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Plasma and magnetic flux transport associated with auroral breakups

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Abstract. Auroral breakups are the first visible sign of a substorm expansion onset. Keying the plasma sheet behavior to onset times of auroral breakups may help to identify the substorm onset process. With this goal in mind, we have identified a list of auroral breakups based on global imaging data from the Ultraviolet Imager of the POLAR spacecraft for two favorable viewing periods and have examined the simultaneous plasma measurements in the tail from GEOTAIL. Synoptic patterns of plasma transport and magnetic field changes in the tail surrounding the times of auroral breakups are constructed. The results indicate that the plasma sheet activities associated with auroral breakups are transient and spatially localized. These findings are consistent with the scenario in which expansion phase activities are dominated by localized, transient disturbances as portrayed by the substorm synthesis model.

1. Introduction

The magnetotail is a reservoir for energy and particles from magnetospheric processes. The plasma sheet exhibits dynamic changes during substorms and is recognized as the site of powerful physical processes responsible for energy conversion from fields to particles. Therefore, plasma sheet activities during substorms are important not only in locating the regions where these processes occur but also in ascertaining their characteristics for better understanding and identification.

Many studies of plasma flows in the plasma sheet have been conducted. Most are event-based studies, while a few are statistical surveys [e.g., *Lui et al.*, 1977; *Frank and Paterson*, 1994]. The global pattern of plasma flow around the substorm onset is crucial in establishing the sequence of events leading to substorm expansion onset and the subsequent activities in the magnetotail.

Several phenomena have been used in timing plasma sheet activities, for example, plasma sheet thinning and expansion at the spacecraft location [*Lui et al.*, 1977; *Hones and Schindler*, 1979]. The plasma flow observations reported by *Lui et al.* [1977] showed that at the time of plasma sheet thinning, plasma flows are predominantly earthward, although large tailward flows are seen mostly beyond ~30 R_E. In contrast, *Hones and Schindler* [1979] found about equal likelihood of earthward and tailward plasma flows within the downstream distance of ~35 R_E (although no synoptic flow pattern was shown). Recently, *Nagai et al.* [1998] used ground Pi2 micropulsations to identify substorm onsets and reported that plasma flows are mainly earthward within the downstream distance of ~20–30 R_E and mainly tailward beyond. Overall, the plasma flow pattern during the course of a substorm is still ill defined.

In this study, we adopted auroral breakups to time plasma sheet behavior. Global observations of aurora from the Ultraviolet Imager (UVI) on the POLAR spacecraft are used to determine auroral breakups. Auroral breakups are presumably better in defining magnetospheric substorm expansion onsets than onsets of magnetic bays in the polar region, since they are recognized as the first sign of expansion onset at substorm inception [*Akasofu*, 1964]. The use of global imaging observation also eliminates the inadequacy faced by ground magnetogram studies caused when a magnetic station is not near enough to the onset location. Pi2 onsets can also be delayed with respect to auroral breakups, as illustrated by *Liou et al.* [1998].

2. Observations

We examined UVI data for March–July, 1996, and January–October, 1997, when favorable viewing of the northern polar region was available. For these two periods, 558 auroral breakups were identified visually by scanning the time sequence of global auroral images. Of these, 102 events occurred when GEOTAIL was in the region tailward of $X_{gsm} \approx -7\ R_E$ and $|Y_{gsm}| \leq 20\ R_E$. We present one such event to illustrate the tail observations with the simultaneous global auroral morphology. We then summarize the tail observations in association with auroral breakups by constructing the time sequence of the synoptic patterns of plasma flow and magnetic field changes based on observations from these 102 events.

April 28, 1996

Figure 1 shows a time sequence of auroral images from POLAR. The auroral breakup occurred at ~1622 UT in the premidnight sector (~23 MLT). After expansion onset, the main auroral disturbance spread in local time and latitude, developing into an auroral bulge as expected for a substorm evolution. Poleward expansion was rather gradual for this substorm, ~1° at 1628 UT, ~2° at 1633 UT, ~3° at 1639 UT, and ~5° at 1650 UT.

