Structured Currents Associated with Tail Bursty Flows During Turbulent Plasma Sheet Conditions

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Abstract

Flow in the tail often consists of highly structured bursts. Here we use Geotail spacecraft data to show that bursty flows in the tail are associated with significant (~5 nT) magnetic structure indicating structured currents with estimated densities of \( \geq 1 \times 10^{-10} \text{ A/m}^2 \). When mapped along field lines to the auroral ionosphere, these currents appear to be sufficiently intense (\( \geq 1 \times 10^{-6} \text{ A/m}^2 \)) to account for auroral poleward boundary intensifications, which are nightside geomagnetic disturbances having an auroral signature that moves equatorward from the poleward boundary of the auroral oval. Our analysis suggests that there is a dramatic difference between two states of the tail plasma sheet: a stable state with a minimum of bursty flow activity and associated structured currents and a turbulent state with considerable bursty flow activity and structured currents. The transition between these two states can be quite abrupt; however intermediate states also exist. Structured currents appear to be just as important a part of the turbulent plasma sheet as are the bursty flows, so that the concept of a stable tail current distribution may not be appropriate when the plasma sheet is in its turbulent state. We furthermore find that significant flows and structured currents, when present, appear to exist throughout the entire height of the tail plasma sheet during the turbulent periods, suggesting that it may generally be inappropriate to separate plasma sheet flows within the central plasma sheet from those within plasma sheet boundary layer. We also find that dipolarizations of the magnetic field do not accompany the majority of flow burst events that we have examined. However, dipolarizations are occasionally seen, primarily during substorm associated bursty flow activity.

1. Introduction

Plasma flow in the geomagnetic tail often exhibits large temporal variations. Individual flow bursts often have peak speeds of \( \sim 250-1000 \text{ km/s} \) [Baumjohann et al., 1990; Angelopoulos et al., 1992]. Peak velocities are in the \( \pm x \) direction, whereas plasma sheet turbulence at lower (\( \leq 250 \text{ km/s} \)) velocities appear to be isotropic[Borovsky et al., 1997]. Bursty plasma sheet flows are believed to have significant spatial structure, so that there should be significant shears and currents associated with the flows.

Periods of bursty flows in the tail have been found to correspond to periods when disturbances (here referred to as “poleward boundary intensifications” or “PBIs”) having an auroral signature that moves equatorward from the magnetic separatrix are frequently observed in
the ionosphere [Kauristie et al., 1996; Yeoman and Lühr, 1997; Lyons et al., 1999]. Periods without PBIs are found to correspond to periods when the plasma sheet is far more stable. Discrete auroral arcs are generally associated with upward currents that connect along field lines to the magnetosphere, and PBIs are presumably associated with such currents. Thus the association of PBIs with bursty flows in the tail further suggests that significant currents are associated with the bursty flows within the plasma sheet.

Here we examine Geotail measurements which indicate that structured currents in the tail are indeed associated with bursty flows in the tail and that such currents are generally absent when bursty flows are absent. Studies of bursty flows [e.g., Baumjohann et al., 1990; Angelopoulos et al., 1992, 1994] have been careful to distinguish central plasma sheet flows that are perpendicular to the ambient magnetic field from the field-aligned flows observed within the plasma sheet boundary layer (PSBL) [Eastman et al., 1984, 1985]. We find evidence that the flows within the central plasma sheet and those within the PSBL may not be distinct phenomena. We also find a significant distinction between periods when the plasma sheet is highly turbulent with considerable bursty flow activity and associated structured currents and periods when the plasma sheet is stable with a minimum of such flows and currents.

