBFs and their occurrence does not depend on BBF velocity magnitude. TWABs have a flow convection pattern consistent with the general tailward flows (GTWs) in the plasma sheet and they do not resemble vortical-like flows. However, TWABs have a flow velocity magnitude twice larger than the GTWs. The plasma density and temperature of TWABs are comparable with BBFs. It is more common to observe a TWAB succeeding than preceding a BBF. However, there is no distinctive difference (in flow pattern, plasma density and temperature) between preceding and succeeding TWABs. We suggest that TWABs are likely the "freshly" rebounded BBFs from the near-Earth region where the magnetic field is stronger. TWABs may represent the early stage of the evolution of tailward flows in the plasma sheet. We also discuss and argue that other mechanisms such as shear-induced vortical flows and tailward slipping of depleted flux tubes cannot be the principal causes of TWABs.

Plain Language Summary In Earth's magnetotail, the plasma sheet is generally populated with slow earthward moving plasma. This plasma sheet is often perturbed by short bursts of earthward high speed flows, commonly known as the bursty bulk flows (BBFs). These BBFs are closely associated with the formation mechanisms of tailward flows in the magnetotail. The dynamic interaction between these tailward flows and BBFs can affect the energy, mass and momentum transport in the coupled magnetosphere-ionosphere system. In this work, we conduct a statistical study on the tailward flows with a particular focus on those observed in the vicinity of BBFs (or TWABs, tailward flows around BBFs in short). We find that TWABs are common. They have a flow convection pattern consistent with, but a velocity magnitude twice larger than the general tailward flows in the plasma sheet. We also find that the plasma density and temperature of TWABs are comparable with BBFs. Based on their characteristics, we suggest that TWABs primarily result from the rebound of earthward flows in the near-Earth region, where the magnetic field is stronger.

1. Introduction

In the Earth's magnetotail plasma sheet, the average plasma convection is slow and mainly directed earthward (Angelopoulos, Kennel, Coroniti, Pellat, Spence, et al., 1993; Juusola et al., 2011; Zhu, 1993). This plasma sheet is often perturbed by short bursts of earthward high speed flows with speed reaching >400 km/s, commonly known as the bursty bulk flows (BBFs) (Angelopoulos, Baumjohann, et al., 1992; Angelopoulos, Kennel, Coroniti, Pellat, Kivelson, et al., 1994; Baumjohann, Paschmann, & Lühr, 1990).

On the other hand, in the region tailward of the magnetic *X*-line, tailward flows with southward magnetic field ($B_z < 0$ nT) are generally associated with the accelerated plasma ejected tailward of the X-line. However, the same mechanism cannot explain the observation of tailward flows with northward magnetic field ($B_z > 0$ nT) (Juusola et al., 2011; McPherron et al., 2011; Ohtani et al., 2009; Pitkänen, Kullen, et al., 2019; Zhang et al., 2015). A number of formation mechanisms have been postulated: (1) the overshooting and the subsequent rebound of the BBFs from the stronger dipolar magnetic field (Birn, Nakamura, et al., 2011; Chen & Wolf, 1999; Nakamura et al., 2013; Ohtani et al., 2009; Panov, Nakamura, Baumjohann, Angelopoulos,



et al., 2010; Panov, Nakamura, Baumjohann, Sergeev, et al., 2010); (2) the slipping of depleted flux tubes around the BBFs (Walsh et al., 2009); and (3) shear-induced vortical flows (Birn, Nakamura, et al., 2011; Birn, Raeder, et al., 2004; Hamrin et al., 2013; Keika et al., 2009; Keiling et al., 2009; Merkin et al., 2019; Panov, Nakamura, Baumjohann, Angelopoulos, et al., 2010; Pitkänen, Aikio, Amm, et al., 2011; Turkakin et al., 2014).

One common aspect among these studies is the association of BBFs with the formations of tailward flows in the magnetotail's plasma sheet. Tailward flows in the vicinity of BBFs (will be referred to TWABs – Tailward flows around BBFs in short, hereon) are not an uncommon observation. In fact, the tailward flow events reported in the in situ observational studies mentioned above (which lead to the respective postulated formation mechanisms of tailward flows) are observed in the vicinity of BBFs (i.e., TWABs) (e.g., Keika et al., 2009; Nakamura et al., 2013; Panov, Nakamura, Baumjohann, Angelopoulos, et al., 2010; Panov, Nakamura, Baumjohann, Sergeev, et al., 2010; Pitkänen, Aikio, Amm, et al., 2011; Walsh et al., 2009). In addition, highly meandered and vortical-like flows (with tailward flow components) in the vicinity of BBFs have also been successfully simulated in numerical works (e.g., Birn, Nakamura, et al., 2011; Turkakin et al., 2014; Wiltberger et al., 2015). The above postulated formation mechanisms each highlights different key characteristics (e.g., flow pattern and plasma origins) of the resulting tailward flows. This implies that TWABs would likely hold unique information on its origin. Therefore, by researching TWABs, it is likely that we are identifying the tailward flows that are in the early stage of their evolution. This will allow us to investigate the significance of different mechanisms in causing tailward flows.

