IMF dependence of the azimuthal direction of earthward magnetotail fast flows

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[1] Cluster magnetotail data together with ACE solar wind data from 2001 to 2009 are used to investigate the dependence of the azimuthal flow direction of earthward magnetotail fast flows on the interplanetary magnetic field (IMF). We find an indication that fast flows have favored azimuthal directions that have dependence on the IMF. Our results suggest that for positive IMF B_y, the favored azimuthal direction of the fast flows is dawnward in the northern plasma sheet and duskward in the southern plasma sheet. For negative IMF B_y, an opposite situation takes place, the favored azimuthal flow directions are then duskward and dawnward in the northern and southern plasma sheet, respectively. As a possible explanation for the results, it is suggested that the untwisting reconnected magnetic field lines may direct the fast flows in the magnetotail, the field line twist itself being dependent on the IMF. **Citation:** Pitkänen, T., M. Hamrin, P. Norqvist, T. Karlsson, and H. Nilsson (2013), IMF dependence of the azimuthal direction of earthward magnetotail fast flows, *Geophys. Res. Lett.*, *40*, 5598–5604, doi:10.1002/2013GL058136.

1. Introduction

[2] It is well established that the interplanetary magnetic field (IMF) controls the large-scale plasma convection in the magnetosphere and ionosphere [e.g., *Cowley and Lockwood*, 1992; *Ruohoniemi and Greenwald*, 2005; *Haaland et al.*, 2007]. For instance, pure southward IMF conditions lead to a convection pattern, which appears in the ionosphere as a symmetric two-cell flow pattern. Plasma is flowing from the dayside to the nightside across the polar cap and returning back to the dayside at lower latitudes roughly within the auroral oval. A nonzero IMF B_y component distorts this symmetric flow pattern. When IMF $B_y > 0$, the evening cell in the northern hemisphere is more rounded-like and the morning cell more crescent-like [see e.g., *Cowley and Lockwood*, 1992, Figure 1]. When $B_y < 0$, the opposite asymmetrical flow pattern takes place, the morning cell is then more rounded-like and the evening cell more crescent-like. The convection pattern in the southern hemisphere is generally a mirror image of the asymmetric northern hemisphere pattern.

[3] The asymmetric convection and the subsequent asymmetric addition of magnetic flux to the tail lobes also affect the magnetotail configuration. It has been shown theoretically and observed both in situ and in simulations that a nonzero IMF B_y causes the magnetotail to twist from the north-south symmetry: A B_y component in the same direction as the IMF B_y is superimposed on the tail magnetic field [*Cowley*, 1981; *Kaymaz et al.*, 1994, 1995; *Kullen and Janhunen*, 2004a, 2004b].

[4] The earthward plasma transport from the X line in the nightside magnetotail is known to be an intermittent process consisting of fast transient bulk flows in the plasma sheet, often termed as bursty bulk flows [e.g., *Angelopoulos et al.*, 1994; *Cao et al.*, 2006]. Their flow signatures have also been observed in the ionosphere [e.g., *Pitkänen et al.*, 2011]. The twisted magnetotail together with the large-scale asymmetric ionospheric convection suggest a significant azimuthal flow component for these fast flows. Indeed, fast transient azimuthal flow bursts have been observed in the ionospheric convection in the midnight sector [*Senior et al.*, 2002; *Grocott et al.*, 2003, 2004]. These observations have been limited, however, to northward IMF conditions with dominant B_y contribution. The flow bursts have been suggested to be caused by untwisting of the twisted newly reconnected magnetic field lines in the magnetotail [*Grocott et al.*, 2004].

[5] Interhemispheric observations of similar kinds of ionospheric azimuthal flow bursts support the idea that the bursts are a result of reconnection in a twisted magnetotail [*Grocott et al.*, 2005, 2007] and suggest that the untwisting of the twisted field lines further causes earthward magnetospheric fast flows with a significant azimuthal flow component. According to that hypothesis, magnetotail fast flows are preferably expected to deviate to the opposite azimuthal directions in the opposite hemispheres, i.e., on the opposite sides of the neutral sheet, consistently with the ionospheric observations. When the IMF $B_y > 0$, the preferred azimuthal magnetotail fast flow direction is expected to be dawnward in the northern plasma sheet and duskward in the southern plasma sheet. Correspondingly, when the IMF $B_y < 0$, the preferred azimuthal flow direction is expected to be duskward in the northern plasma sheet and dawnward in the southern plasma sheet. Some indications of the existence of this hemispheric asymmetry in the azimuthal components of magnetotail fast flows have been observed in a case study by *Grocott et al.* [2007] for northward, B_y dominating IMF conditions, and in a case study by *Walsh et al.* [2009] for southward, B_y dominating IMF conditions.

