The Influence of Localized Dynamics on Dusk-Dawn Convection in the Earth’s Magnetotail

J. H. Lane, A. Grocott, and N. A. Case

1Department of Physics, Lancaster University, Lancaster, UK

Abstract Previous work has shown that earthward convective flow bursts in the magnetotail have a dusk-dawn (\(\mathbf{B}_\|\)) component that is controlled by the historical state of the Interplanetary Magnetic Field (IMF) \(\mathbf{B}_z\) component. Here, we analyze 27 years of Cluster, THEMIS and Geotail plasma and magnetic field data and identify 1,639 magnetotail fast flow “detections” that demonstrate a dusk-dawn asymmetry. We find that ~70% has a dusk-dawn direction consistent with that expected from the penetration of IMF \(\mathbf{B}_z\). Superposed epoch analysis suggests that the inconsistency of the remaining ~30% is not due to a lack of the expected IMF \(\mathbf{B}_z\) penetration. Instead, we find that on average, the expected sense of IMF \(\mathbf{B}_z\) penetration is associated with flows irrespective of whether those flows agree or disagree with the expected dusk-dawn asymmetry. IMF \(\mathbf{B}_z\) and the penetrated \(\mathbf{B}_z\) do, however, tend to be stronger for “agree” flows. Detections which agree (disagree) tend to be accompanied by a localized perturbation to the \(\mathbf{B}_z\) component of the magnetotail magnetic field in the same sign as (opposite to) the prevailing IMF \(\mathbf{B}_z\) conditions, which temporally enhances (overrides) the penetrated field. Agree (disagree) flows also appear to be observed further away from (closer to) the neutral sheet (\(\mathbf{B}_z = 0\)) and are associated with weaker (stronger) magnetic field dipolarization. Finally, we find that the slower “background” convective flow has an average direction which is consistent with penetration of the expected IMF \(\mathbf{B}_z\), regardless of whether the fast flow itself agrees or disagrees.

1. Introduction

It is well known that the nature of convection in the magnetosphere-ionosphere system is controlled by the Interplanetary Magnetic Field (IMF) (e.g., Lockwood et al., 1990). The reconnection of the IMF with the Earth’s dayside terrestrial field drives the large-scale circulation of magnetic flux, known as the Dungey Cycle (Dungey, 1961). When open field lines reconnect in the magnetotail, the release of magnetic tension triggers Earthward (and tailward) plasma “return” flows which are often bursty in nature (e.g., Sergeev et al., 1992), resulting in dipolarization of the magnetic field (e.g., Schmid et al., 2011). Studies such as Kissinger et al. (2012) have suggested that these flows are (on average) symmetric with respect to midnight, such that flows in the post-midnight sector are usually dawnward and flows in the pre-midnight sector are usually duskward.

It is also well known, however, that the IMF dusk-dawn (\(\mathbf{B}_\|\)) component is expected to introduce asymmetries into the Earth’s magnetosphere (e.g., Cowley, 1981). Asymmetric flux loading into the lobes (e.g., Case et al., 2018; Haaland et al., 2008) resulting from dayside reconnection of the Earth’s terrestrial field with a non-zero IMF \(\mathbf{B}_z\) is known to introduce a twist into the magnetotail - a superimposed \(\mathbf{B}_z\) component with the same sign as the preceding IMF \(\mathbf{B}_z\) conditions (e.g., Grocott, 2017; Reistad et al., 2018; Tenfjord et al., 2015, 2017). This process is suggested to take anywhere from a few tens of minutes (e.g., Tenfjord et al., 2015, 2017) to a few hours (Browett et al., 2017). The magnetotail “untwisting hypothesis” discussed by Grocott et al. (2007) suggests that following nightside reconnection of twisted tail field lines, the tail is expected to untwist, as the release of magnetic tension excites fast convective flow bursts (e.g., Grocott et al., 2007; Tenfjord et al., 2015). These flows are expected to have both an earthward and a duskward or dawnward component and occur both in the magnetotail and the nightside ionosphere (Grocott et al., 2007; Reistad et al., 2016, 2018).

The influence of the IMF \(\mathbf{B}_z\) component on these convective magnetotail flows has been investigated in numerous studies (see e.g., Grocott et al., 2007; Pitkänen et al., 2013, 2015, 2017). Statistically, it has been demonstrated that under prolonged IMF \(\mathbf{B}_z > 0\) conditions, the earthward flows are expected to exhibit a duskward component in the northern magnetic hemisphere (NH, \(\mathbf{B}_z > 0\)) and a duskward component in the southern magnetic hemisphere (SH, \(\mathbf{B}_z < 0\), with an opposite dependence expected for IMF \(\mathbf{B}_z < 0\) (Pitkänen et al., 2013). The statistical study of Pitkänen et al. (2013), however, suggested that 25%–30% of the time, the convective dusk-dawn...
direction of the magnetotail fast flows did not agree with that expected from the preceding IMF $B_y$ conditions. This disagreement was reduced to just $\sim 10\%$ when Pitkänen et al. (2013) further imposed that the local (observed) $B_y$ be oriented in the same sense as the preceding IMF $B_y$, in order to remove any ambiguity regarding the time uncertainty for IMF $B_y$ to penetrate into the magnetotail (e.g., Browett et al., 2017). However, they failed to consider that other sources of tail $B_y$ exist, which can lead to a bias in detecting the expected dusk-dawn sense of fast flows that may not be indicative of an IMF $B_y$ effect (Lane et al., 2021).