McPherron et al. (2011) and Ohtani et al. (2009) have conducted statistical analyses on fast tailward flows. In McPherron et al. (2011), a superposed epoch analysis of 43 fast ($V_{\perp Bx} < -150$ km/s) tailward flow events shows that a tailward flow peak is generally preceded by an earthward flow peak 4 min earlier. In Ohtani et al. (2009), nine out of 24 fast ($V_{\perp Bx} < -200$ km/s) tailward flow events are observed 5 min within the observations of fast earthward flows ($V_{\perp Bx} > 300$ km/s). In particular, seven of them succeed and only two preceed the observations of fast earthward flows. While these studies hint that TWABs can indeed be common, there is not yet an established consensus on the extent the occurrence of tailward flows depends on the dynamics of BBFs. Moreover, there is also an indication that an asymmetry in the occurrence rate between preceding and succeeding TWABs (depending on its sequence to the observation of BBFs) exists. However, it is yet to be investigated if they have common origins.

To better understand the evolution of tailward flows in the plasma sheet, we will conduct a statistical survey on TWABs using data from the Cluster mission. This study can be divided into three main parts. First, we will examine the occurrence and the characteristics of TWABs (Section 4.1). Second, we will compare the plasma properties between TWABs and the general tailward flows in the plasma sheet (Section 4.2). Third, we will compare the plasma properties of TWABs depending on whether they are observed to precede or succeed the observation of BBFs (Section 4.3). We will also investigate the significance of different mechanisms in causing tailward flows. This work will shed light on the evolutionary pathway of tailward flows in the plasma sheet.

2. Instrumentation

Data from the Cluster 4 spacecraft of the Cluster mission (Escoubet et al., 1997) from 2001 to 2004 are used in this study. The proton data are obtained from the Cluster Ion Spectrometry (CIS) instrument (Rème et al., 2001) using the ion Composition Distribution Function (CODIF) analyzer. High time resolution (0.2 s) magnetic field data are obtained from the Fluxgate Magnetometer (FGM) experiment (Balogh et al., 2001). Geocentric solar magnetospheric (GSM) coordinate system is used throughout this study.

3. Data Selection

3.1. Database of All Tailward Flows (GTWs)

First, we compile a database of all tailward flows in the magnetotail's plasma sheet (i.e., $B_z > 0$ nT and plasma $\beta > 0.5$ (Baumjohann, Paschmann, & Cattell, 1989; Baumjohann, Paschmann, Sckopke, et al., 1988; Boakes et al., 2014)). The database is limited to $X_{\text{GSM}} < -7$ R_E and $|Y_{\text{GSM}}| < 10$ R_E. Plasma data with $V_x < 0$ km/s are



considered tailward flows. This results in a total of 141,256 tailward data points. This database of tailward flows in the magnetotail's plasma sheet with positive B_z will be referred to GTWs (general tailward flows, in short).

3.2. Database of Tailward Flows That are Observed Around BBFs

In this work, BBFs are identified in an approach similar to Angelopoulos, Kennel, Coroniti, Pellat, Kivelson, et al. (1994) and Cao et al. (2006): BBFs are intervals of plasma velocity perpendicular to the instantaneous magnetic field along *X*-axis ($V_{\perp Bx}$) greater than 100 km/s with at least one data point exceeding 250 km/s in the plasma sheet ($\beta > 0.5$). To minimize the effect of the fluctuating instrumental noise of CODIF, a minimum duration of 24 s (\sim 3 × the sampling period of CODIF) is required for all BBFs. We only select intervals where the average magnitude of perpendicular velocity component $V_{\perp B}$ is greater than the field-aligned velocity component $V_{\parallel B}$. This is to distinguish the BBFs from the magnetic field-aligned flows which are common in the plasma sheet boundary layer (PSBL) (Baumjohann, Paschmann, Sckopke, et al., 1988; Decoster & Frank, 1979; Takahashi & Hones, 1988). We merge BBFs to become a single BBF if the beginning and the end of the consecutive BBFs are observed within 5 min from each other. For each BBF, the instance when $V_{\perp Bx}$ first exceeds (drops below) 100 km/s is considered the begin (end) of the BBF. In total, 217 BBFs, which amounts to a total of 8,551 data points, are identified.