[6] In this study, we investigate the general dependence of the azimuthal flow direction of earthward magnetotail fast flows on the IMF. We investigate statistically whether the preferability and hemispheric asymmetry in the azimuthal

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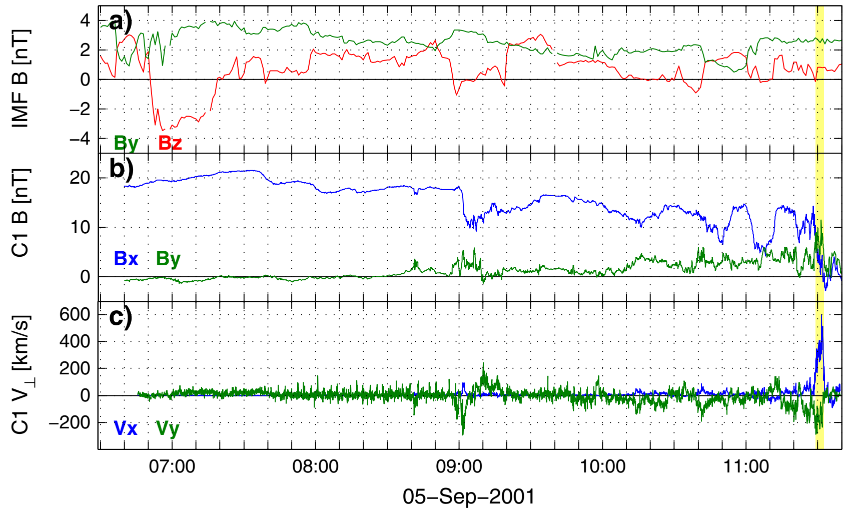

Figure 1. (a) IMF, (b) C1 B, and (c) C1 $V_\perp$ components during the 5 h period prior a fast flow event occurring at 11:29 UT on 5 September 2001. The time interval of the fast flow is marked by yellow shading.

components of the fast flows exist in the magnetosphere, as it is suggested by the previous ionospheric observations.

2. Data and Event Selection

[7] Magnetotail data for this study are provided by the Cluster satellites. In total 9 years of Cluster tail season (June-December), data from 2001 to 2009 from the Cluster 1 (C1) spacecraft are used. Data from later years (from 2010 onward) are not used due to unfavorable Cluster orbits for probing the plasma sheet. We use data from the Hot Ion Analyzer detector of the Cluster Ion spectrometry (CIS) instrument [*Rème et al.*, 2001] for particle moments and from the FluxGate Magnetometer experiment (FGM) [*Balogh et al.*, 2001] for magnetic field. For the IMF data, 1 min ACE satellite data propagated to the bow shock nose provided by the OMNI database (http://omniweb.gsfc.nasa.gov/) are used. The geocentric solar magnetic (GSM) coordinates are used throughout the study.

[8] The earthward magnetotail fast flows were identified from the bulk flow data perpendicular to the magnetic field in the region located tailward of –14 R_E in the X and limited from –7 to +7 R_E in the Y direction. The –14 R_E limit in the X direction was chosen in order to exclude the flow events contaminated by azimuthal flow diversion expected in the flow braking region closer to the Earth. The Y limits were chosen to include only the flow events occurring within the midnight sector in order to reduce the effect of flaring of the tail on the plasma sheet B_y component.

[9] To be classified as a fast flow event, the XY speed perpendicular to the magnetic field $V_{xy} = \sqrt{V_{\perp x}^2 + V_{\perp y}^2} >$ 200 km/s with simultaneous $V_{\perp x} > 0$, for at least 30 s. Single V_{xy} samples below the 200 km/s threshold in the segment are neglected. To ensure that the fast flow occurs in the plasma sheet, it is required that the median ion $\beta > 0.5$ during the fast flow event. The IMF conditions are linked to the fast flows by averaging the IMF components over a time period of 130 min prior to each fast flow event. This choice for the IMF averaging period is discussed further in section 4.