In this paper, we examine a database of asymmetric magnetotail fast flow “detections.” We define flows as “asymmetric” if they are directed toward midnight ($Y_{GSM} = 0$) from the pre- or post-midnight sectors to explicitly distinguish them from the symmetric duskward or dawnward flows described by Kissinger et al. (2012). We find that only $\sim 70\%$ (1,157 out of 1,639) of the asymmetric flows exhibit a $v_{1y}$ direction that is consistent with the penetration of IMF $B_y$ (“agree” detections). Given that a complete absence of IMF $B_y$ control ought to yield a 50% agreement with IMF $B_y$, simply by chance, then 70% actually indicates only a rather modest level of control. We therefore investigate possible factors that might be responsible for the apparent lack of IMF $B_y$ control in the remaining $\sim 30\%$ (482 out of 1,639) of cases (“disagree” detections). We find that on average, the expected sense of IMF $B_y$ penetration is associated with both the agree (AG) and disagree (DAG) detections, although for the AG detections, IMF $B_y$ and the penetrated $B_y$ tend to be stronger. AG (DAG) flows also tend to be accompanied by a transient perturbation to the $B_y$ component of the magnetotail magnetic field in the same sign as (opposite to) the prevailing IMF $B_y$ conditions, which temporarily enhances (overrides) the penetrated field. We also find that AG (DAG) flows tend to be observed further away from (closer to) the neutral sheet ($B_y \approx 0$) and associated with weaker (stronger) magnetic field dipolarization. Finally, we find evidence to suggest that regardless of whether the fast flows themselves appear to be IMF $B_y$-controlled, they are simply transient perturbations to a “background” of slower convective flow that, on average, displays no disagreement with IMF $B_y$.

### 2. Data and Flow Detections

The magnetospheric observations presented in this study were recorded by the Cluster, Time History of Events and Macroscale Interactions during Substorms (THEMIS) and Geotail missions. We make use of the fluxgate magnetometer (FGM) onboard the Cluster spacecraft to obtain magnetic field measurements at 5 Hz resolution (Balogh et al., 2001), and obtain our bulk ion velocity data from the Hot Ion Analyzer (HIA) calculated as on-board moments at $\sim 4$ s resolution (Rème et al., 1997). Only data from Cluster 1 (C1) and Cluster 3 (C3) are used because C2 and C4 do not provide bulk ion velocity data. Onboard THEMIS, we use make use of the low resolution (4 Hz) FGM data (Auster et al., 2008). We also use spin-resolution (approximately 3 s) bulk ion velocity flow data calculated on the ground from the combined Electrostatic Analyzer (ESA) (McFadden et al., 2008) and Solid-State Telescope (SST) moments (Larson et al., 2009). Finally, from Geotail, we use spin-averaged (3 s) magnetic field data from the MGF instrument (Kokubun et al., 1994), and four-spin resolution (12 s) bulk ion flow velocities from the Low Energy Particle (LEP) experiment (Mukai et al., 1994). We have also applied the appropriate daily Geotail $B_y$ MGF offset, as detailed in the caveat section of the Data Archive and Transmission System (DARTS). Our final dataset consists of C1 (years 2001–2018), C3 (years 2001–2009), THEMIS (years 2007–2019), and Geotail (years 1993–2006). For this analysis, all data are resampled to a common 1-min resolution via median averaging and are presented in Geocentric Solar Magnetospheric (GSM) coordinates.

Using our dataset, we apply similar criteria to Pitkänen et al. (2013, 2017) to identify magnetotail fast flow “detections.” A detection was flagged for any 1-min data point where: (a) the ion plasma beta, $\beta > 0.5$, (b) $-31 < X_{GSM} < -14 R_E$ and $|Y_{GSM}| < 7 R_E$, and (c) the magnitude of the field-perpendicular (convective) flow in the X-Y plane, $v_{1xy} > 200$ km s$^{-1}$, where $v_{1xy} = \sqrt{v_{1x}^2 + v_{1y}^2}$ and $v_{1x} > 0$.

In total, 5,647 detections were identified. This includes 625 detections from C1, 396 from C3, 591 from THEMIS B, 663 from THEMIS C, 37 from THEMIS D, and 3,335 from Geotail. We note that THEMIS A and E never actually entered the region bound by our “fast flow detection space” ($-31 < X_{GSM} < -14 R_E$ and $|Y_{GSM}| < 7 R_E$) during the years surveyed. From these detections, we further required that there be continual spacecraft (plasma and magnetic field) data for $\pm 5$ min about the detection time to ensure that we had complete data coverage in our flow identifications. We also required that to be IMF data, taken from the OMNIWeb and thus propagated to the bow shock nose (King & Papitashvili, 2005), for at least 120 out of 130 min prior to each flow to ensure that our IMF $B_y$ averages (mean-averaged over the 130 min prior to each flow detection, to be used in the statistical
study) were reliable. We further imposed that the preceding 130-min mean-averaged IMF $B_z$ for each flow detection had to have a coefficient of variation magnitude (absolute value of the ratio of standard deviation to mean) of less than 2. This was to ensure that only detections that occurred when the preceding IMF $B_z$ conditions were somewhat steady were included. On occasion, detections were observed simultaneously by two spacecraft (e.g., by C1 and C3, or by THEMIS B and C). If the observations were associated with the same signs of $V_{GSM}^z$, $B_z$ and $v_{Lz}$ (key parameters related to the untwisting hypothesis), and the spacecraft were $<3$ RE apart in the $Y_{GSM}$-$Z_{GSM}$ plane (the typical spatial extent of fast flows, e.g., Frühauff & Glassmeier, 2016; Nakamura et al., 2004), then we included just one of the detections (chosen arbitrarily) to avoid the possibility of “double counting”; otherwise, we included them separately.

Our final consideration was in relation to the “asymmetry” of the observed flow. We argue that a single-point observation of flow only explicitly demonstrates an asymmetry if it is directed toward midnight, for example, duskward in the post-midnight sector or dawnward in the pre-midnight sector. Since the untwisting hypothesis requires flow asymmetry, we thus only include such flows in our study. After imposing such considerations, the total number of flow detections used in this study was reduced to 1639.