To identify TWABs, we scan the plasma data 5 min before the beginnings and 5 min after the ends of the BBFs. The criteria of plasma $\beta > 0.5$ and $B_z > 0$ nT are applied to rule out (1) the tailward flows that are ejected tailward of the reconnection sites, and (2) tailward field-aligned flows in the PSBL. Any continuous interval of $V_x < 0$ km/s for at least 24 s (~3 × the sampling period of CODIF) is considered a TWAB in this study. TWABs begin and end when V_x first drops below and exceed 0 km/s, respectively. Note that there are cases where more than one interval of tailward flows are separated by intervals of earthward flows during the 5 min window scan. Multiple flow reversals could be related to sloshing-like phenomena (e.g., De Spiegeleer et al., 2017). In such cases, only the interval that is closest to the BBF is considered to be a TWAB. We further categorize TWABs according to their sequence with the BBFs: TWABs that precede the observation of BBFs and TWABs that succeed the observation of BBFs. They will be referred to as "Pre. TWABs" and "Suc. TWABs" respectively hereon. In total, 219 TWABs, which amounts to a total of 2,479 data points, are identified. Note that these 2,479 data points are a subset of database GTW.

4. Results

4.1. Occurrence of TWABs

In this subsection, we analyze the occurrence of TWABs and its relation to the dynamics of BBFs. A summary of the results on the identification of TWABs is shown in Figures 1a and 1b. In total, 217 BBFs are identified; 162 (~75%) of the BBFs are associated with TWABs and 55 (~25%) of them are not associated with any TWABs. Of the 162 BBFs that are associated with TWABs; 28 (~13%) are associated with only Pre. TWABs, 77 (~35%) are associated with only Suc. TWABs, and 57 (~27%) are associated with both Pre. and Suc. TWABs. In total, our database consists of 219 TWABs where 85 (~39%) are Pre. TWABs and 134 (~61%) are Suc. TWABs.

The typical duration of TWABs is ~1 min (average duration is 66 ± 5 s). Further analysis shows that there are only seven (out of 219) TWABs that have durations longer than the 5 min window scan (all are <7 min). On average, TWABs are observed within 2 min (107 \pm 5 s) of the beginning and the end of the BBFs. In total, out of the 219 TWABs, 75 (~34%) are observed in cases with more than one interval of tailward flows that are separated by intervals of earthward flows during the 5 min window scan, that is, could be related to sloshing-like phenomena (e.g., De Spiegeleer et al., 2017).

Figure 1c shows two distributions of BBF velocity magnitude (|V|); that is, all BBFs and only BBFs where TWABs are observed in its vicinity. Both distributions are similar. In general, TWABs can be observed regardless of the |V| of BBFs. In brief, observation of TWABs in the vicinity of BBFs is common and their occurrence does not depend on BBF velocity magnitude. Also, it is more common to observe Suc. TWAB than Pre. TWAB.







Figure 1. A summary of the results on the identification of tailward flows around BBFs (TWABs). In total, (a) 217 bursty bulk flows (BBFs) and (b) 219 TWABs are identified. Note that 219 TWABs = 2×57 BOTH Pre. and Suc. TWABs + 28 ONLY Pre. TWABs + 77 ONLY Suc. TWABs. Refer to text in Section 4.1 for more detailed information. (c) The distributions of velocity magnitude (|**V**|) for all identified BBFs (blue-colored) and only BBFs where TWABs are observed in its vicinity (red-colored). Regions of overlapped histograms are shaded in purple. σ and $\sigma_{\overline{x}}$ represent the standard deviation and standard error respectively. The occurrence is normalized with respect to the relative probability, so that the sum of the occurrences over all binned variables equals 1. All presented data in this work are normalized in the same manner.

IVI[km/s]

4.2. GTWs Versus TWABs

In this subsection, we compare the plasma properties between GTWs and TWABs.

4.2.1. Plasma Flow Velocity

In Figure 2, we show the average plasma flow vectors in the *X*-*Y* plane and *X*-*Z* plane for GTWs (a and c) and TWABs (b and d) respectively. The flow velocity of both GTWs and TWABs are mainly in the *X*-*Y* plane while the contributions along the *Z*-axis are minimal. Observable from Figure 2a, the plasma flows of GTWs



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Figure 3. The distributions of (a) plasma density and (b) plasma temperature for GTWs (blue-colored), TWABs (redcolored) and BBFs (yellow-colored) respectively. The distributions of (c) plasma density and (d) plasma temperature for Pre. TWABs (green-colored) and Suc. TWABs (cyan-colored), respectively. The number of data points that are not included (due to the *X*-axis limit) is noted on the lower right corner of the histograms. The median values of the distributions are also marked.

generally deflect rather symmetrically along the dawn-dusk axis in the *X*-*Y* plane. For instance, the tailward flows in the dawnside tend to have a predominantly dawnward component and those in the duskside tend to have a predominantly duskward component. In the *X*-*Z* plane, the plasma flows have a weak tendency to converge toward Z = 0 R_E (i.e., Figure 2c).