[10] In total, 194 fast flow events having simultaneous IMF data available were identified for southward IMF and 92 events for northward IMF conditions. The distributions of the events in the GSM XY plane are shown in Figure S1 in the supporting information. An example event occurring at 11:29 UT on 5 September 2001 is shown in Figure 1. At the time of the event, C1 was located at [–19.1 1.0 1.7] R_E in GSM in the premidnight sector. From Figure 1a, we note that the IMF B_y and B_z were on the average positive during a 5 h period prior to the flow event. This yields also for the 130 min averaging used. Thus, this event is classified to the IMF in Figure 2c (see section 3 below). From the C1 magnetic field data (Figure 1b), we notice that the B_y turned and stayed positive after 08:30 UT for a 3 h period prior to the fast flow event. The Cluster B_y was hence collinear with the IMF B_y for several hours before the fast flow, which is in agreement with the tail twisting hypothesis (in a nontwisting situation, the tail magnetic field in the premidnight northern hemisphere would be expected to have a negative B_y due to the flaring effect).

[11] From the C1 velocity data (Figure 1c), we see that the $V_{\perp y}$ was mostly negative during the fast flow, i.e., the flow had a dawnward component. This is consistent with what would be expected for the flows being directed by untwisting of field lines. For positive B_y-twisting scenario, flows are expected to have a dawnward component in the northern plasma sheet. Just in the end of the flow event, the $V_{\perp y}$ turned duskward in association with the B_x change from positive to negative. Although the duskward $V_{\perp y}$ was very low (< 26 km/s), we suggest that this could be a signature of the flow shear occurring across the neutral sheet, which is predicted by the twisting hypothesis. A possible manifestation of it has previously been observed by *Walsh et al.* [2009]. Fast flow-associated flow shears will be a subject for future studies.

3. Statistical Results

[12] Figure 2 presents the statistical results of the investigation. Each panel corresponds to a different set of IMF

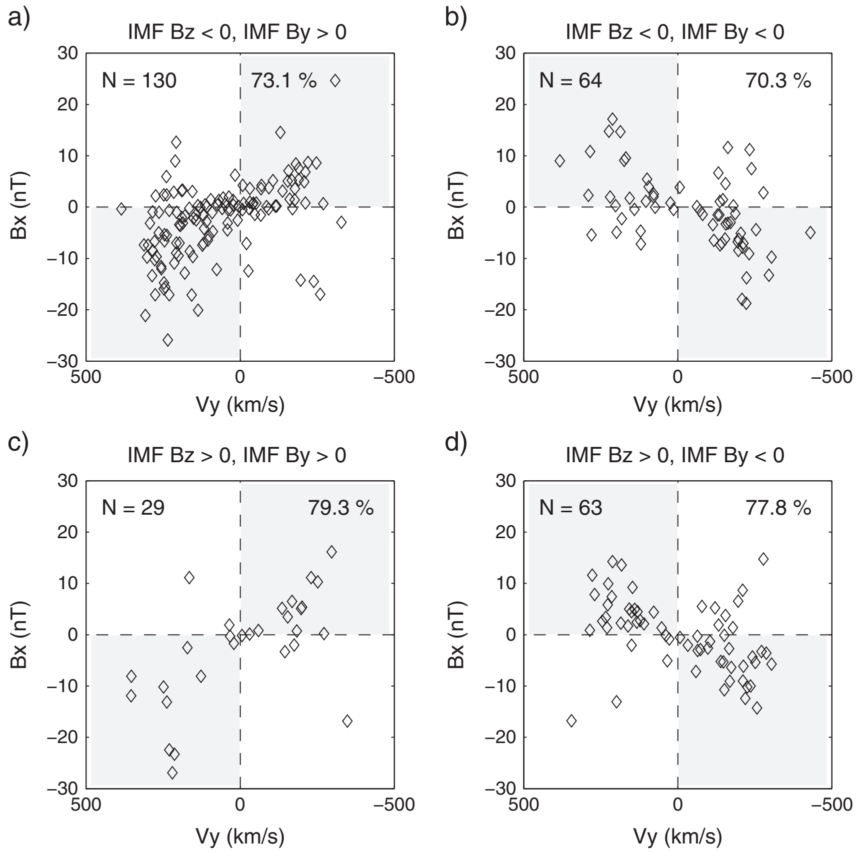

Figure 2. (a–d) Mean $V_{\perp y}$ components of the fast flows plotted versus the mean B_x components for four different IMF conditions. N indicates the number of fast flow events in each IMF category. The number in the upper right quadrant in each panel indicates the percentage of the fast flow events lying in the expected quadrants (marked by grey shading, see details in text).

conditions. Figures 2a and 2b correspond to southward IMF and Figures 2c and 2d to northward IMF. IMF B_y is positive for Figures 2a and 2c on the left and negative for Figures 2b and 2d on the right.