We note that, in the subsequent analyses, we treat each 1-min fast flow detection as being “unique” in a similar way to Frühauff and Glassmeier (2016), despite them often occurring in succession (i.e., as part of a longer period of enhanced flow activity, see e.g., Angelopoulos et al., 1992). This choice is addressed in our discussion in Section 4.

3. Observations and Results

3.1. Example Event

To better convey the motivation for the statistical study to follow, in Figure 1 we present an example event consisting of magnetotail plasma sheet observations made by the C3 spacecraft on 20 August 2003 from 05:05 to 05:30 UT when C3 was located at ($X_{GSM} \approx -18.0$, $Y_{GSM} \approx -5.0$, $Z_{GSM} \approx 1.2$) RE. The concurrent IMF conditions (Figure 1a) show that since $\sim03:25$ UT, the IMF $B_z$ had been positive and IMF $B_x$ had been mostly negative, apart from a few small and short-lived positive excursions at for example, 04:25 UT, 04:45 UT. The interval of C3 data (Figure 1b, presented and described below at high resolution (green), but also shown at 1-min resolution (red) for completeness) shows a series of bursty earthward convective flows (solid lines in panel v). During this time, in which C3 remained mostly in the northern hemisphere ($B_y > 0$, panel i) and observed $B_z > 0$ (panel ii), the flow had a predominantly dawnward $v_{Lz}$ component (solid lines in panel vi). Between 05:08–05:09 UT (gray shaded region), however, a fast earthward and short-lived duskward flow burst ($v_{Lz} \approx 600$ km s$^{-1}$, $v_{Lx} \approx 400$ km s$^{-1}$) was observed in conjunction with a reversal in $B_x$ and a large (more than 20 nT) dipolarization [increase in $B_z$ (panel iii) and magnetic field elevation angle, $\theta = \tan^{-1}\left(\frac{B_z}{\sqrt{B_x^2+B_y^2}}\right)$ (panel iv)]. This observed flow also had a significant southward convective component ($v_{Lz} \approx -400$ km s$^{-1}$, panel vii). Concurrent with the fast flow was a small (and short-lived) decrease in the plasma $\beta$ (panel ix) to below 0.5, although we note that $\beta$ was above 0.5 immediately prior to, and after, the flow. This indicates that, rather than leaving the plasma sheet, the spacecraft encountered a transient change in the plasma sheet parameters. Such changes in $\beta$ in association with the flow and dipolarization are not an uncommon signature of a bursty flow passage over/through an observing spacecraft (see e.g., Ohtani et al., 2004; Walsh et al., 2009), in association with stronger magnetic pressure (solid lines in panel viii) and a reduced plasma pressure (dotted lines in panel viii).

Based on the concurrent and prolonged ($\sim$1 hr 40 min) IMF $B_x > 0$ conditions prior to 05:05 UT and the post-midnight NH location of Cluster, the observed (asymmetric) duskward flow burst between 05:08–05:09 UT is inconsistent with the untwisting hypothesis (Pitkänen et al., 2013). However, this flow burst appeared to be a transient feature amongst a “background” of mostly dawnward flow with the latter being consistent with the untwisting hypothesis. Owing to the post-midnight location of Cluster, however, it is possible that this dawnward flow might be associated with the dawn convection cell, and thus simply be part of the symmetric flow expected in that region (e.g., Kissinger et al., 2012). The ramifications of this are that we cannot argue that this dawnward background flow is conclusive evidence for the expected IMF $B_y > 0$ asymmetry, but it is certainly consistent with that, and quite clearly distinct from the duskward flow burst at 05:09 UT. This issue is discussed further.
in Section 4. In the following sections, we statistically examine whether isolated dusk-dawn flow bursts which disagree with the untwisting hypothesis, such as the one presented in Figure 1b, typically occur within a “background” of dusk-dawn flow that does not display the same disagreement with IMF $B_y$. We also investigate factors

Figure 1. (a) Time series data for IMF $B_x$ (blue) and IMF $B_y$ (red), from 01:00–06:30 UT on 20 August 2003. The vertical dashed lines indicate the start (05:05 UT) and end (05:30 UT) of the interval of C3 data, below. (b) The in-situ C3 spacecraft measurements, presented in high resolution (green) and 1-min resolution (red). Shown first is the local magnetic field data, (i) $B_x$, (ii) $B_y$, (iii) $B_z$ and (iv) $\theta$ (elevation angle), followed by the bulk ion velocity data, (v) $v_x$, (vi) $v_y$, and (vii) $v_z$ (dotted lines). The field-perpendicular component of the ion flow (indicative of the $E \times B$ convection) is shown in panels (v) to (vii) by the solid lines. The magnetic ($\mu_0 B^2 / 2$) and thermal ion ($nkT$) pressures are shown by the solid and dotted lines respectively, in panel (viii). Here, $\mu_0$ is the vacuum permeability constant, $n$ is the number density, $k$ is Boltzmann’s constant, and $T$ is temperature. Finally, the ion plasma beta, $\beta$, is shown in panel (ix). The horizontal dashed line marks $\beta = 0.5$. The gray shaded region marks a time of interest (discussed in text).
that might explain why such flows appear to disagree with the untwisting hypothesis (i.e., overriding or preventing IMF $B_y$ control).