2. Geotail Observations

We first examine Geotail magnetic field and plasma moment observations (Figure 1) from a 3 hr conjunction on November 13, 1996 between Geotail in the tail plasma sheet and the Canadian Auroral Network for the OPEN Program Unified Study (CANOPUS) ground array in central Canada. Figure 1 and subsequent figures show the x, y, and z component of magnetic field $B_x$, $B_y$, and $B_z$, the total magnetic field $B_t$, the x, y, and z components of ion velocity $V_x$, $V_y$, and $V_z$, density, ion temperature, and plasma $P_{\text{plasma}}$ and total $P_{\text{tot}}$ (magnetic plus plasma, heavier line in pressure panel) pressures. The heavier lines in the velocity panels give $V_{\text{perp},x}$, $V_{\text{perp},y}$, and $V_{\text{perp},z}$, which are the x, y, and z components, respectively, of the velocity component perpendicular to the measured magnetic field. Spacecraft locations in units of $R_E$ are given in the bottom of the figure. GSM coordinates are used.

The time interval shown in Figure 1 included a substorm with an onset time indicated by the arrow at the bottom of the figure. Except for a few minutes near the time of the substorm onset, $V_{\text{perp},x} \approx V_x$ and $B_x$ was small, implying that the spacecraft was near the center of the tail.
current sheet. The substorm was identified as a global substorm using data from the CANOPUS
ground magnetometers and meridian scanning photometers (MSPs). The magnetic X component
and Pi 2 pulsation data from a representative CANOPUS station (Fort Churchill) are shown in the
upper left panel of Figure 2 (see Rostoker et al., [1995] for CANOPUS instrument descriptions
and station locations). As indicated at the top of Figure 1, PBIs were observed in the MSP data for
an approximately two hour period following the substorm onset (see Figures 5 and 6 of Lyons et
al., 1999). It has not yet been determined whether the above relation of PBIs to substorms is
common. Such a relation is at least occasionally seen; however, PBIs are also often seen at other
times, including the growth phase of substorms, quiet times, and convection bays [Lyons et
al., 1998]. Figure 1 clearly shows that bursty flows were more prevalent during the period when PBIs
where observed than during the ~ 50 min period before the onset when PBIs were not observed.
Notice that the magnetic field data show significantly less structure during the period without PBIs
and structured flows than during the ensuing period. This implies that there were structured
currents throughout the period of the bursty flows, and that such currents were generally not
present during the period without the flows.

Many of the rapid magnetic changes seen in B_y and B_z were of magnitude ~5 nT. Bursty
flows in the tail are believed to be longitudinally localized structures, and Angelopolous et al.
[1994, 1996] have used ~1-3 R_E as representative scale sizes for the structures. Since the
magnetic structures are associated with gradients in the flows, their spatial scale size should be
similar in magnitude to, or perhaps smaller than, the scale size of the bursty flows. Taking the
maximum spatial scale size for a “localized structure” to be 4 R_E (1/10 of the tail diameter), we
assume that the scale sizes for the magnetic changes are ≤ 4 R_E. With this assumption, we find
that ~5 nT magnetic changes correspond to a current density J ≥ 1.6 x 10^{-10} A/m^2. Mapping this
along field lines to the ionosphere from a tail region of ~10 nT total field would give J ≥ 1 x 10^{-6}
A/m^2. This is sufficiently intense to require a field-aligned potential drop, and to thus account for
the auroral enhancements associated with PBIs. (For a magnetospheric electron population of
density 1 cm^{-3} and thermal energy a few tenths of keV, a significant field-aligned potential drop
will form when the upward field-aligned current density from the ionosphere exceeds ~0.5 x 10^{-6}
A/m^2 [Lyons, 1981]).
To determine whether the association between bursty flows and structured currents may be a general feature of the tail, we have examined Geotail data from a data set that we are currently using for a study of plasma sheet dynamics in association with substorms. Each example is for a time interval when observations from CANOPUS allowed the identification of global substorm onsets. Magnetic X-component and Pi 2 data from a representative CANOPUS station are shown in Figure 2 for each example used in the present paper. Optically, substorm onsets show most clearly in the CANOPUS MSPs (at Gillam and Fort Smith) that are located at ~67° magnetic latitude, whereas PBI identification requires MSP observations from the more poleward CANOPUS station (Rankin Inlet at 73° magnetic latitude). Unfortunately, except for the example in Figure 1, PBI identifications were not possible for events selected for the present study due to either poor longitudinal conjunctions between Geotail and Rankin Inlet or poor ground viewing conditions at Rankin Inlet. Since studies have associated some bursty flows with substorms [e.g., Nagai et al., 1998], our use of this data allows possible associations with substorms to be considered. However, this is not a primary goal of the present study. Here, we have selected clear examples of periods with and without bursty flow activity and examples showing a well-defined series of flows bursts. The selected examples are representative of our entire data set, other than we have not emphasized examples with weak flows for which the transitions between intervals with and without flows are less definitive than in the examples presented.