[13] In each panel, we have plotted the mean $V_{\perp y}$ components of the fast flows versus the mean B_x measured by Cluster during the fast flow events. The positive and negative $V_{\perp y}$ values indicate duskward and dawnward components in the flow velocity vector, respectively. Positive B_x values indicate that the C1 spacecraft traversed the magnetotail in the northern plasma sheet and negative values that C1 was in the southern plasma sheet. The situation in the figure has some analogy with a situation in which one would be looking along the GSM X axis from the tail toward the Earth. The number N tells the total amount of fast flow events in each IMF category.

[14] We notice that regardless of the IMF B_z direction, most of the data points lie in the upper right and lower left quadrants when the IMF B_y is positive (Figures 2a and 2c) and in the upper left and lower right quadrants when the IMF B_y is negative (Figures 2b and 2d). These quadrants are shaded by grey color in Figure 2, and the percentages of the fast flow events lying in these quadrants are shown in the figure in each panel to the right of the N number.

[15] This implies that most, or in numbers, 73.1% of the fast flows for southward, $B_y > 0$ IMF conditions have a dawnward azimuthal velocity component in the northern plasma sheet, and a duskward azimuthal velocity component in the southern plasma sheet (Figure 2a). Similarly, for southward, $B_y < 0$ IMF conditions, 70.3% of fast flows have the duskward and dawnward azimuthal flow components in the northern and southern plasma sheet, respectively (Figure 2b). The corresponding percentages for the northward, $B_y > 0$ and $B_y < 0$ IMF conditions, are 79.3% and 77.8%, respectively (Figures 2c and 2d).

[16] We have also investigated the instantaneous $V_{\perp y}$ at the $V_{\perp x}$ peak of the fast flow versus the mean B_x for all fast flow events of the same data set with similar results (data not shown). In that case, the corresponding percentages for the fast flows in the same order as above are 70.0% and 75.0% for southward IMF and 75.9% and 74.6% for northward IMF conditions.

[17] These results show that the earthward magnetotail fast flows have a favored azimuthal flow direction, which has dependence on the IMF conditions. Moreover, the favored azimuthal flow directions of the fast flows are exactly as would be expected from the correspondingly twisted magnetotail configuration, as was discussed in section 1. The preferred azimuthal flow directions are expected to be dawnward and duskward in the northern and southern plasma sheet, respectively, for the IMF $B_y > 0$ conditions, and vice versa for the IMF $B_y < 0$ conditions. Below, we discuss the statistical significance of our results.