### 3.2. Statistical Overview

In this section, we provide a statistical overview our 1,639 asymmetric fast flow detections. To recap, a flow detection is defined as “asymmetric” only if it is directed toward midnight, that is, duskward in the post-midnight sector, or dawnward in the pre-midnight sector. We first split our flow detections into “agree” (AG), and “disagree” (DAG) categories. AG flows (1,157 detections) are flows which exhibit the expected dusk-dawn asymmetry, that is, flows which are dawnward (duskward) in the NH (SH) for IMF $B_y > 0$, or duskward (dawnward) in the NH (SH) for IMF $B_y < 0$, where IMF $B_y$ is mean-averaged over 130 min prior to each flow detection, in common with the method of Pitkänen et al. (2013). By contrast, DAG flows (482 detections) are flows which do not exhibit the expected dusk-dawn asymmetry, that is, flows which are duskward (dawnward) in the NH (SH) for IMF $B_y > 0$, or dawnward (duskward) in the NH (SH) for IMF $B_y < 0$. With our flow detections divided into these two categories, we then examine the distributions of a number of key parameters associated with our detections. These are listed and described as follows:

1. $|IMF B_y|$, the magnitude of the 130-min mean-averaged IMF $B_y$ prior to each flow.
2. $|B_{\text{z,pen}}|$, the “penetrated $B_z$,” Here, we have removed the effects of magnetotail flaring (Fairfield, 1979) and dipole tilt (Petrukovich, 2011) from the local (observed) $B_z$, using the TA15 model (Tsyganenko & Andreeva, 2015).

   We parameterized TA15 with a zero IMF $B_z$, and 130-min mean-averaged solar wind dynamic pressure and IMF $B_y$, to obtain modeled “zero penetration” $B_z$ values at the time and location of each flow detection. These have then been subtracted from the local $B_z$ values to acquire $B_{\text{z,pen}}$, that is: $B_{\text{z,pen}} = Local \ B_z - Model \ B_z$.
3. $|B_y|$ to provide a proxy for how close to the neutral sheet ($B_y = 0$) the flows occur.
4. $\theta$, the magnetic field elevation angle, to provide a further indication of the relative location of the fast earthward flows with respect to the neutral sheet as well as any dipolarization of the magnetic field.
5. $v_{\text{LY}}$, the convective dusk-dawn flow velocity. As a simplification, we “map” our SH flows into the NH by multiplying any SH $v_{\text{LY}}$ values by a factor of $-1$. We therefore discuss all our results from the perspective of the NH.

In Figure 2, we show histograms of the above parameters for our two separate AG and DAG populations. In panels (a)–(d), the histograms have been normalized to better indicate the relative variability within each category. The histogram in panel (e) shows number of detections, indicating the number of flows in each category.

Figure 2 reveals a number of interesting features when comparing the AG and DAG flow populations. Figures 2a and 2b suggest that more AG (DAG) flows occur when $|IMF B_y|$ and, in turn, our inference for the penetrated field, $|B_{\text{z,pen}}|$, is stronger (weaker). This is indicated by the larger (smaller) mean values of $|IMF B_y|$ and $|B_{\text{z,pen}}|$ for AG (DAG) flows. We also note that almost 35% of DAG flows were observed when $|B_{\text{y,pen}}| < 1 \text{ nT}$, compared with around 16% of AG flows. For the DAG flows, the distribution of $|B_{\text{y,pen}}|$ begin to “tail off” sharply, such that at $|B_{\text{y,pen}}| > 2 \text{ nT}$, there is always a greater proportion of AG flows.

Figure 2c suggests that a greater proportion of AG (DAG) flows were observed when $|B_y|$ was larger (smaller), indicating lesser (greater) proximity to the neutral sheet ($B_y \approx 0$). Similar to $|B_{\text{z,pen}}|$, almost 35% of DAG flows occurred when $|B_y| < 1 \text{ nT}$, compared with just 17% of AG flows.

Figure 2d reveals a clear tendency for AG flows to be observed when $\theta$ is smaller, centered on $\sim 20^\circ$, whereas DAG flows tend to be observed when $\theta$ is larger, centered on $\sim 60^\circ$; collectively, forming an almost bimodal distribution.

Finally, Figure 2e reveals a clear tendency for flows to exhibit a dusk-dawn direction which is consistent with the preceding IMF $B_y$ conditions – in almost every $v_{\text{LY}}$ “bin” there are more AG flows than DAG. In total, for IMF $B_y > 0$, there are 561 (223) AG (DAG) flows, and thus 71.6% exhibit the expected dusk-dawn direction. For IMF $B_y < 0$, these values are 596 (259) and hence 69.7%, respectively. Comparison of our results to a random binomial distribution, for which exactly 50% of events had the expected and unexpected dusk-dawn direction, yields differences in expected values of 12.1σ and 11.5σ for IMF $B_y > 0$ and IMF $B_y < 0$, respectively. These values, being equal to several times the standard deviation, imply that such a result is unlikely to occur by chance. To obtain
these results we followed the method outlined in Pitkänen et al. (2013), and we note that whilst our percentages are consistent with their results, they are more statistically significant (they found $\sim 4.9 \sigma$ and $\sim 3.8 \sigma$ for IMF $B_y > 0$ and IMF $B_y < 0$, respectively). Lastly, we also note that the mean $|v_{y,\perp}|$ is noticeably larger (smaller) for AG (DAG) flows; these values are 205.3 km s$^{-1}$ (157.3 km s$^{-1}$) for IMF $B_y > 0$ and 186.8 km s$^{-1}$ (146.6 km s$^{-1}$) for IMF $B_y < 0$.

Overall, the histograms shown in Figure 2 indicate a high degree of variability and overlap between the AG and DAG flow distributions. However, these histograms also reveal intrinsic differences between the populations of AG and DAG flows. This overview is, however, only shown with respect to the time of the fast flow detection itself. It does not take into account the possibility that variations in these parameters both prior to and following a flow detection might be significant in explaining the differences between AG and DAG flows. We address this issue in the following section.

