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Comment on "Geotail survey of ion flow in the plasma sheet: Observations between 10 and 50 R_E" by W. R. Paterson et al.

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1. Introduction

On the basis of a statistical analysis on central plasma sheet flow samples *Paterson et al.* [1998] concluded that there is no evidence that bursty bulk flows (BBFs) are significant contributors to transport. This contradicts published results from different databases [e.g., *Angelopoulos et al.*, 1994]. The purpose of this commentary is to show that the apparent contradiction results from the fact that Paterson et al., in considering only the frequency of occurrence of the large flows, fail to appreciate the significant amount of transport associated with them. The issue of importance is the relative transport accomplished by BBFs, not the occurrence frequency of their velocity peaks. We use data from two new International Solar Terrestrial Physics (ISTP) data sets to show that in agreement with older studies, BBFs contribute >50% of the total observed flux transport even if they are present <15% of the time in the midnight central plasma sheet at distances $-16 < X_{GSM} < -20\ R_E$.

2. BBF Concept

Angelopoulos et al. [1992a, b] noticed that the near-neutral sheet high-speed flow samples which had been discussed earlier by *Baumjohann et al.* [1990] are parts of plasma sheet activity enhancements that last several minutes. The enhanced activity is characterized by flows with speeds several times larger than average and which are consistently unidirectional (primarily earthward, but occasionally tailward). The unidirectionality of the flows was contrasted to "quiet plasma sheet" intervals that exhibit no preference in flow direction [*Baumjohann et al.*, 1989; *Angelopoulos et al.*, 1993]. The activity is also accompanied by ion temperature increases, magnetic field variability and dipolarization. These intervals can be identified by the short-lived (rise-and-fall time of 1 min), high-speed "flow bursts" within them but are flow units that ought to be considered in their entirety (typical BBF duration is 10 min) because they are coherent. Thus the BBF concept entails the temporal envelope of unidirectional flow surrounding a near-neutral sheet flow burst.

BBFs owe their flux-transport efficiency to three factors: (1) the preferentially earthward direction of BBF flow samples, (2) the positive correlation of the flow direction and the z component of the magnetic field, B_z, and (3) the presence of higher-than-average flow speed (transport-efficient) samples within BBFs. When studying the BBFs, one should select them so as to avoid a circular argument in the study of their properties. By selecting them on the basis of flow magnitude one avoids imparting a preconceived notion on the study of flow direction. By avoiding the use of $V_{x\perp}$ (the X_{GSM} component of the flow velocity vector component that is perpendicular to the instantaneous magnetic field) in the selection one evades a circular argument on BBF correlation with dipolarizations. By selecting them on the basis of timeseries data one keeps the notion of the temporal flow coherence as part of the selection. BBFs may extend to the plasma sheet boundary layer, but their identification in that region requires usage of the ion distribution functions in order to separate them from boundary layer beams, an altogether different phenomenon.

A working definition of BBFs used by *Angelopoulos et al.* [1994] can be easily implemented on a computer, uses plasma beta (β_i) to define the plasma sheet center, and employs the total ion speed to define the flow bursts. The proposed working definition of BBFs consists of three steps:

1. Identify fast flow samples (V_i > 400 km/s, where V_i is the total ion flow magnitude) in the near-neutral sheet (β_i > 0.5, therein termed the "inner plasma sheet"). These signify the presence of a BBF.
2. Consider fast flow samples separated by <10 min as parts of the same event.
3. Mark the beginning (end) of the BBF as the first (last) time within the plasma sheet proper prior to (after) the fast flow sample that the flow magnitude rises above 100 km/s.

Since a BBF lasts longer than the flow peaks that are used to identify it, it is composed of contiguous flow samples that span the entire range of magnitudes from zero to the local Alfven speed (not only V_i > 400 km/s). All flow magnitudes contribute to transport even though the earthward transport efficiency of a sample increases with flow magnitude as was shown by *Angelopoulos et al.* [1992a]. The established correlation between V_i and B_z [*Angelopoulos et al.*, 1992a] further enhances the effectiveness of BBFs in transporting magnetic flux as compared to the transport of an advected quantity uncorrelated to V_i.

3. Presence of BBFs in the Geotail Database

Several authors have presented studies of near-neutral sheet fast flows in the Geotail database within the region studied by *Paterson et al.* [1998] (e.g., *Slavin et al.*, 1997; *Fairfield et al.*, 1998; *Nagai et al.*, 1999). These studies reinforce the need for a resolution of the discrepancy between the Paterson et al. conclusions and the conclusions of previous studies. A case of a BBF event that should also be present in the database of Paterson et al. is presented here in order to explain the BBF definition.