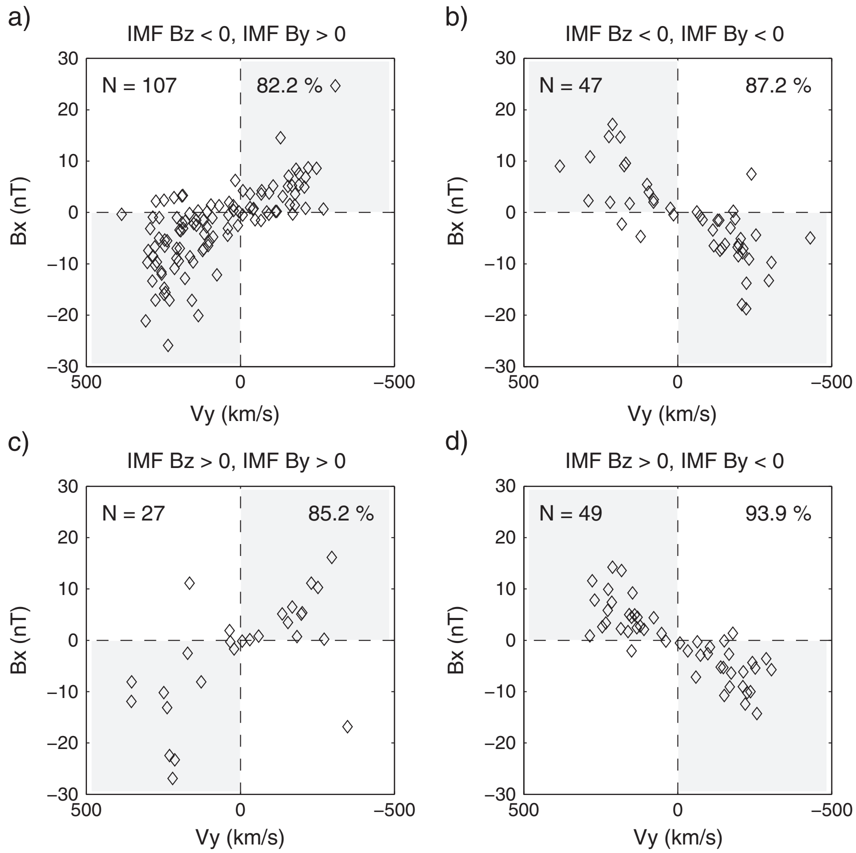

Figure 3. Same as Figure 2, but now only the fast flow events that have the mean B_y component to the same direction as the IMF B_y are included.

[18] To evaluate the statistical significance of the above results, we performed the following simple analysis. We compared our results to a situation where the fast flow events would be distributed randomly to the expected and unexpected quadrants. If the flow events would be distributed randomly, 50% would lie in the expected quadrants and the other 50% would lie in the unexpected quadrants in a particular IMF category. Hence, the expectation value m for the amount of the events lying in the expected quadrants is $N/2$, where N is the total number of the fast flow events in that IMF category. The probability of an event lying in the expected quadrants is 1/2. Thus, it yields (from the binomial distribution) that the standard deviation $\sigma = \sqrt{N}/2$. Let the true number of the flow events in the expected quadrants be x. In the analysis, we calculated the difference between the true number of the flow events in the expected quadrants and the expectation value, $x - m$, and compared this with σ. If a distribution would be purely coincidental, $x - m$ would be close to zero. It yields 5.3σ, 3.3σ, 3.2σ, and 4.4σ for Figures 2a–2d, respectively. This means that the distributions in Figure 2 are very unlikely to be purely coincidental but are truly reflecting the underlying physics.

[19] However, the results in Figure 2 also show scattering and "wings" in the unexpected quadrants, e.g., in the upper left and lower right quadrants of Figure 2a and the upper right and lower left quadrants of Figure 2b, as well as in the upper right and lower left quadrants of Figure 2d. These "wings" indicate fast flow events which have the azimuthal flow components to the opposite directions than expected for the prevailing IMF conditions.

[20] In order to investigate the possible cause for the scattering, we did the following. We compiled a new data set by excluding all those fast flow events for which the mean B_y is to the opposite direction than the IMF B_y. In other words, we included only those fast flows for which the B_y in the magnetotail is to the same direction as the IMF B_y, so that the Cluster measurement is consistent with the twisted configuration suggested by the prevailing IMF conditions. The result is shown in Figure 3.

[21] From Figure 3, we notice that the total number of fast flow events is somewhat smaller in each category compared to the original data set in Figure 2. The unexpected "wings" have now disappeared from the data, and the percentages of the fast flow events having the expected azimuthal flow component are high. From 82.2% up to 93.9% of the fast flows in each IMF category have the $V_{\perp y}$ direction as expected in the IMF-induced twisted magnetotail configuration. The differences $x - m$ are 6.7σ, 5.1σ, 3.7σ, and 6.1σ for Figures 3a–3d, respectively.

[22] On the basis of Figure 3, we suggest that one possible explanation for the scattering in the form of the "wings" in Figure 2 is due to that for these (scattered) fast flow events the magnetotail may have not yet been adjusted, at least in the region where the fast flow event is observed, and also plausibly where it is created, to the current prevailing IMF conditions. Thus, these fast flow events experience the twist

of the tail field lines that is opposite with respect to what would be expected from the corresponding IMF conditions.