Similar to GTW, the plasma flow vectors of TWABs also have the tendency to diverge along the dawn-dusk axis in the *X*-*Y* plane (i.e., Figure 2b). However, the tendency of converging flow vectors toward Z = 0 R_E in the *X*-*Z* plane is less apparent for TWABs (i.e., Figure 2d). In addition, the degree of the diversion along the dawn-dusk axis is greater for TWABs compared to GTWs. This can be due to the lower statistical power hence greater variability for TWABs.

One noteworthy difference in the plasma flows between GTWs and TWABs is the velocity magnitude (|V|) of the plasma flows. Figure 2e shows the |V| for GTWs (blue-shaded) and TWABs (orange-shaded) respectively. GTWs have a median |V| of 64 km/s and TWABs have a median |V| of 136 km/s. Deducible from Figure 2e, the average |V| of TWABs is twice larger than the GTWs.

4.2.2. Plasma Density and Temperature

We compare the distributions of plasma density and temperature for GTWs (blue-colored) and TWABs (red-colored) respectively in Figures 3a and 3b. The histograms are over-plotted with the distributions

Figure 2. The distribution of velocity vectors in the *X*-*Y* and *X*-*Z* plane for (a and c) general tailward flows (GTWs) and (b and d) TWABs respectively. Flow vectors are binned in 1×1 R_{*E*} square bins. Note that the scales of the velocity vector used in both distributions are the same. They are reflected in the lower left corners of each plots. Only bins with five or more measurements are shown. Note the difference in the *X*-axis limits as no TWAB is observed at X > -12 R_{*E*}. The total number of utilized data points per bin is included in Figure S1. (e) The distributions of velocity magnitude |**V**| for GTWs (blue-colored) and TWABs (red-colored). Regions of overlapped histograms are shaded in purple. The number of tailward flows that are not included (due to the *X*-axis limit) is noted on the lower right corner of the histogram. The median values of the two distributions are also marked respectively.



of BBFs (yellow-colored) respectively. By comparing the marked median values between the respective distributions in Figures 3a and 3b, it is deducible that the plasma properties of TWABs are more similar to BBFs compared to GTWs. For instance, the median values of the plasma density of TWABs and BBFs are 0.22 cm^{-3} and 0.19 cm^{-3} , respectively. These values are comparably different to those of GTWs, which is 0.30 cm^{-3} . Similarly, the median values of the plasma temperature of TWABs and BBFs are 4.79 and 4.77 keV, respectively. These values are comparably different to those of S30 keV.

In brief, while the spatial distribution of the flow direction stays rather consistent between GTWs and TWABs (i.e., Figures 2a–2d), it appears that the $|\mathbf{V}|$ of tailward flows is different depending whether or not they are observed in the vicinity of fast earthward flows (i.e., Figure 2e). Furthermore, we also find that the plasma properties (i.e., plasma density and temperature) of TWABs are more similar to the BBFs while being comparatively different to the GTWs.

4.3. Pre. and Suc. TWABs

Analysis in Section 4.1 reveals that there is a slight asymmetry in the occurrence rates between Pre. and Suc. TWABs (i.e., \sim 39% and \sim 61%, respectively). In this subsection, we investigate the plasma properties between Pre. and Suc. TWABs. We will first present two single-event studies, then followed by a statistical analysis on Pre. and Suc. TWABs, respectively.

4.3.1. Example Events

We present two example events of Pre. and Suc. TWAB in Figure 4. Throughout the intervals shown in Figure 4, the plasma β is consistently >0.5 (Figures 4e and 4m) and $B_z > 0$ nT (Figures 4b and 4j), indicating that the spacecrafts are in the central plasma sheet. Both examples are observed by C4 at \approx [-18.4, -5.1, 0.1] R_E and \sim [-15.3, -9.3, 2.6] R_E, respectively. Note that the plasma sheet on August 20, 2003 has a lower density but higher temperature while the plasma sheet on August 5, 2003 has a higher density but lower temperature. Both TWABs are characterized by their tailward flow component (i.e., $V_x < 0$ km/s, see Figures 4a and 4i), as per their selection criteria. They reach a maximum $|\mathbf{V}|$ of \approx 226 and 99 km/s respectively. They both have a dawnward flow component (i.e., $V_y < 0$ km/s), which coincide with their locations in the dawnside plasma sheet. The dependence of TWAB V_y on their locations in the plasma sheet will be investigated statistically in the following section.