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Figure 1 shows magnetic field and flow velocity data from Geotail in the inner plasma sheet ($\beta_i > 0.5$) at a time of a BBF event. Magnetic field data are taken from the magnetic field (MGF) instrument [*Kokubun et al.*, 1994], while ion moments are taken from the Low Energy Particle (LEP) plasma instrument [*Mukai et al.*, 1994]. The X_{GSE} component of the flow velocity perpendicular to the instantaneous field direction computed from the plasma instrument is shown in the shaded area below the total flow trace. The same component can also be computed from the electric field (EFD) instrument [*Tsuruda et al.*, 1994], using the frozen-in condition and the condition that there is no parallel electric field (see, e.g., *Angelopoulos et al.* [1996] for the procedure). Both the flow magnitude and the X_{GSE} component of the flow speed perpendicular to the magnetic field exceeded the value of 400 km/s a few times within the event. However, the event also incorporates slow flows that also contribute to the earthward transport. The magnetic field variability renders the perpendicular flow trace much more variable than the total flow, which is, for the most part, identical to V_x (not shown).

While the high-speed flow samples ($V_i > 400$ km/s; see dashed horizontal line in Figure 1 (middle)) are used to identify the event, both LEP and EFD instruments are in agreement that all velocities contribute to the total transport. This BBF event, defined according to the *Angelopoulos et al.* [1994] criteria, lasts 20 min, as indicated by the horizontal arrow in Figure 1 (middle).

4. The Approach of Paterson et al. [1998]

Paterson et al. [1998] studied flow samples statistically and chose $V_{x\perp} > 300$ km/s as a criterion of a fast flow. On the basis of the low-occurrence rate of such flows (0.1%) they reached the conclusion that bursty bulk flows are not important for transport. The argument is incorrect in the following ways: (1) BBFs are temporally organized, coherent flow units obvious in the time series data. BBFs cannot be identified on statistics of flow samples alone. (2) Fast convective flows are a part of BBF structure but not the only part. In particular, the convective component within BBFs can be significantly smaller than V_i or V_x because of the pronounced magnetic field variability in the active, high-beta plasma sheet. The cumulative flux transport of all BBF flows, however, is still very significant. (3) The fast, inner plasma sheet flows are indeed few as first pointed out by *Baumjohann et al.* [1990] but are very significant as pointed out by *Angelopoulos et al.* [1994]. They signify the presence of a local plasma sheet activation (a BBF) in the timeseries data. (4) The statistics on $V_{x\perp}$ alone are not the proper way of either studying the transport efficiency of BBFs or of revealing the dependence of flux transport on flow magnitude. This is because the B field magnitude is not accounted for in $V_{x\perp}$ although it does contribute to flux transport. A proper way of doing so is to plot the transport (or cumulative transport) versus flow magnitude. Such plots can be found in Figures 1, 2, and 3 of *Angelopoulos et al.* [1992a].