Figure 2. Histograms of AG flows (red) and DAG flows (blue) for various parameters (normalized in panels a–d): (a) $|\text{IMF } B_y|$, (b) $|B_{y,\text{pen}}|$ (penetrated $B_y$), (c) $|B_x|$, (d) $\theta$ (magnetic field elevation angle), and (e) $v_{y,\perp}$ (the convective dusk-dawn flow velocity). In total, there are 1,157 AG flows, and 482 DAG flows. The vertical dashed lines in each panel indicate the mean data values.
3.3. Superposed Epoch Analysis

To better understand the time-variable nature of the above parameters, here we subject them to a superposed epoch analysis (SEA). SEA, used previously by Frühauff and Glassmeier (2016) and Case et al. (2020) in studies of magnetotail flows, allows us to examine how the mean-averaged (superposed) time series our parameters vary relative to “Epoch 0,” defined here as being the fast flow detection time. We examine the time frame of $A_A \pm 20\text{ min}$ about each fast flow detection. Rather than just split our flows by AG and DAG, here we also split by sign of IMF $B_y$, resulting in four categories; this is to allow us to inspect the sign of IMF $B_y$, $B_{y,\text{pen}}$ and $A_A \perp y$, and not just their magnitudes. As before, we note that these categories are defined based on the flow at, and 130-min averaged IMF $B_y$ conditions relative to, Epoch 0. As discussed previously, our SH flow data is mapped into the NH by multiplying any SH $v_{s \perp}$ values by $-1$ before taking the superposed average. Additionally, we only include flow data from the respective time series of a flow detection where the observing spacecraft was located in the same magnetic hemisphere as it was at Epoch 0. This is done to avoid any difficulties in interpretation where a spacecraft has switched hemispheres during a single “event” ($\pm 20\text{ min}$ period). We also only include $A_A \perp y$ flow data in the superposed average at a given epoch time if the concurrent $v_{s \perp}$ was positive (earthward). This is due to expecting the dusk-dawn sense of the flow to reverse if the earthward-tailward sense does too (see Figures 2 and 3 of Pitkänen et al., 2019). The results of this analysis are shown in Figure 3.

In each panel of Figure 3, four curves are shown, one for each of the four categories. In panel (a) at each epoch time is the superposed (mean) IMF $B_y$ values for each category. It is noticeable that $|\text{IMF } B_y|$ is $\sim 1\text{ nT}$ larger for
AG flows than DAG flows, and that there is only subtle variation in each curve. In panel (b) we show the superposed time series of \( B_{x,\text{pen}} \). In all categories, at times well away from Epoch 0 the sign of \( B_{x,\text{pen}} \) is clearly in agreement with the average prevailing IMF \( B_z \) conditions. We note that \( |B_{x,\text{pen}}| \) is larger for AG than DAG flows, which may be as a consequence of the greater \( |\text{IMF} B_z| \) (i.e., indicating more substantial penetration on average). At Epoch 0 on the other hand, there is a clear difference between the AG and DAG flows. For the AG flows, \( |B_{x,\text{pen}}| \) increases by the order of 1 nT, in the same sign as the prevailing IMF \( B_z \) conditions. The DAG flows, however, show a change of the order of 1 nT opposite to that of the prevailing IMF \( B_z \) conditions, such the average \( B_{x,\text{pen}} \) is close to zero in these cases.

In panel (c), we show the superposed epoch of \( |B_y| \). In all categories, \( |B_y| \) begins at larger values and slowly decreases, minimizing at Epoch 0 before decreasing slightly and leveling off at values generally larger than they were several minutes prior Epoch 0. For the AG flows, the increase in \( \theta \) prior to Epoch 0 is much steadier than the DAG flows, and \( \theta \) peaks at less than 30°. Conversely, for the DAG flows, the superposed \( \theta \) is more variable, and has larger peaks of close to 50°.

Finally, in panel (e), we show a superposed epoch of \( v_{z,y} \). In all categories, it can be seen that at Epoch ~20 min, \( v_{z,y} \) has a low magnitude of <50 km s⁻¹, in all cases in the “agree” direction, and remains at similar levels until ~6 min. For the AG flows \( v_{z,y} \) then increases in magnitude, reaching at Epoch 0 before decreasing toward ~+6 min, then leveling off toward Epoch +20 min; the direction of the average \( v_{z,y} \) never changes sign. Conversely, for the DAG flows, at Epoch ~6 min, \( v_{z,y} \) decreases in magnitude with \( v_{z,y} \), changing sign at Epoch ~−3 min, peaking at Epoch 0. \( v_{z,y} \) then decreases in magnitude, changing sign again at Epoch ~+3 min, and again leveling off toward Epoch +20 min. For the DAG flows, and contrary to the AG flows, the average direction of \( v_{z,y} \) at times away from Epoch 0 (beyond epoch time ±3 min), which we refer to as the “background” flow, is in the opposite direction to the flow at Epoch 0.

Overall, the results presented in Figure 3 reveal clear differences (on average) between convective fast flows which do and do not exhibit the expected dusk-dawn asymmetry when examined on a temporal scale of ±20 min. We discuss the implications of this in the following section.

4. Discussion

The idea that the dusk-dawn direction of magnetotail convection should be controlled by the penetration of the IMF \( B_z \) component is well-established (e.g., Grocott et al., 2007; Pitkänen et al., 2015) and the results presented above are consistent with previous studies (e.g., Pitkänen et al., 2013), suggesting this to be the case about 70% of the time. However, it is worth noting that 70% is not indicative of a strong correlation with IMF \( B_z \); if completely uncorrelated we would still expect the flow direction to agree with the IMF \( B_z \) direction 50% of the time, purely by chance. A more interesting question thus concerns what is responsible for the significant fraction of so-called “disagree flows”? We have attempted to address some of the possibilities in this paper.

The event study presented in Section 3.1 illustrated observations of a duskward flow burst in the NH post-midnight sector (\( Y_{\text{GSM}} \approx \sim5.0 R_E \), that occurred during an interval where IMF \( B_y > 0 \). Based on the categorizations for our SEA, this event would be classified as an “\( \text{IMF} B_y > 0 \), DAG” flow. Indeed, the features observed in that event are somewhat manifested in the statistical results presented in Figure 3; the isolated duskward flow burst in a period of mostly dawnward “background” flow, significant dipolarization, and a sharp reversal in \( B_y \) (opposite to the prevailing IMF \( B_y > 0 \)) at the time of the duskward flow. This suggests that the observed duskward flow burst was associated with transient dynamics that were potentially overriding the expected IMF \( B_y \) control. We consider this further in the discussion below.