[23] However, the scattering in Figure 2 could also be because during the scattered flow events there does not exist a significant twist in the magnetotail, which intuitively could be expected in a situation when the magnitude of the IMF B_y is not dominating over the magnitude of IMF B_z and when the magnitude of the IMF B_y is small. We have investigated this possibility by examining another subset of the fast flow events, which is formed by the flow events for which the IMF B_y magnitude dominates over IMF B_z magnitude. The number of flow events and the percentage of the events lying in the expected quadrants in each four IMF category for this subset are (a) N = 106, 70.8%; (b) N = 46, 71.7%; (c) N = 22, 77.3%; and (d) N = 45, 75.6% (Figure S2).

[24] By comparing the numbers with Figure 2, we notice that most of the flow events of the total data set have IMF B_y dominating conditions. We also notice that most of the scattering seen in Figure 2 is still present. Dividing this subset further to three subsubsets for which the IMF B_y magnitude is 0–3 nT, 3–6 nT, and > 6 nT reveals that the scattering is overall stronger in the first two subsubsets in which the IMF B_y is closer to zero (except 0–3 nT subsubset in Figure S3b). This suggests that the azimuthal flow component direction of the fast flows may be to some extent sensitive to the magnitude of the IMF B_y, which could be reflecting the possible twist strength dependence on the IMF B_y magnitude. So, these results suggest that for some cases with a small IMF B_y component present, even in a IMF B_y dominating situation, there may not be twisting significant enough, (or the current twist may be (possibly locally) opposite as it is already suggested above), in the tail to produce fast flow directions as would be expected in the twisting scenario.

[25] In addition to the above discussion, there exists still another possibility that may be affecting to the results and scattering. Azimuthal deviations from earthward directed flow are associated with the vortical flow patterns at the two sides of the fast flow channel [e.g., *Birn et al.*, 2004; *Pitkänen et al.*, 2013] and may be included in the velocity measurements. However, the speed constraint of V_{xy} > 200 km/s in the *XY* plane for the fast flows, we have used means that only the fastest part of the actual flow event is here considered as a flow event. Also, typically, the flows in a flow event have much higher speeds than 200 km/s, and about 80% of the flow events have the $V_{\perp x}$ component magnitude greater than the $V_{\perp y}$ magnitude, so most of the flows are directed more earthward than toward flanks. In addition, using the instantaneous $V_{\perp y}$ at the $V_{\perp x}$ peak of the fast flow instead of the mean $V_{\perp y}$ gives practically the same results (see above). Hence, although we cannot for sure completely exclude the possibility of inclusion of azimuthal flows related to the vortical motion around the fast flow proper flow channel in our data set, we argue that the effect of those flows to our results is only small.

[26] In conclusion, the correlations between the expected azimuthal flow direction and the IMF in all the IMF categories enhance significantly when all those fast flow events for which the B_y is to the opposite direction compared to the IMF B_y are excluded (Figure 3). This suggests that the azimuthal flow direction for most of the fast flows may be determined by the current twist of the magnetotail, which in some cases can be opposite than the IMF conditions would propose. In addition, the results also suggest that in some cases, predominantly for small IMF B_y magnitudes, there may not exist a twist in the magnetotail that is sufficient to direct the fast flows.

4. Discussion

[27] The association of the IMF to the fast flow events is not straightforward. Ultimately, the question is in what time scale the magnetotail adjusts to the changing IMF conditions on the dayside magnetopause and there does not exist a consensus for the answer. Different time scales have been applied when linking the IMF to nightside phenomena. For example, *Juusola et al.* [2011] used an IMF averaging over preceding 30 min + the actual duration of the flow events (from seconds to minutes) when studying plasma sheet convection statistically. *Fu et al.* [2012] used an IMF B_z averaging period from 50 min to 10 min before dipolarization fronts were observed in the plasma sheet in their statistical study of dipolarization fronts. These values are close to that obtained by *Walker et al.* [1999], who found in a MHD simulation study that the plasma sheet twist occurred 45–60 min after an IMF change reached the dayside magnetopause.

[28] However, longer time scales have also been suggested. Recently, *Fear and Milan* [2012] have studied the IMF dependence of the local time of transpolar arc formation, and they found that the correlation between the IMF B_y and the location of transpolar arc formation maximized when the IMF was averaged between 3 and 4 h prior to arc formation. They suggested this value to represent a likely flux transport time scale from the dayside magnetosphere to the magnetotail plasma sheet. However, *Fear and Milan* [2012] also found significant correlation already when the IMF was averaged over 1–2 h period before the transpolar arc formation, which does not differ much from the 130 min period we have used in this study.