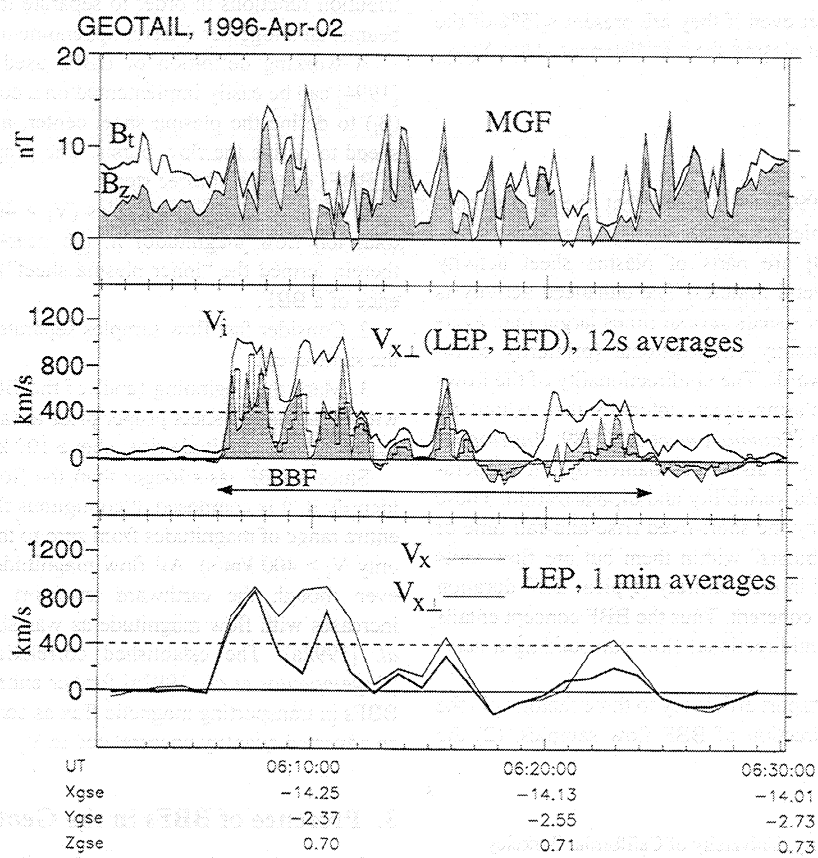
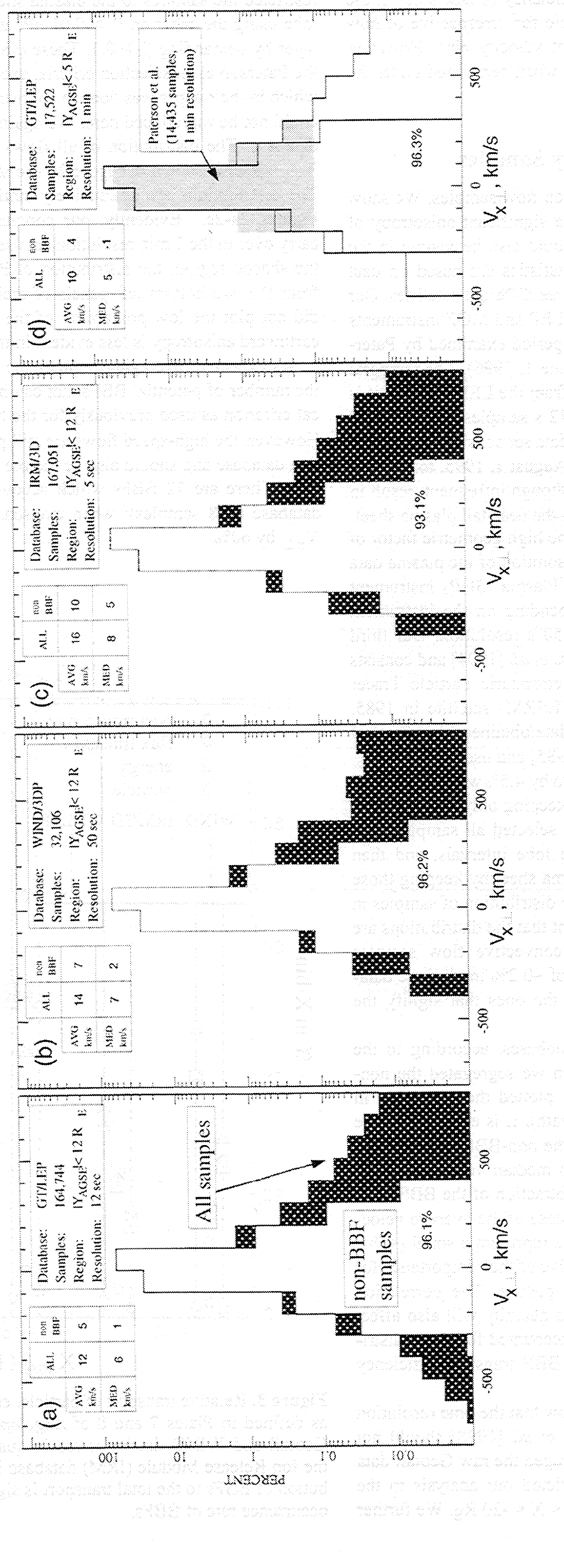


Figure 1. Data from a bursty bulk flow (BBF) event in the Geotail database. (top) The total and the Z_{GSM} components of the magnetic field from the MGF instrument. (middle) The total flow direction as computed from the Low Energy Particle (LEP) instrument data (heavy line). The X_{GSM} component of the ion flow perpendicular to the magnetic field is shown grey-shaded, as computed from LEP, and in histogram format as computed from the electric field instrument (EFD). (bottom) V_x and $V_{x\perp}$ at 1 min resolution computed from LEP moment and magnetic field averages on 1 min centers. They show that some BBF peaks do survive the averaging and should also exist in the database of *Paterson et al.* [1998]. This panel is to be compared with Figure 2 of *Paterson et al.* [this issue].