Pitkänen et al. (2013) suggested that fast flows with an unexpected dusk-dawn sense could be attributed to a misidentification of the sense of IMF \( B_y \) penetration. As noted in Section 1, there exists some ambiguity regarding the time uncertainty for IMF \( B_y \) to penetrate into the magnetotail, and so they attempted to remove this ambiguity by demanding that the local tail \( B_y \) have the same sense as IMF \( B_y \). However, this does not account for the effects that magnetotail flaring and dipole tilt have on \( B_y \) in the magnetotail, which are dependent on location and can be
stronger than the penetrated $B_y$ effect (Petrukovich, 2011; see Figure 5 of Lane et al., 2021). It is likely that this choice artificially increased the percentage of flows exhibiting the expected dusk-dawn asymmetry. For example, in the northern hemisphere the flaring effect produces a negative $B_y$ in the pre-midnight sector such that even in the presence of a positive IMF $B_y$ penetration, the criterion of Pitkänen et al. (2013) might result in the erroneous exclusion of an event observed at a pre-midnight location. Given that statistically, pre-midnight events are more likely to be duskward than dawnward (e.g., Kissinger et al., 2012), then the same criteria would be more likely to exclude duskward northern hemisphere flows which are, by definition, classified as “disagree” for positive IMF $B_y$ and hence, by the same reasoning, favor flows classified as “agree.”

To avoid the possibility of such bias in our statistical analysis we have not filtered by tail $B_y$ but instead inspected the behavior of $B_y$ at and around the time of the fast flows. We attempted to exclude factors unrelated to IMF $B_y$ penetration by consideration of the warping and flaring effects (as discussed in Section 3.2). We also avoided inclusion of any flows which might be classified as “symmetric” following the work of Kissinger et al. (2012) by considering only flows which can be explicitly identified as “asymmetric,” as discussed in Section 2. Our results appear to refute the idea that an unexpected sense of IMF $B_y$ penetration could result in the unexpected dusk-dawn sense of the fast flows, at least on a statistical scale. The data presented in Figures 3a and 3b clearly indicate that, in-fact, the expected IMF $B_y$ component had (on average) penetrated into the magnetotail and remained steady throughout the 40 min regardless of whether the flow burst at Epoch 0 had the expected dusk-dawn direction (AG) or not (DAG). This suggests that it is not necessarily appropriate to attribute a transient flow with the unexpected sense of $v_{1y}$ to a “lack” of IMF $B_y$ penetration. It may be the case, however, that the penetration of a weaker IMF $B_y$ component might be insufficient to direct such dusk-dawn flows. This was suggested by Pitkänen et al. (2013) and we provide supporting evidence for this, as IMF $B_y$ was at least 1 nT larger for AG flows than DAG flows, reflected in the stronger (weaker) $B_{y,pen}$ values for AG (DAG) flows seen in Figures 2 and 3.

As a further matter, only close to Epoch 0 did $B_{y,pen}$ exhibit any significant change, strengthening in the AG categories whilst becoming notably weaker (and possibly changing sign) in the DAG categories. This change was therefore in the same sign as (opposite to) the prevailing IMF $B_y$ conditions for AG (DAG) flows. We note that due to the stability of the model $B_y$ values with minute-scale changes in spacecraft position and our 130-min averaged model parameterizations, the changes in $B_{y,pen}$ at Epoch 0 can only be explained by transient dynamics (i.e., sudden changes in the local $B_y$), and are thus not a true reflection of the “penetrated $B_y$” in this instance. The argument that this could be an effect of “sudden” IMF $B_y$ penetration, rather than a transient change, can be refuted on the basis that $B_{y,pen}$ returns to similar levels a few minutes after Epoch 0. Of course, the role of IMF $B_y$ is to introduce a $B_y$ perturbation (i.e., “twist”) into the magnetotail (e.g., Petrukovich, 2011). The subsequent Dungey cycle return flows are expected to remove this twist, implying that the flows are IMF $B_y$-controlled (e.g., Grocott et al., 2007; Pitkänen et al., 2013, 2015). However, our analysis implies that even if there was clear IMF $B_y > 0$ penetration, for example, but at Epoch 0 a transient change in the local $B_y$ component (unrelated to any IMF $B_y$-effect), then this may be what the coincident convective flow would be associated with; that is, localized, transient dynamics potentially “overriding” (or preventing) the expected IMF $B_y$ control. Determining the origins of the perturbations in $B_y$ is beyond the scope of the current study, but previous work has shown that transitory $B_y$ (and concurrent dusk-dawn flow) dynamics could be related to activity associated with current sheet flapping (Lane et al., 2021; Volwerk et al., 2008), flow vortices (Keika et al., 2009; Pitkänen et al., 2011), or bursty bulk flows and associated magnetic field dipolarizations (e.g., Walsh et al., 2009).

The SEA of $|B_y|$ shown in Figure 3c revealed a minimum in all categories at Epoch 0, regardless of whether a flow was AG or DAG. This is itself an unsurprising result as closer to the neutral sheet one would expect $v_{1x}$ and $β$ (which part-define our fast flows) to be larger (Baumjohann et al., 1989). However, Figure 3c also revealed that DAG flows have a tendency to be observed at smaller $|B_y|$, and therefore closer to the neutral sheet than AG flows. Inspection of the distributions of the calculated $β$ for the AG and DAG flows (not shown) also revealed that DAG flows tended to be associated with larger values of $β$ (at Epoch 0: median $β$ ~ 6, mean $β$ ~ 26) than AG flows (at Epoch 0: median $β$ ~ 3, mean $β$ ~ 13). This suggests, tentatively, that DAG flows are more strongly governing the dynamics of the field (higher $β$) than the AG flows, that is, that they may be “overriding” the large-scale nature of the magnetic field, whereas AG flows are more likely to be driven by the large-scale untwisting of the field itself (lower $β$). A further complication arises from the fact that the neutral sheet is a highly dynamic region, where phenomena such as “flapping” may be able to influence dusk-dawn flow (e.g., Lane et al., 2021;
Volwerk et al., 2008). Perhaps, therefore, a number of DAG flows are being observed during such intervals where the observing spacecraft may be crossing the neutral sheet. The extent to which this is true will be examined in a further study.