The variation in plasma properties upon crossing the TWAB and BBF are similar in both cases of Pre. and Suc. TWAB. In general, the traversals into the TWABs and their respective associated BBFs can be characterized by a decrease in plasma density, an increase in plasma temperature, and a presence of ion population with higher energy and narrower intensity. For instance, in the case of Pre. TWAB (Figures 4a–4h), the spacecraft traversal into the TWAB is marked by a decrease in plasma density and an increase in plasma temperature at around 07:38 UTC (line 1 in Figures 4c and 4d). The presence of this plasma with decreased density and increased temperature can be continuously observed from the traversal of TWAB through to BBF (line 1–4). At around 07:51 UTC, the spacecraft then traversed into a region with plasma properties similar to prior crossing into the Pre. TWAB, that is, higher density and lower temperature.

The increase in plasma temperature in the Pre. TWAB and BBF is likely due to the presence of ions with higher energy and narrower intensity (Figure 4f). To better visualize this, we show the ion particle flux from 1st to 3rd and from the 9th to 11th of CODIF energy channels in Figures 4g, 4h, 4o, and 4p. The 1st to 3rd energy channels (Figures 4g and 4o) are chosen to better visualize the presence/absence of ions with high energy. The 9th to 11th energy channels (Figures 4h and 4p) are chosen to better visualize the presence/absence of ions with medium energy. Combined observations of the ions with high and medium energy could allow us to examine the energy intensity of the ions. For instance, the traversal of Pre. TWAB and BBF can be characterized by the presence of ions with high energy and an absence of ions with medium energy, indicating the presence of ions with higher energy and narrower intensity (see Figures 4f–4h).

The spacecraft observation of Suc. TWAB (Figures 4i-4p) is similar to the case of Pre. TWAB but in a reversed manner; that is, spacecraft first crossed into the BBF and then the TWAB. For instance, the crossing into the BBF is marked by a decrease in plasma density and an increase in plasma temperature at around 20:04 UTC (line 1 in Figures 4k-4l). Although the values are somewhat different, such plasma with







Figure 4. C4 observations of a Pre. TWAB event on August 20, 2003 (left panels) and Suc. TWAB on August 5, 2003 (right panels), respectively. The panels show from top to bottom the *X*, *Y*, *Z* components of **V**, B_z , plasma density, plasma temperature, plasma β , ion energy-time spectrogram of energy flux, the ion energy flux at 1st to 3rd CODIF energy channels, and the ion energy flux at 9th to 11th CODIF energy channels. Note that the *Y*-axis limits are different between Pre. and Suc. TWAB. Intervals of the identified BBF, Pre. and Suc. TWAB are also marked accordingly. The BBFs of the respective Pre. and Suc TWAB cases are recorded by C4 at \approx [-18.4, -5.1, 0.1] R_E and \sim [-15.3, -9.3, 2.6] R_E, respectively.

decreased density and increased temperature can be observed from the traversal of BBF to Suc. TWAB (line 1–4). As the spacecraft exits Suc. TWAB, the plasma density and temperature gradually increases and decreases respectively but never reach the values of the region prior crossing into the BBF (prior to line 1). Observable from Figures 4n–4p, both BBF and Suc. TWAB can also be characterized by the presence of ions with higher energy and narrower intensity, similar to the case of Pre.

TWAB and its associated BBF.

Table 1

Plasma Properties of TWAB, BBF, and GTW for Pre. and Suc TWAB, Respectively

	Pre. TWAB			Suc. TWAB		
Properties	TWAB	BBF	GTW	TWAB	BBF	GTW
Density [cm ⁻³]	0.26	0.26	0.31	0.70	0.66	0.88
Temperature [keV]	7.29	8.15	5.30	3.68	3.96	2.84

Note. GTW is estimated in the regions 1 h before and 1 h after the spacecraft crossing of TWAB and BBF. For instance, for the case of Pre. TWAB, GTW is selected from 06:38:00 UT to 07:38:00 UT and from 07:45:40 UT to 08:45:40 UT on August 5, 2003. For the case of Suc. TWAB, GTW is selected from 19:04:20 UT to 20:04:20 UT and from 20:10:20 UT to 21:10:20 UT on August 5, 2003. Median values are shown.

Note that in both cases, the values of both the plasma density and temperature are somewhat different (but consistent) between the TWABs and their respective associated BBFs. The consistency between the TWABs and BBFs is clearer when compared with the respective GTWs (measured 1 h before and 1 h after the crossing of TWAB and BBF). We compare the plasma properties between TWAB, BBF, and GTW in Table 1. In general, both the Pre. and Suc. TWAB have plasma properties (plasma density and temperature) more comparatively similar to its respective BBF than the GTW (of respective orbits).