	ALL	non BBF
AVG km/s	12	5
MED km/s	6	1

	ALL	non BBF
AVG km/s	14	7
MED km/s	7	2

	ALL	non BBF
AVG km/s	16	10
MED km/s	8	5

	ALL	non BBF
AVG km/s	10	4
MED km/s	5	-1

Figure 2. (a)-(c) Distribution of plasma sheet samples in $V_{x\perp}$ space using three different databases. (d) Data from the Geotail/LEP database cast at 1 min resolution and restricted in the same manner as in *Paterson et al.* [1998] are plotted in the same fashion as in Figure 2a. The Paterson et al. results adapted from their Figure 4 are superimposed for comparison.

The ultimate test of the transport efficiency of BBFs lies in the amount of transport they are responsible for, irrespective of how that transport is distributed in different velocity bins. However, sample statistics can be quite revealing when performed under the light of the BBF concept.

5. Proper Statistics on Velocity Samples

In this section we perform statistics on flow samples. We show that BBF samples are responsible for a significant anisotropy of the flow distributions and that they should also be visible in the *Paterson et al.* [1998] analysis. Our statistics are based on data from three independent databases on three different satellites. Our first database consists of data from the LEP and MGF instruments on board the Geotail satellite from the period examined by Paterson et al. (i.e., December 1, 1994, to June 1, 1996). The temporal resolution of the plasma data obtained from the LEP instrument is 12 s. We performed statistics both on 12 s samples and on 1 min averages of those samples. The second data set consists of the perigee passes of the WIND satellite from August 1, 1995, to October 31, 1997. The WIND perigee passes, although infrequent, result in a data set with considerable residence in the near-tail plasma sheet. The importance of that data set lies in the high geometric factor of the plasma instrument. The temporal resolution of the plasma data obtained from the Three-Dimensional Plasma (3DP) instrument [*Lin et al.*, 1995] is 25 s or 50 s, depending on the instrument mode. The data were cast at uniform 50 s resolution. Our third database is the one used by *Angelopoulos et al.* [1994] and consists of the tail passes of the Active Magnetospheric Particle Tracer Explorers/Ion Release Module (AMPTE/IRM) satellite in 1985. The temporal resolution of the plasma data obtained from the 3-D plasma instrument [*Paschmann et al.*, 1985] and used here is 5 s.

After aberrating the GSE position data by 4.5°, we restricted the study to the near-Earth magnetotail by keeping only samples with $|Y| < 12\ R_E$ and $-8 < X < -20\ R_E$. We selected all samples with pressure $P_i > 0.01$ nPa to remove the lobe intervals, and then restricted them further to the inner plasma sheet by keeping those which had ion beta $\beta_i > 0.5$. We plot the distribution of samples in $V_{x\perp}$ space in Figures 2a-2c. It is evident that the distributions are skewed to positive values. The fast convective flow samples ($V_{x\perp} > 300$ km/s) are few (occurrence of ~0.2% in all three databases) but important because they are the ones that signify the presence of BBFs in the timeseries data.

We identified BBFs in the three databases, according to the working criterion in Section 2, and then we segregated the non-BBF samples in the total database and plotted them together in Figures 2a-2c (white histogram underneath). It is evident that the anisotropy is much less pronounced in the non-BBF data set. The top left insert indicates the average and median velocities in the full and the non-BBF databases. The subtraction of the BBF samples results in a significant (>37%) decrease of the average velocity, despite the fact that the BBF samples represent a small (<7%) fraction of the databases. This is suggestive of their importance for transport. It is still not the definitive picture. The correlation between the velocity and the transported quantity will also affect the transport efficiency, and that is not accounted for in the distribution of samples in $V_{x\perp}$ space. The BBF transport efficiency will be studied in Section 6.

In the remainder of this section we show that the time resolution and selection criteria used by *Paterson et al.* [1998] should not have affected their conclusions. We averaged the raw Geotail data on consecutive 1 min centers and restricted our analysis to the aberrated GSE region: $|Y| < 5\ R_E$ and $-8 < X < -20\ R_E$. We further restricted the samples to the plasma sheet center by excluding the lobe using the criterion $P_i > 0.01$ nPa and plasma sheet boundary layer by demanding $\beta_i > 0.1$. These criteria are nearly identical to the Paterson et al. selection criteria, except for the lobe extraction, which in their paper was done in an instrument-dependent way and could not be reproduced here. We again defined BBFs in this new database. The distribution of all flows and of non-BBF flows in $V_{x\perp}$ space is shown in Figure 2d (no shading below histograms). The distributions are qualitatively similar to the distributions in Figures 2a-2c. Evidently, our conclusions from Figures 2a-2c carry over to the 1 min resolution data set. Figure 2d also shows, in the shaded region, the distribution of Paterson et al., constructed from the two bottom left panels of their Figure 4. These authors did not plot the low probability of the faster flows, and thus the earthward anisotropy is less evident in their plot.