The argument that localized dynamics may override or prevent any IMF $B_y$ control is reinforced further by considering the data presented in Figure 3d. This shows that in all cases, the magnetic field elevation angle appeared to remain at higher levels following Epoch 0 than before, likely indicating a local dipolarization of the magnetic field, occurring as the magnetic field turns from being strongly parallel, to perpendicular with the neutral sheet (Schmid et al., 2011) (i.e., becoming more “vertical”). This peak in $\theta$ is therefore consistent with the minima in $|B_y|$ (see Figure 3 of Ohtani et al., 2004). However, DAG flows had a ~20 ° larger superposed $\theta$ than AG flows. We suggest that this is related to the high proportion of small (large) $\theta$ detections in the AG (DAG) categories (Figure 2d), indicating weaker (stronger) dipolarization. This result therefore indicates that weaker dipolarization may be more commonly associated with the AG flows, and stronger dipolarization is more closely associated with the DAG flows. Of course, it is well known that dipolarizations are expected to occur in conjunction with episodes of transient magnetotail dynamics, and the earthward propagation of bursty flows (e.g., Nakamura et al., 2005; Sergeev et al., 1996), which are attributed to localized reconnection (e.g., Chen & Wolf, 1993; Sergeev et al., 1992). These flows are known to exhibit variable dusk-dawn components (e.g., Sergeev et al., 1996) and have a dusk-dawn influence on the ambient plasma (e.g., Liu et al., 2013). One possibility, therefore, is that DAG flows are more likely to be associated with more enhanced transitory dynamics, and coincident dipolarization, where any expected IMF $B_y$ control is being suppressed (e.g., Reistad et al., 2018), possibly occurring within a background of the larger-scale Dungey cycle convection.

It is also apparent from the SEA in Figure 3e that the direction of the “background” flow (flow away from Epoch 0) appears to be, on average, consistent with the expected IMF $B_y$ penetration in all flow categories. This is in agreement with the results of Pitkänen et al. (2019), whose study of the average patterns of “slower” flows ($v_{\perp y} < 200$ km s$^{-1}$) suggested that the flows exhibited a dominant dusk-dawn direction which was in accordance with IMF $B_y$. We have shown that this trend holds, irrespective of whether the fast flow at Epoch 0 has the expected dusk-dawn direction or not. For example, if one considers the blue curve (IMF $B_y > 0$, DAG) in Figure 3e, then at Epoch 0, the flow is duskward (by definition). However, once beyond ±3 min away from Epoch 0, this flow has reversed to be weakly downward such that this “background” flow now seems to agree with the expected dusk-dawn direction. A similar effect is observed in the case of IMF $B_y < 0$, DAG flows.

In addition, we note from Figure 3e that the changes in $v_{\perp y}$ toward in Epoch 0 are in-fact relatively steady and prolonged, beginning as early as Epoch ±6 min. Inherently, one might question why a transient 1-min flow detection would show superposed average signatures of variability over such a timeframe. As we noted in Section 2, however, it is not uncommon for 1-min timescale flows to be observed successively, as part of an extended period of bursty bulk flow activity (Angelopoulos et al., 1992). Consequently, the time-series of a number of our flow detections often overlap. The result of taking a superposed average of these overlapping epochs would then be to introduce a “smoothing” effect, reducing the sharpness of the transitions. To test this, we repeated our analysis using only “isolated” flow detections, whereby no other detections were observed in a given ±10-min timeframe centered on each detection. Imposing such a constraint on our fast flow dataset reduced the total number of asymmetric flow detections to just 165; around 1/10th of the original number (1639), indicating the scarcity of isolated detections. For IMF $B_y > 0$, there were now 63 (29) AG (DAG) flows, and thus 68.4% exhibit the expected dusk-dawn direction. For IMF $B_y < 0$, these values were 55 (18) and hence 75.3%, respectively. Despite the reduction in numbers, these percentages are similar to those given in Section 3.2 for the original analysis. Furthermore, whilst now being less smooth in general and exhibiting the expected much sharper transition about Epoch 0, the overall trends in the superposed epoch analysis remained the same, such that there is no significant impact on our conclusions. The results of this analysis are shown in Figure S1 in Supporting Information S1.

Finally, as noted in Section 3.1, the constraint on the flow at Epoch 0 being asymmetric does limit the extent to which we can make inferences about asymmetry in the DAG background flows. In the case of any AG background flows, these are on average in the same sense as the fast flow at Epoch 0. This implies that there is strong evidence for the expected IMF $B_y$-driven asymmetry being present in the “background” flow pattern. The DAG background flows on the other hand are on average in the opposite direction to the fast flow at Epoch 0. The asymmetry constraint thus implies that the average DAG background flow must be “symmetric” (i.e., duskward in the pre-midnight sector, or dawnward in the post-midnight sector). In other words, such a flow does not explicitly
demonstrate the presence of the expected IMF $B_x$-asymmetry, even though it is consistent with it. What we can be certain of, however, is that there is less disagreement than at Epoch 0, that is, if an asymmetry inconsistent with IMF $B_y$ was present in the large-scale convection, then its presence must be reduced in the background flow; otherwise we would not see the dusk-dawn sense of the flow reverse. Thus, there is a measurable transient effect on the flow at the time of the DAG fast flows that is distinct from the AG case.