In brief, both the Pre. and Suc. TWAB presented here possess similar characteristics. For instance, both TWABs are observed at dawnside plasma sheet that also coincide with its dawnward velocity component. In



addition, they have plasma properties (density, temperature and the presence of ion with high energy and narrower intensity) similar to their associated BBF while comparatively different to the GTW of respective orbits.

4.3.2. Plasma Flow Velocity

In the following sections, we conduct a statistical analysis on all the identified TWABs according to Section 3. In Figure 5, we show the average plasma flow vectors in the *X*-*Y* plane and *X*-*Z* plane for Pre. TWABs (a and c) and Suc. TWABs (b and d), respectively. The spatial distributions of the flow direction between Pre. and Suc. TWABs are similar. In general, they are consistent with the distribution of TWABs, as shown in Figures 2b and 2d. For instance, the tailward flows in the dawnside tend to have a predominantly dawnward component and those in the duskside tend to have a predominantly duskward component. In addition, the plasma flows have a weak tendency to converge toward Z = 0 R_{*E*} in the *X*-*Z* plane.

We further compare the |V| between Pre. and Suc. TWABs in Figure 5e. In general, the plasma flow velocity magnitude of both Pre. and Suc. TWABs are rather similar. For instance, the median values of |V| of Pre. and Suc. TWABs are 145 and 133 km/s, respectively.

4.3.3. Plasma Density and Temperature

Figure 3 shows the distributions of the (c) plasma density and (d) plasma temperature for Pre. TWABs (blue-colored) and Suc. TWABs (red-colored) respectively. The plasma density and temperature of Pre. and Suc. TWABs are comparatively similar. For instance, the median values of the plasma density of Pre. and Suc. TWABs are 0.23 and 0.21 cm⁻³, respectively. Similarly, the median values of the plasma temperature of Pre. and Suc. TWABs are 4.78 and 4.79 keV, respectively.

In brief, we find that, besides the occurrence asymmetry, there is no distinctive difference (in flow pattern, plasma density and temperature) between Pre. and Suc. TWABs.

5. Discussion and Summary

The rebound of earthward flows in the near-Earth region is a widely accepted mechanism in the origin of tailward flows in the magnetotail (Birn, Nakamura, et al., 2011; Chen & Wolf, 1999; Nakamura et al., 2013; Ohtani et al., 2009; Panov, Nakamura, Baumjohann, Angelopoulos, et al., 2010; Panov, Nakamura, Baumjohann, Sergeev, et al., 2010). Based on the results from this study, we argue that the reported TWABs are likely the "freshly" rebounded BBFs. An illustrative sketch of this mechanism is depicted in Figure 6. BBFs continuously decelerate as the magnetic flux tubes build up ahead of them. These BBFs can sometimes overshoot their equilibrium positions (Chen & Wolf, 1999). As a result, the subsequent azimuthal and tailward expansion of the piled-up magnetic field (Birn, Nakamura, et al., 2011) at the reflection point can lead to the formation of tailward flows with high $|\mathbf{V}|$. This is consistent with the results where TWABs have $|\mathbf{V}|$ twice larger than the GTWs. Furthermore, "freshly" rebounded flows would retain similar plasma from the incident BBFs. Indeed, the plasma properties (i.e., plasma density and temperature) of TWABs are more similar to the BBFs while being comparatively different to the GTWs. The substantial decrease in $|\mathbf{V}|$ from TWABs to GTWs (Figure 2e) suggests that a rapid deceleration mechanism would closely follow the formation of tailward flows with high $|\mathbf{V}|$.

In brief, we suggest that the tailward expansion of the magnetic field would be continuously accelerating the plasma, until the magnetic field ceases expanding. Subsequently, the tailward enhancement on the tailward flows would begin to diminish and the tailward flows will start decelerating, eventually resulting in tailward flows with low $|\mathbf{V}|$. We postulate that the deceleration process will continue until a balance on plasma entropy and momentum with the ambient plasma sheet is reached. The interaction between tailward flows and its earthward counterparts is also a probability which can also contribute to the deceleration of tailward flows. On another note, spatial distribution analysis of the TWAB plasma velocity vectors (Figures 2b and 2d) indicate that the rebound of BBFs is a systematic mechanism. For instance, the flow vectors of the rebounded flows are diverged quasi-orderly and quasi-symmetrically along the dawn-dusk axis (i.e., Figure 2b).





Figure 5. Descriptions are same as Figure 2 but comparing between Pre. and Suc. TWABs. For (a–d), the total number of utilized data points per bin is included in Figure S2. The distributions of velocity magnitude $|\mathbf{V}|$ for Pre. and Suc. TWABs are green- and cyan-colored, respectively.