Figure 3 shows Geotail data from a 1 hr interval on February 10, 1998. Throughout this interval, the magnetic and plasma pressures were about equal, implying that Geotail was well within the plasma sheet but away from the current sheet. During some time intervals, we find that the plasma sheet is extremely stable and has almost no detectable bursty flows, and the data in Figure 3 is from such a period. It can be seen that the magnetic field measured by Geotail was quite smooth, consistent with an absence of large field-aligned current densities in the tail in the vicinity of the spacecraft.

During other time intervals, Geotail detected a nearly continuous sequence of bursty flow activity, such as during the one hour interval on February 19, 1996 shown in Figure 4. Geotail was at approximately the same y (~7 R_E) during this time interval as during the time interval shown in Figure 3, but was ~10 R_E closer to the Earth. Figure 4 includes periods when Geotail was quite near the current sheet, as indicted by $P_{\text{plasma}} = P_{\text{tot}}$, and some periods when Geotail...
moved away from the current sheet but was still within the plasma sheet. A highly structured magnetic field, which is very different from the smooth magnetic field seen in Figure 3, can be seen during the time interval of bursty flows shown in Figure 4. Rapid fluctuations, some on time scales < 1 min, can be seen, though it is not possible to determine the extent to which any particular fluctuation is spatial or temporal. $B_x$ variations can be related to motions of the tail current sheet over the spacecraft. However much of the variations in $B_y$ and $B_z$ are not associated with specific variations in $B_x$, and must be related to structured currents. Much of the changes in $B_y$ and $B_z$ are in the range of ~2-10 nT, as is the case for the data in Figure 1 and the data shown in subsequent figures. The data in Figures 3 and 4 do not show an association between bursty flows observed at the satellite location and substorm activity.

The flow bursts in Figure 4 are generally largest in the x direction, which is typical of the flow bursts seen by Geotail. At times, the bursts have little perpendicular component of $V$ in the x-direction ($V_{\text{perp},x} \ll V_x$). When this occurs, $|B_x|$ is large as expected for the primarily field-aligned flows of the PSBL. At other times, $V_{\text{perp},x} \approx V_x$. When this occur, the spacecraft can be seen to have been near the center sheet of the current as indicated by $|B_x| \approx 0$. Note that the flows appear to be nearly continuous at times when the spacecraft moved from/to the PSBL to/from the current sheet and that there is a continuous increase/decrease in $V_{\text{perp},x}$ relative to $V_x$ at these times. (For example, this occurred a number of times between 0805 and 0830 UT.) It thus appears that the bursty flows and associated structured currents engulf the entire plasma sheet, and are not confined to either the PSBL or the central plasma sheet.