GEOTAIL was located at GSM coordinates (–14, 9, –1) R_E during this substorm. Figure 2 shows plasma measurements made by the Low Energy Particle (LEP) instrument [*Mukai et al.*, 1994] and magnetic field measurements from GEOTAIL [*Kokubun et al.*, 1994]. After auroral breakup, GEOTAIL was embedded well within the central plasma sheet with the number density in the range ~0.6–0.8 cm^{-3}. Note that in two intervals (near ~1630 and ~1636 UT), B_x was nearly zero, indicating that GEOTAIL was very close to the neutral sheet, and yet

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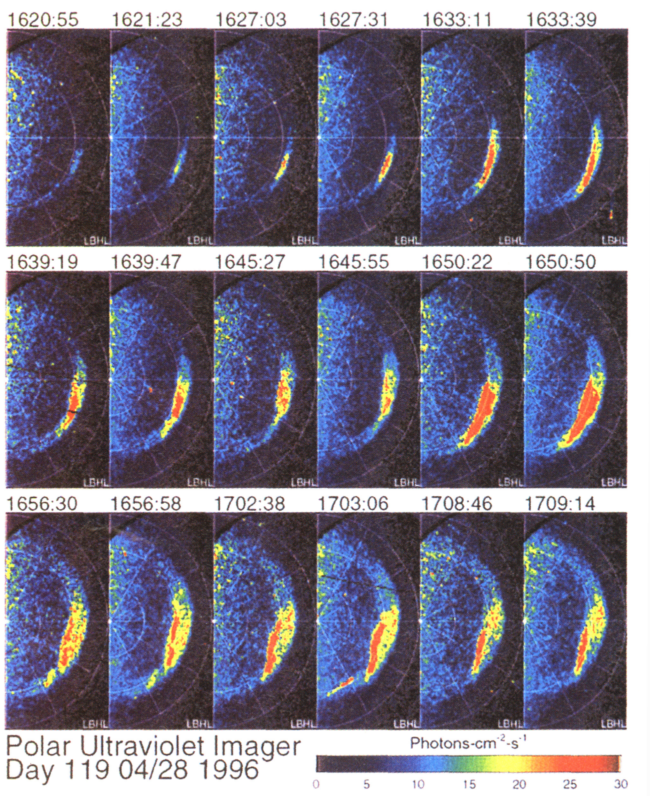

Figure 1. A temporal sequence of global auroral images from POLAR UVI (LBHL [long] filter images only) showing the auroral substorm on April 28, 1996. The MLT meridians are given in 2-hour intervals, with dusk at the bottom, midnight to the right, and dawn at the top. AACGM latitudes are given in 10° increments.

no large flow ($|V_x| > 200$ km/s) was observed. Significant tailward–duskward plasma flow was observed only at ~1650 UT, i.e., ~28 min after the auroral breakup, and was accompanied by positive B_z (not conforming to neutral line signature). Therefore, even at this late stage of the substorm, there was no indication of significant earthward transport of plasma and magnetic flux from the mid-tail to the near-Earth region. Note also the B_z was occasionally negative (e.g., 1645–1646 UT) but was not accompanied by significant tailward flow (also not conforming to neutral line signature). This event serves as a good example to demonstrate that not all substorms necessarily generate significant flow activity within the entire midnight sector ($|Y_{gsm}| \leq 10\ R_E$) of the plasma sheet at substorm onset and within the entire substorm-disturbance MLT sector of the plasma sheet during substorm expansion.