Figure 6. Illustration shows how TWABs with high |V| can be interpreted as the "freshly" rebounded flows of BBFs in the XY-plane. The BBFs are assumed to rebound at the "reflection point" in the near-Earth region, where the dipolar magnetic field magnitude is strong. The mechanism can be summarized as follow: (1) Magnetic flux tubes pile up ahead of the BBF, (2) BBF overshoots its equilibrium position and eventually stops at the reflection point, (3) piled-up magnetic flux tubes expand tailward, (4) formation of tailward flows, (5) tailward flows continuously decelerate until an equilibrium is reached, and (6) the tailward flows may eventually stop. Note that the tailward flows interaction with its earthward counterparts could also contribute to the deceleration of tailward flows. However, we emphasize that their eventual fates remain an open question. This sketch only serves as an illustration purpose and is not drawn to scale. Note that the reflection region is depicted in a concave-shaped body to interpret the diverging property of TWABs and GTW along the dawn-dusk axis.

We suggest that while the TWABs (typically associated with high |V|) may represent the early stages of rebounded flows, on the other hand, tailward flows that are associated with lower |V| may represent the tailward flows that are (1) rebounded from the slower earthward flows, or (2) in the later stages of evolutions of the rebounded flows. The exact evolution of tailward flows in the magnetotail is out of the scope of this study, but it shall be explored further in future work.

However, the "freshly" rebounded BBFs as a postulated cause for TWABs raises a number of consequential questions: If TWABs are mainly caused by the rebound of BBFs, then why are around 25% of the BBFs identified in this work not associated with any TWAB in its vicinity? In fact, we find that TWABs are not necessarily observed in the vicinity of BBFs with large mean |V| (i.e., up to 700 km/s). On the other hand, TWABs are observed in the vicinity of BBFs with lower mean $|\mathbf{V}|$ (i.e., ≈ 200 km/s). One possible explanation is that the spacecraft simply did not encounter the associated tailward flows by chance. Another possibility is that not all earthward flows are rebounded. Lastly, if the rebounded flows are continuously braked in manners similar to BBFs (but in the opposite direction), then perhaps not all rebounded flows could arrive at the spacecraft before they are eventually stopped. There are dynamic conditions (e.g., strength of the piled-up dipolarization fronts, plasma flow magnitude, etc.) that govern the rebound mechanism of earthward flows which are yet to be understood.

This study identified a total of 219 TWABs where 39% are Pre. TWABs and 61% are Suc. TWABs. Previous works have reported that tailward flows rarely precede BBFs (McPherron et al., 2011; Ohtani et al., 2009). Although less common than Suc. TWABs, it is noteworthy to mention that significant number of Pre. TWABs are observed in this study. Additional analysis also reveals that there is no distinctive difference (in flow pattern, plasma density and temperature) between Pre. and Suc. TWABs. We suggest that the BBFs are more likely to have rebounded tailward (and are subsequently observed by the spacecraft) if the BBFs have al-

ready flowed past (or passing over) the spacecraft. Hence, higher occurrence rate of Suc. TWABs. In contrast, before the BBFs pass over the spacecraft, it is likely that the rebounded flows have not formed, simply because that the BBFs have not arrived at the reflection point. Hence, lower occurrence rate of Pre. TWABs.

Another potential generation mechanism of TWABs is the shear-induced vortical flows that can arise (1) between the BBF and the ambient plasma sheet, as well as (2) between the rebound flows and the ambient plasma sheet (Birn, Nakamura, et al., 2011; Birn, Raeder, et al., 2004; Keika et al., 2009; Keiling et al., 2009; Merkin et al., 2019; Panov, Nakamura, Baumjohann, Angelopoulos, et al., 2010; Turkakin et al., 2014). For a tailward flow that is resulted from a "solid-body" vortex (i.e., the tangential velocity magnitude increases gradually from the center to the edge of an idealized circular flow vortex (e.g., Figure 7 in Keiling et al. [2009])), the distributions of the total dawnward and duskward velocity components should be similar, regardless of its rotational directions (e.g., clockwise or counter-clockwise). For instance, the probability of spacecraft observing the dawnward and duskward components of a tailward vortical flow should be similar. However, the dawn-dusk velocity components of TWABs reported in this study do not appear to be randomly oriented as expected from vortical flows (see Figures 2b and 2d). Rather, they show dependence with respect to their locations. In general, they appear to follow the GTW convection whose flow components diverge quasi-symmetrically along the dawn-dusk axis. Therefore, we argue that it is unlikely that the TWABs reported in this work are primarily caused by tailward vortical flows in the plasma sheet. However, we do not rule out the possibility that the vortical flows have an overall drifting velocity pattern that diverges along the dawn-dusk axis.