The data in Figures 3 and 4 show that the plasma sheet can be in a stable state without significant bursty flows and magnetic perturbations due to structured currents or can be in a very turbulent state with considerable bursty flow activity and associated structured currents. Figures 5 and 6 show data that illustrate the transition from one state to the other, transitions being identified in each figure by vertical short-dashed lines. In both examples, the magnetic field is relatively stable during the time periods without bursty flows but shows considerable structure of the type expected from structured currents during the intervals with significant bursty flow activity. It can be seen that the transitions between stable and turbulent plasma sheet are quite abrupt and that they occur at nearly the same time in both the flow and magnetic field data.
Figure 5 shows a transition from a stable to a turbulent plasma sheet that occurred at ~0724 UT on January 12, 1997 during a prolonged interval when Geotail was very near the center of the cross-tail current sheet ($P_{\text{plasma}} \approx P_{\text{tot}}$ and $|B|_x$ is small), and Figure 6 shows a such transition at ~0420 UT on March 30, 1997 when Geotail was near the outer edge of the plasma sheet ($P_{\text{plasma}}$ considerably less than $P_{\text{tot}}$ and $|B|_x$ is large). This supports the inference above that when the bursty flows exist, they engulf the entire plasma sheet and are not confined to either the PSBL or the central plasma sheet. The data in Figure 6 before 0420 UT also suggest that significant flows along the outer portion of the plasma sheet may not exist when the plasma sheet is in a stable mode.

The above two transitions to a turbulent plasma sheet were observed at positive values of $y$ where Nagai et al. [1994, 1998] have reported plasma sheet flows associated with substorms, and both of these transitions may be associated with substorms. The transition near the center of the current sheet in Figure 5 occurred ~2 min before a substorm onset was observed using the CANOPUS ground observations (See Figure 2). Note that none of the flow bursts in this or the previous examples were associated with identifiable dipolarizations of the magnetic field. The transition in Figure 6 occurred approximately midway between two onsets spaced 18 min apart and was associated with a temporal transition from a stretched to a significantly more dipolar configuration of the tail magnetic field ($B_z$ increased from ~0 nT at 0421 UT to ~10 nT at 0435 UT, and $B_x$ was ~25 nT at the beginning and near the end of this interval). This dipolarization and associated period of bursty flows looks very much like dipolarizations and bursty flows that Nagai et al. [1999] found closer to the Earth within the longitude range of substorm onset. In addition to the case in Figure 6, a dipolarization can be seen following a short, substorm-associated, period of flow bursts that occurred from 0525 to 0533 UT on March 17, 1996 (See Figure 7). While such dipolarizations and associated flows are likely an important aspect of substorms, the majority of bursty flows examined here are not clearly associated with substorm onsets and are not associated with significant dipolarizations of the tail magnetic field. Clearly a more detailed study of the relation between bursty flows, substorms, and dipolarizations is needed. Bursty flows associated with dipolarizations and those not associated with dipolarizations are both associated with a similar magnetic field structure.
The data in Figures 1 and 2-6 show an absence of structured currents in the absence of the bursty flows and the presence of such currents when bursty flows are present. However, it is difficult to identify individual flow bursts and the direct association between the shears associated with the bursts and currents. Occasionally, however, a series of distinct flow bursts can be identified. Several such series are identified in the Geotail examples shown in Figures 7 (1 hr interval on March, 17, 1996) and 8 (0.5 hr intervals on Feb. 10, 1997 and March 24, 1997). Figures 7 and 8 include cases when bursts were observed at positions within the plasma sheet varying from very near the center of the current sheet (e.g., the bursts between 0525 and 0533 UT on March 17, 1996) and to the outer edge of the plasma sheet (e.g., the bursts seen in the March 24, 1997 example, some of which occurred as the plasma sheet traversed the boundary between the lobes and the plasma sheet). The vertical small-dashed lines in Figures 7 and 8 identify the beginning of 23 distinct bursts of flow in the x-direction. It can be seen that the rapid increase in $|V_x|$ immediately following each vertical line is associated with a corresponding rapid ~2-10 nT change in $B_y$ or $B_z$, and generally with a rapid change in both $B_y$ or $B_z$. This correspondence is equally good for the rapid decreases in $|V_x|$ the follows the peak $|V_x|$ of each burst. These correspondences show quite clearly that individual bursts are accompanied by a pair of, presumably oppositely directed, currents. This is just what is expected if the shears associated with individual flow bursts are directly associated with significant current structures.