5. Summary

In this study, we have statistically analyzed 27 years of plasma and magnetic field data from Cluster, THEMIS and Geotail to further probe the known link between IMF $B_y$ and the dusk-dawn sense of the convection. From this data, we identified 1,639 magnetotail fast flow “detections” that explicitly demonstrated a dusk-dawn asymmetry. The results presented suggest that fast flows tend to exhibit a dusk-dawn direction which is consistent with the penetration of IMF $B_y$ around 70% (1,157 out of 1,639 detections) of the time (“Agree” flows), leaving ∼30% (482 out of 1,639 detections) of flows which do not (“Disagree” flows). We performed a superposed epoch analysis to better understand the differences between the two populations of flows. We summarize the key results from our investigation below:

1. The expected sense of IMF $B_y$ penetration is associated with both Agree and Disagree flows, although IMF $B_y$ and the penetrated $B_\parallel$ tend to be stronger for Agree flows.

2. Agree (Disagree) flows tend to be accompanied by a localized perturbation to the $B_\parallel$ component of the magnetotail magnetic field in the same sign as (opposite to) the prevailing IMF $B_y$ conditions, which temporarily enhances (overrides) the penetrated field.

3. Agree (Disagree) flows tend to be observed at larger (smaller) $B_\parallel$, suggesting that they occur further away from (closer to) the neutral sheet ($B_\parallel = 0$). They also occur in association with weaker (stronger) magnetic field dipolarization (enhancement in magnetic field elevation angle).

4. The average dusk-dawn direction of the slower “background” convection is consistent with the expected IMF $B_y$ penetration, irrespective of whether the fast flow itself is Agree or Disagree.

Our results overall suggest that a likely explanation for the ∼30% disagreement may be in relation to transient, localized dynamics overriding or preventing IMF $B_y$ control of fast flows, particularly when IMF $B_y$ is weaker. This is reinforced by the fact that the average dusk-dawn sense of the slower, “background” flow, occurring when conditions in the magnetotail are likely to be less perturbed, is not in disagreement with IMF $B_y$. These transient dynamics may be associated with phenomena such as current sheet flapping, dipolarization, and transitory changes in the local $B_\parallel$ component. The extent to which these phenomena influence dusk-dawn convection and suppress IMF $B_y$ control of the flows must be interrogated further in future studies.

Data Availability Statement

The Cluster data used in this study were obtained from the Cluster Science Archive (https://www.cosmos.esa.int/web/csa). The THEMIS data used in this study were obtained through the Space Science Laboratory at University of California, Berkeley (http://themis.ssl.berkeley.edu/data_products). The Geotail data used in this study were obtained from NASA’s Space Physics Data Facility (https://spdf.gsfc.nasa.gov/pub/data/). The Geotail daily $B_y$ offset values were provided by The Data Archive and Transmission System (https://darts.isas.jaxa.jp/stp/geotail/bzoffset.html). The solar wind and IMF data used in this study were provided by the OMNIWeb (https://omniweb.gsfc.nasa.gov).

References

Angelopoulos, V., Baumjohann, W., Kennel, C. F., Coroniti, F. V., Kivelson, M. G., Pellat, R., et al. (1992). Bursty bulk flows in the inner central plasma sheet. Journal of Geophysical Research, 97(A4), 4027–4039. https://doi.org/10.1029/91JA02701

Auster, H. U., Glassmeier, K. H., Magnes, O., Aydoger, O., Baumjohann, W., Constantinescu, D., et al. (2008). The THEMIS fluxgate magnetometer. Space Science Reviews, 141, 235–264. https://doi.org/10.1007/s11214–008–9365–9

Balogh, A., Carr, C. M., Acuña, M. H., Dunlop, M. W., Beek, T. J., Brown, P., et al. (2001). The Cluster magnetic field investigation: Overview of in-flight performance and initial results. Annales Geophysicae, 19, 1207–1217. https://doi.org/10.5194/angeo-19-1207-2001

Baumjohann, W., Paschmann, G., & Cattell, C. A. (1989). Average plasma properties in the central plasma sheet. Journal of Geophysical Research, 94(A6), 6597–6606. https://doi.org/10.1029/ja094ia06p06597
Tenfjord, P., Østgaard, N., Snekvik, K., Laundal, K. M., Reistad, J. P., Haaland, S., & Milan, S. E. (2015). How the IMF by induces a by component in the closed magnetosphere and how it leads to asymmetric currents and convection patterns in the two hemispheres. *Journal of Geophysical Research: Space Physics*, 120(11), 9368–9384. https://doi.org/10.1002/2015JA021579

Tenfjord, P., Østgaard, N., Strangeway, R., Haaland, S., Snekvik, K., Laundal, K. M., et al. (2017). Magnetospheric response and reconfiguration times following IMF by reversals. *Journal of Geophysical Research: Space Physics*, 122(1), 417–431. https://doi.org/10.1002/2016JA023018

Tsyganenko, N. A., & Andreeva, V. A. (2015). A forecasting model of the magnetosphere driven by an optimal solar wind coupling function. *Journal of Geophysical Research*, 120(10), 8401–8425. https://doi.org/10.1002/2015ja021641

Volwerk, M., Zhang, T. L., Glassmeier, K. H., Runov, A., Baumjohann, W., Balogh, A., et al. (2008). Study of Waves in the magnetotail region with cluster and DSP. *Advances in Space Research*, 41(10), 1593–1597. https://doi.org/10.1016/j.asr.2007.04.005

Walsh, A. P., Fazakerley, A. N., Lahiff, A. D., Volwerk, M., Grocott, A., Dunlop, M. W., et al. (2009). Cluster and Double Star multipoint observations of a plasma bubble. *Annales Geophysicae*, 27, 725–743. https://doi.org/10.5194/angeo-27-725-2009