On a different note, previous observational and numerical works have demonstrated that vortical flows do exist, excited by the strong shear flow across the BBF boundaries (Birn, Raeder, et al., 2004; Turkakin et al., 2014; Volwerk et al., 2007). However, our results of quasi-orderly rather than randomly oriented dawn-dusk flow components indicate that TWABs are unlikely vortical-like. The question is: Why is there a lack of observation in vortical flows? One possible reason is that the BBF boundary may not always have sufficient time to become a rolled-up vortical flow before the flows are stopped in the near-Earth region. Another explanation could be that the vortical flows are generally short-lived where their dawn-dusk flow components are eventually dominated by the tailward component in later stages of their evolution. Furthermore, the selection of TWABs with a minimum of three data points (>24 s) could have excluded the more bursty tailward flows. Bursty tailward flows are commonly associated with the non-linear stage of Kelvin-Helmholtz induced BBF boundary wave (Volwerk et al., 2007). Therefore, on the assumption that there is a finite distance for BBFs to travel before they are stopped at near-Earth region, it is an interest for future work to investigate if the BBF boundary always have sufficient time to evolve into a shear-induced vortical flow.

Another generation mechanism of tailward flows conceptualized by Walsh et al. (2009) interprets that the slipping of depleted flux tubes around the BBFs can also lead to tailward flows. This mechanism highlights the presence of density-depleted and field-aligned plasma flows. While our study finds that the plasma density of TWABs in general is comparatively lower than the GTWs (i.e., 0.22 cm⁻³ compared to 0.30 cm⁻³), we also find that the flows of TWABs are largely convective (see Figure S3). These properties of TWABs, including its characteristic diverging flows along the dawn-dusk axis are inconsistent with those conceptualized by Walsh et al. (2009). Therefore, present work indicates that tailward slipping of depleted flux tubes cannot be the principal causes of TWABs. However, its role, albeit minor, should not be ruled out in the overall formation mechanisms of tailward flows. On another note, tailward flows with enhanced and depleted plasma density have both been reported before (Ohtani et al., 2009; Pitkänen, Aikio, Amm, et al., 2011; Pitkänen, Aikio, and Juusola, 2013; Walsh et al., 2009). In fact, Pitkänen, Aikio, Amm, et al. (2011) and Pitkänen, Aikio, and Juusola (2013) have observed two tailward flows on each side of a BBF with different plasma properties; one with enhanced and another with depleted plasma density. The causes of tailward flows with enhanced plasma density remains an open question.

6. Conclusion

In conclusion, we present a work that, for the first time, explores the occurrence of tailward flows in relation to the dynamics of BBFs. We find that TWABs are common. They are observed in the vicinity of ~75% of the identified BBFs. The occurrence of TWABs does not depend on BBF velocity magnitude. TWABs have flow pattern similar to GTWs and they do not resemble vortical-like flows. TWABs have $|\mathbf{V}|$ twice larger than GTW. Further analysis reveals that the plasma density and temperature of TWABs are more similar to BBFs than to GTW. In addition, besides the occurrence asymmetry, there is no distinctive difference (in flow pattern, plasma density and temperature) between Pre. and Suc. TWABs.

We suggest that TWABs are likely the "freshly" rebounded BBFs. The rebound of BBFs appears to be a systematic mechanism: the rebounded plasma flows diverge quasi-symmetrically along the dawn-dusk axis. The substantial decrease in $|\mathbf{V}|$ from TWABs to GTWs suggests that the early stage of plasma acceleration process is quickly followed by a rapid deceleration process. Tailward flows may start to decelerate when the magnetic field ceases expanding tailward. We also discussed and argued that other potential mechanisms such as shear-induced vortical flows and tailward slipping of depleted flux tubes cannot be the principal causes of TWABs.

This work brings insights on the evolutionary pathways of tailward flows in the magnetotail. However, further works are needed to better understand the eventual fates of tailward flows and their significance in the energy, mass and momentum transport in the coupled magnetosphere-ionosphere system.



Data Availability Statement

The authors would like to thank all the Cluster team members for the successful operation of the instrument and the calibration of the data. All Cluster data is available from Cluster Science Archive at https:// www.cosmos.esa.int/web/csa.

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Acknowledgments

Participants from Umeå University received financial assistance from the Swedish National Space Agency (SNSA) Grant 81/17 and 108/18. T. Pitkänen would like to acknowledge the financial assistance from SNSA Grant 118/17 and from the Natural Science Foundation of China (NSFC) Grant 41750110486. The authors would like to thank the reviewers for their valuable comments.





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