[29] When defining the IMF averaging time interval to be linked to fast flows, we made the following procedure. By starting from a 0–30 min period preceding the fast flows, we averaged the IMF in different time intervals increasing the time interval with 10 min increments to a 0–300 min (= 5 h) period to produce scatterplots similar like Figure 2. After that we continued starting again from a 30–60 min period and increased the time interval with 10 min steps to a 30–330 min (= 5 h) period preceding the fast flows creating another set of scatterplots. We checked out similarly also time intervals ranging from 60–90 min to 60–360 min (= 5 h), from 90–120 min to 90–390 min (= 5 h), from 120–150 min to 120–420 min (= 5 h), from 150–180 min to 150–450 min (= 5 h), and from 180–210 min to 180–480 min (= 5 h). By comparing the scatterplot results, we found that the best overall correlation between the IMF B_y and the Cluster $V_{\perp y}$ occurred when using the IMF averaging over the period 0–130 min prior to the fast flows.

[30] We also compared the scatterplots made using the IMF averaging from 0 to 1, 1 to 2, 2 to 3, 3 to 4, and 4 to 5 h periods following *Fear and Milan* [2012] and found that the best correlation in these five cases is given by the period 1–2 h. The percentages are 73.7%, 72.6%, 75.0%, and 71.8% for Figures 2a–2d, respectively. The period 3–4 h that was found to have the maximum correlation in *Fear and Milan* [2012] for transpolar arc formation gives in our study percentages 68.3%, 71.0%, 60.0%, and 64.0%.

[31] The above investigation of the effect of the different IMF-averaging intervals also revealed that the correlation between the IMF B_y and Cluster $V_{\perp y}$ generally stays relatively high regardless of the IMF averaging period. This is due to the fact that the IMF B_y component was rather stable during several hours before the fast flow for most of the events. Only ~15% of the 286 flow events have intervals of longer than 1 h of oppositely directed IMF B_y within a 5 h interval prior to the fast flow. Of the scattered 74 events in Figure 2, only nine events belong to this 15%, so most of the scattering cannot be explained by such conditions.

5. Summary and Conclusions

[32] In this study, we have used the Cluster observations in the Earth's magnetotail together with the ACE solar wind data from the years 2001–2009 to investigate the dependence of the azimuthal flow direction of earthward magnetotail fast flows on the interplanetary magnetic field. In the statistical investigation, we found an indication that the azimuthal flow direction correlates with the orientation of the IMF.

[33] Regardless of the IMF B_z direction, the fast flows have a favored azimuthal direction, which for the IMF $B_y > 0$ is dawnward in the northern plasma sheet and duskward in the southern plasma sheet. During $B_y < 0$ conditions, an opposite behavior is observed, the favored azimuthal flow directions are then duskward and dawnward in the northern and southern plasma sheet, respectively. The azimuthal flow directions are hence to the opposite directions on the opposite sides of the neutral sheet for the particular IMF conditions.

[34] The results are in accordance with the previous observations of fast azimuthal plasma flow bursts made in the ionosphere but limited to northward, dominating B_y IMF conditions [e.g., *Grocott et al.*, 2005, 2008]. They are also in agreement with the case observations by *Grocott et al.* [2007] and *Walsh et al.* [2009] who, in addition to the consistent ionospheric flow pattern, have also reported of an indication of a velocity shear across the neutral sheet for a fast flow event from in situ magnetospheric observations. The results hence support the idea of untwisting of the twisted reconnected field lines directing the fast flows in the magnetotail.

[35] However, our results also show fast flows which have azimuthal components to the opposite directions than expected for the prevailing IMF conditions. As a possible explanation, we suggest that this may be due to that for these fast flows the magnetotail may have not yet been adjusted, at least in the region where the fast flow event is observed, and also plausibly where it is created, to the prevailing IMF conditions. This causes that these fast flows experience the tail twist which is opposite with respect to what would be expected from the corresponding IMF conditions. In addition to that, it is also suggested that in some cases, predominantly for small IMF B_y magnitudes, there may not exist a twist in the magnetotail that is sufficient to direct the fast flows.

[36] In conclusion, our results suggest that the untwisting of the twisted reconnected magnetic field lines may direct the fast flows in the magnetotail, the magnetotail twist itself being dependent on the IMF.

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