3. Discussion and Conclusions

Bursty flows in the tail are an important dynamical feature of the magnetosphere-ionosphere system. Here we have presented evidence that bursty flows are associated with equivalently important structured currents in tail. Current densities are estimated to often be $\approx 1 \times 10^{-10}$ A/m$^2$. This would map along field lines to current densities of $\approx 1 \times 10^{-6}$ A/m$^2$ in the auroral ionosphere, which is sufficient to account for PBIs.

The data considered here indicates that there is a dramatic difference between two states of the tail: a stable state with a minimum of bursty $\approx 250$ km/s flow activity, and structured currents and a turbulent state with considerable $\approx 250$ km/s bursty flow activity and associated structured currents. The transition between these two states can be quite abrupt. These two distinct states are often clearly identifiable in the data we have examined; however intermediate states also exist (e.g., 0533 to 0600 UT on March 17, 1996; see Figure 7). We have not determined the frequency
of occurrence of different states. The data suggests that, when present, significant flows and structured currents exist throughout the height of the tail plasma sheet during the turbulent periods. On the other hand, such flows and currents appear to not be present anywhere from the center of the tail current sheet to the edge of the plasma sheet during the stable periods. While a difference clearly exists between the current sheet region where flows are primarily perpendicular to $\mathbf{B}$ and the PSBL region where flows are primarily parallel to $\mathbf{B}$, flows appear to be continuous from one region to the other. Such a continuity of flows can be explained as being the result of Speiser motion [e.g., Speiser, 1965] of particles in a local current sheet region with enhanced electric fields, and the subsequent ejection of particles along field lines from the current region [Lyons et al., 1999].

We have also found that dipolarizations of the magnetic field did not occur in association with the majority of flow burst events we have examined. We do see some dipolarizations, and these occur primarily in association with substorm-associated flow bursts. A superposed epoch analysis by Angelopolous et al. [1992] shows some dipolarization of the field in association with flow bursts, and this is often interpreted as indicating that flow bursts are generally associated with dipolarizations. We do not see such a general association. But, since Angelopolous et al. [1992] included both substorm-onset related and non-onset related flow bursts in their analysis, their superposed epoch analysis would show a dipolarization even if dipolarizations do not occur for a majority of events. Thus their results are consistent with our results.

Finally, since magnetic perturbations associated with current structures within the turbulent plasma sheet are often of the same magnitude as the ambient field and are up to $\sim 1/2$ of the lobe field strength, the concept of a stable tail current distribution may not be applicable when the plasma sheet is in its turbulent state.

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References


Figure Captions

Figure 1. Geotail magnetic and plasma data for 0330 to 0630 UT on November 13, 1996. Vertical arrow indicates time of global substorm onset.

Figure 2. Magnetic X-component and Pi 2 data from a representative CANOPUS station for each example used in the present paper. Vertical dashed lines indicate the times of global substorm onsets identified using all CANOPUS magnetic, Pi 2, and MSP data. Stations in this figure are Fort Churchill (CHU), Fort Simpson (SIM), Rabbit Lake (RAB), and Gillam (GIL).

Figure 3. Geotail magnetic and plasma data for 0700 to 0800 UT on February 10, 1998. Vertical arrows indicate times of global substorm onsets.

Figure 4. Geotail magnetic and plasma data for 0800 to 0900 UT on February 19, 1996. Vertical arrow indicates time of global substorm onset.

Figure 5. Geotail magnetic and plasma data for 0700 to 0800 UT on January 12, 1997. Vertical arrow indicates time of global substorm onset.

Figure 6. Geotail magnetic and plasma data for 0400 to 0500 UT on March 30, 1997. Vertical arrows indicate times of global substorm onset.

Figure 7. Geotail magnetic and plasma data for 0500 to 0600 UT on March 17, 1996. Vertical arrows indicate times of global substorm onset.

Figure 8. Geotail magnetic and plasma data for 0530 to 0600 UT on February 10, 1997 and for 1030 to 1100 UT on March 24, 1997. Vertical arrows indicate times of global substorm onset.