As expected, averaging reduces the number of fast flows and the number of potential BBFs that can be selected using an identical criterion as used previously for the higher-resolution data sets. However, the high-speed flows are still present in the 1 min resolution database and should also be visible in the Paterson et al. database. There are 72 BBFs which account for 3.7% of the 1 min database (648 samples); when excised, they reduce the average $V_{x\perp}$ by 60%.

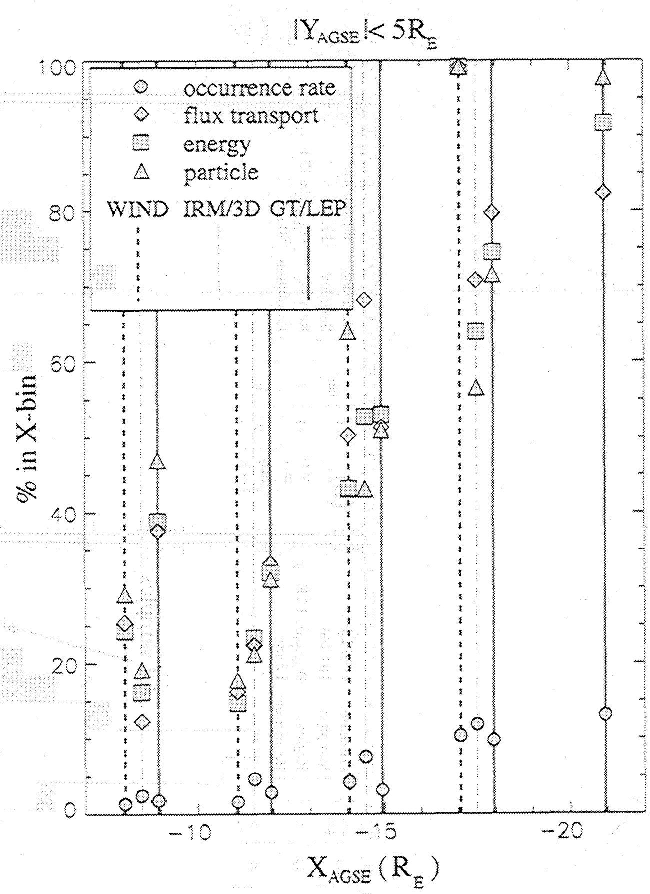


Figure 3. Relative transport of particle, energy, and magnetic flux, as defined in Plates 7 and 8 of *Angelopoulos et al.*, [1994]. The Geotail and WIND databases are in quantitative agreement with the Ion Release Module (IRM) database in that the relative contribution of BBFs to the total transport is significant, despite the low-occurrence rate of BBFs.

6. BBF Relative Transport

The ultimate proof that Geotail BBFs are important for transport lies in the direct computation of that transport relative to the total transport observed by the spacecraft at various magnetotail locations. To this goal we used the full instrument resolution (not the 1 min averages) and studied the inner plasma sheet (defined as $\beta_i > 0.5$, not $\beta_i > 0.1$), so as to compare directly with previously published results from the AMPTE/IRM database. We then computed the transport in the midnight sector ($|Y_{AGSE}| < 5\ R_E$), where BBFs maximize in occurrence rate. The transport quantities computed are exactly the same as in *Angelopoulos et al.* [1994], i.e, the mass transport, the MHD energy density, and the earthward transport of northward directed magnetic flux. The computations were performed in 3 R_E wide bins in X_{AGSE}. The BBF transport in each bin was compared with the total transport observed past the spacecraft in that spatial bin throughout the entire database. The results are shown in Figure 3.

It is evident that BBFs occur in the region $-16 < X < -22\ R_E$ less frequently than 15% of the time, yet they contribute >50% of the total particle, energy, and flux transport. These results are essentially identical to the previously published results on BBF transport using IRM and ISEE spacecraft data sets and lend credence to the idea that BBFs are important building blocks of magnetospheric transport.

As a final comment, we note that the reduction in BBF occurrence (and thus relative transport) with proximity to Earth is at least partly an effect of the selection criterion of the flow burst peaks ($V_i > 400$ km/s). It does not necessarily reflect a qualitative change in the means by which transport takes place, i.e., via short-lived, transport-efficient bursts of plasma flow. A second-order analysis should therefore involve a flow burst detection criterion that either depends on distance or is based on a quantity that is conserved with downtail distance, such as, possibly, the dawn-dusk electric field.

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