Difference between earthward and tailward flows in their dependences on geomagnetic and IMF conditions

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ABSTRACT

Earthward and tailward perpendicular fast flows in the plasma sheet were studied and their differences in response to geomagnetic conditions and to interplanetary magnetic field (IMF) conditions are discussed. We first identified the plasma sheet from 3.5 years of Geotail plasma and magnetic filed observations between 8 and 32 R_E down the tail. We then studied occurrence rates of fast flows during geomagnetically quiet and active intervals as identified by Kp and ASY indices, and during northward and southward IMF intervals. As a result, both earthward and tailward flows were observed more often during active or southward IMF intervals than during quiet or northward IMF intervals, as expected. On the other hand, we found that there is a difference between earthward and tailward flows: Dependences on geomagnetic conditions are more evident in tailward flows than in earthward flows. We further discuss that tailward flows indicate the substorm expansion phase better than earthward flows do.

Introduction

Reconnection in the magnetotail yields a pair of earthward flow with northward magnetic field and tailward flow with southward field. Thus earthward or tailward flows are often thought to indicate that a satellite is located earthward or tailward of a neutral line. Near the times of the substorm onsets identified by ground magnetic field, Nagai *et al.* (1998) statistically found that the earthward flow with northward magnetic field is seen earthward of 20-30 R_E and the tailward flow with southward field is seen beyond this region. This result can be interpreted as indicating that reconnection occurs somewhere between 20-30 R_E at the onsets, on the assumption that most fast flows at onsets are caused by near-Earth reconnection.

On average, however, many more earthward flows than tailward flows are observed inside $\sim 30 R_E$ (*e.g.*, Paterson *et al.*, 1998). Thus at least some fractions of earthward flows are not likely to be substorm expansion phase signatures. These earthward flows may come from the distant neutral line that is activated during southward IMF intervals. Due to these additional earthward flows, earthward flows could be statistically more associated with IMF conditions than tailward flows are. In other words, tailward flows may better mark the substorm expansion phase than earthward flows do. Thus geomagnetic and IMF conditions may have different significance between earthward and tailward flows, although geomagnetic and IMF conditions are basically correlated with each other. The purpose of this study is to find this difference by comparing earthward and tailward flows under different geomagnetic and IMF conditions.

Identification of IMF and Geomagnetic Conditions

We identified IMF north ($B_z \geq 1$) and south ($B_z \leq -1$) intervals by OMNI 1-hour averages of IMF-B_z data in the GSM coordinates, while we used Kp and ASY indices to identify geomagnetically quiet

Table 1. Plasma Sheet Samples (number ($\times 10^3$), fraction (%))

$\lvert X_{\rm AGSM}\rvert (R_E)$	8-13		13-20		20-27		27-32	
Average $\lvert X\rvert (R_E)$	10.5		16.5		23.7		29.1	
All intervals	164	(100)	172	(100)	177	(100)	188	(100)
All IMF	154	(94)	168	(98)	169	(96)	184	(98)
IMF-$B_z \geq 1$	45	(29)	52	(31)	52	(31)	63	(34)
IMF-$B_z \leq -1$	50	(33)	56	(33)	55	(33)	53	(29)
Active	23	(14)	28	(16)	22	(12)	22	(11)
Quiet	43	(26)	53	(31)	49	(28)	45	(24)

and active conditions in the polar ionosphere, respectively. Longitudinally asymmetric disturbance (ASY) indices provide longitudinal asymmetries in the H and D components of the ground magnetic field among 6 mid-latitude stations with 1 min time resolution (Iyemori and Rao, 1996). The stations (including Dst stations) are located roughly every 60 degrees in longitude. We assumed that the ASY indices were sensitive to a formation of a major substorm current wedge, while the ASY indices are not very sensitive to localized geomagnetic activities at high-latitudes.

The Kp index indicates geomagnetic variations in the sub-auroral regions. Kp is likely to be better than ASY index in identifications of quiet intervals in the polar ionosphere, because the Kp stations are in higher latitudes. On the other hand, Kp is not a suitable index to identify the substorm expansion phase that has much shorter (10-30 min) time scales than the temporal resolution (3 hours) of Kp. However, the long time resolution of Kp is not a crucial problem in identification of quiet intervals.

For the reasons above, we used Kp $<$ 1 (Kp = 0, 0+, and 1-) to identify quiet intervals. To exclude fast flows in the tail that occurred just before the end of a Kp quiet interval and were associated with an enhancement in the next Kp, the last 30 min was excluded when the next Kp was relatively high (Kp $\geq$ 1). We assumed that major substorm expansion phases were excluded in these "quiet intervals" but that weak or localized disturbance was sometimes included. To define geomagnetically active intervals we first calculated the maximum variations in ASY-H (dH) and ASY-D (dD) during 30 min ($\pm$ 15 min) for every 1-min time and defined dASY as higher one of dH or dD. We defined active intervals by dASY $>$ 10 nT. We assumed that our "active intervals" include major substorm expansion phases with time resolution of 15-30 min and are less sensitive to the substorm recovery phase when geomagnetic variations are slower.

Identification of the Plasma Sheet

The plasma sheet was identified with 12-s plasma (Mukai *et al.,* 1994) and magnetic field (Kokubun *et al.,* 1994) data from the Geotail spacecraft for 3.5 years from October 30, 1994 through April 30, 1998. (Geotail plasma data after April 30, 1998 are still under calibration). Geotail orbited in the solar-ecliptic plane and had perigee of $\sim 9R_E$ and apogee of $\sim 31R_E$. We used the aberrated GSM coordinates with an aberration of 4 degrees.

Tailward-moving plasmoids are known to be observed most often around $Y_{\rm AGSM} = 3R_E$ (Ieda *et al.,* 1998). Around the substorm onsets, fast flows also tend to be observed in the pre-midnight region (Nagai *et al.,* 1998). Thus we concentrated on studying the plasma sheet in $-4 \leq Y_{\rm AGSM} < 10R_E$. We further divided the plasma sheet samples into the four regions of $8 < |X| \leq 13R_E$, $13 < |X| \leq 20R_E$, $20 < |X| \leq 27R_E$, and $27 < |X| \leq 32R_E$, so as the sampling numbers are close to each other. The plasma sheet was identified by $\beta \geq 0.1$, where β is the ratio of the plasma pressure to the magnetic pressure. We assumed the ratio of ion to electron temperature as five (Slavin *et al.,* 1985). As a result, we found 701 thousand plasma sheet samples (equivalent to 97 days) as summarized in Table 1, where fractions (%) in IMF northward and southward intervals were normalized by all IMF intervals, and other fractions were normalized by all intervals.

Statistical Results

Figure 1 shows the occurrence rates (%) of earthward perpendicular fast flows ($V_{\rm perp,x} \geq 300$ km/s and $B_z > 0$) on the left, and tailward perpendicular fast flows ($V_{\rm perp,x} < -300$ km/s and $B_z < 0$) on the right against $X_{\rm AGSM}$. $V_{\rm perp,x}$ is the X component of the velocity perpendicular to the magnetic field. Each panel shows fast flows for the all intervals (thin line with filled circles), for the northward IMF (thick line with squares) and the southward IMF (thick line with circles) intervals, and for the quiet (dashed line with squares) and the active intervals (dashed line with circles). For all intervals (thin lines), the occurrence rates of both earthward and tailward flows increased with radial distance. This is consistent with the results by Paterson *et al.* (1998). Earthward flows were observed 10 times more than tailward flows between 20 and 30 R_E, where the near-Earth reconnection is supposed to occur.

We further studied their dependences on geomagnetic and IMF conditions. Both earthward and tailward flows were more often observed during active intervals than during quiet intervals, which have been previously shown inside $\sim 22R_E$ (*e.g.,* Angelopoulos *et al.,* 1994). Both flows were also more often found during southward IMF than during northward IMF intervals, as expected. However, there are differences in the fast flow dependences between geomagnetic and IMF conditions. Tailward flows appear much (three times around 30 R_E) more different between quiet and active intervals than between IMF northward and southward intervals. On the other hand, the dependences on IMF and geomagnetic conditions are close for earthward flows, or even earthward flows between 13 and 20 R_E appear rather dependent of IMF than geomagnetic conditions. Thus tailward flows are relatively (three times around 30 R_E) more sensitive to geomagnetic conditions than earthward flows are.

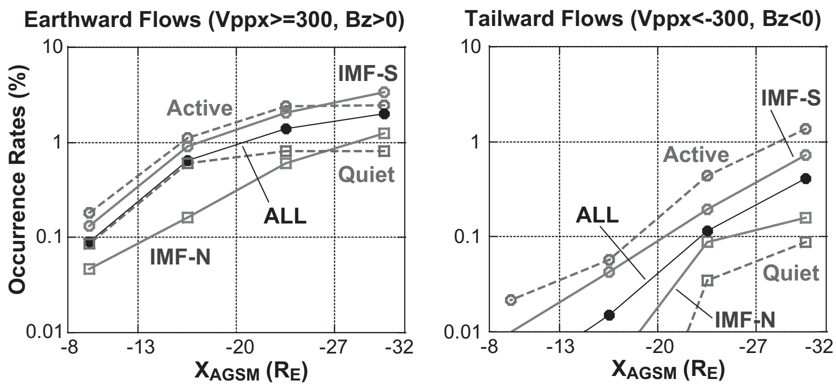

Fig. 1. The occurrence rates (%) of fast flows against $X_{\rm AGSM}$ in $-4 \leq Y_{\rm AGSM} < 10R_E$ of the plasma sheet, which was identified by $\beta \geq 0.1$. Earthward perpendicular fast flows ($V_{\rm perp,x} \geq$ 300 km/s, $B_z > 0$) are shown on the left and tailward perpendicular fast flows ($V_{\rm perp,x} <$ -300 km/s, $B_z < 0$) are shown on the right. Both panels show the results for all, northward and southward IMF, quiet and active intervals as marked.

We also studied slower flows (100-200 km/s and 200-300 km/s, not shown). Their occurrence rates had similar but weaker characteristics as fast flows havein Figure 1, indicating that the selection criterion of 300 km/s for fast flows is not qualitatively critical to our results.
Note that each bin typically has 20 $\times 10^3$ to 60 $\times 10^3$ samples, as shown in Table 1. Thus the occurrence rates of 0.1% contain 20-60 fast flow 12-s samples. If the fast flow events typically continue 1 min, they correspond to 4-12 events. Thus occurrence rates below $\sim$ 0.1% are not very reliable but just indicate that fast flows are rare.

Tailward flows appear more dependent of geomagnetic conditions than of IMF conditions in the right panel of Figure 1. This result is partly because less active intervals were identified than southward IMF intervals with our criteria. Relative importance of IMF to geomagnetic conditions is dependent of the selection criteria of conditions. However, criteria-dependent factors in the relative importance of IMF to geomagnetic conditions can be mostly canceled when comparing earthward and tailward flows. We emphasize that we have compared earthward and tailward flows and they were not separately discussed in this study.

Discussion

There are two possible reasons why fast flows inside $\sim 30R_E$ are more often observed during southward than northward IMF intervals. One is the large-scale convection due to enhanced dayside reconnection and subsequent reconnection in the distant neutral line, presumably around $100R_E$. This only increases the number of earthward flows, especially around the tail axis. The other is near-Earth reconnection around 20-30 R_E, which is supposed to be associated with substorms that occur more often during southward IMF intervals. This increases the number of both earthward and tailward flows in the substorm expansion phase, and predominantly increases that of earthward flows in the recovery phase because neutral lines retreat beyond the Geotail locations.

Thus most tailward flows in the near tail are supposed to be found during the substorm expansion phase. This expectation is consistent with our result that tailward flows are more dependent of geomagnetic conditions than IMF conditions, when compared to earthward flows. The frequent observation of tailward flows during active intervals is consistent with the previously found close association between tailward-moving plasmoids and auroral brightenings [*Ieda et al.,* 2001].

On the other hand, earthward flow can be due to either the distant or the near-Earth neutral line. Our result indicates that earthward flows are relatively more dependent of IMF than of geomagnetic conditions, when compared to tailward flows. Thus significant number of earthward flows are observed during southward IMF but not in the substorm expansion phase. One possible interpretation of this may be that such earthward flows come from the distant neutral line that is activated by southward IMF without substorms. Another possible interpretation is that earthward flows are also observed in the recovery phase [*e.g.,* Baumjohann *et al.,* 1999] and/or growth phase with southward IMF. Earthward flows in the expansion phase were not evident when compared to tailward flows, probably because there are earthward flows during the intervals other than the expansion phase.

Summary

On the basis of Geotail plasma and magnetic field observations, we have studied occurrence rates of fast flows in the plasma sheet from $|X| = 8$ to $32R_E$. We found that earthward and tailward flows respond to geomagnetic and IMF conditions in different ways. In summary: (1) Both earthward and tailward flows were more often observed during active or southward IMF intervals than during quiet or northward IMF intervals, as expected. (2) On the other hand, relative importance of geomagnetic conditions to IMF conditions are different between earthward and tailward flows. Tailward flows are much (three times around 30 R_E) more sensitive to geomagnetic conditions than earthward flows are.

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