Synoptic Pattern of Plasma Flows and Magnetic Field Changes

Figure 3 shows a synoptic flow pattern at 12 time snapshots, from 20 min before to 20 min after auroral breakup. The time relative to the auroral breakup time is given at the top left of each frame. Each snapshot is obtained by averaging the plasma flow measurements (at ~12-s resolution) over a 1-min interval. Open circles denote times when the number density falls below 0.1 cm^{-3} (no flow vector is plotted for these times). This is because the plasma sheet boundary layer has a typical number density of ≤0.1 cm^{-3} [*Baumjohann*, 1993], and we are more interested in flows in the central plasma sheet.

From this superposed epoch analysis, one may notice events with large flows during substorms. In some of these events, large flows also were seen before auroral breakup. This is illustrated by the event at (X, Y) ≈ (–30, 6) R_E, which showed large tailward flow 10 min after onset and slightly reduced flow speed 20 min before onset. Furthermore, for many events, such as that shown in Figure 2, no significant flow was observed near auroral breakup even though the satellite was well embedded within the central plasma sheet. The synoptic flow patterns after breakups show some large flows, similar to that obtained with IMP 6 plasma measurements about two decades ago [*Lui et al.*, 1977]. However, it does not reveal the presence of any large-scale flow pattern of significant magnitude before onset. There were significant tailward flows beyond ~25 R_E after onset, but they were transient, as the time sequence indicates. These results indicate that expansion phase activity is dominated by localized, transient disturbances in the tail plasma sheet as suggested in the substorm synthesis model of *Lui* [1991].

We have also examined the average of flow components as a function of time. The result indicates that $\langle V_x \rangle \approx$ 10–20 km/s and $\langle V_y \rangle \approx$ 10 km/s within ~5 min before substorm onset. Since flows are dominated by localized transient activities, we have also calculated the flow averages excluding high bursty flows (>250 km/s). This procedure gives $\langle V_x \rangle \approx$ 5–10 km/s and $\langle V_y \rangle \approx$ 5 km/s within ~5 min before substorm onset. Therefore, any large-scale flow pattern before a substorm is of small magnitude (≤20 km/s).

For the transport of magnetic flux earthward to give rise to dipolarization, only convective (perpendicular) flows are effective since flows along the magnetic field transport no magnetic

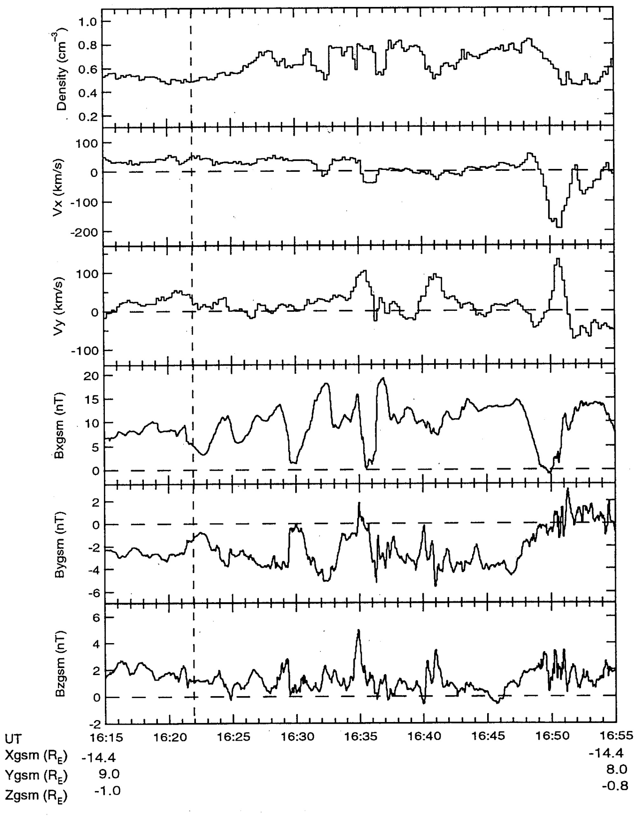

Figure 2. Plasma and magnetic field measurements from GEOTAIL on April 28, 1996. Auroral breakup time at vertical dashed line.

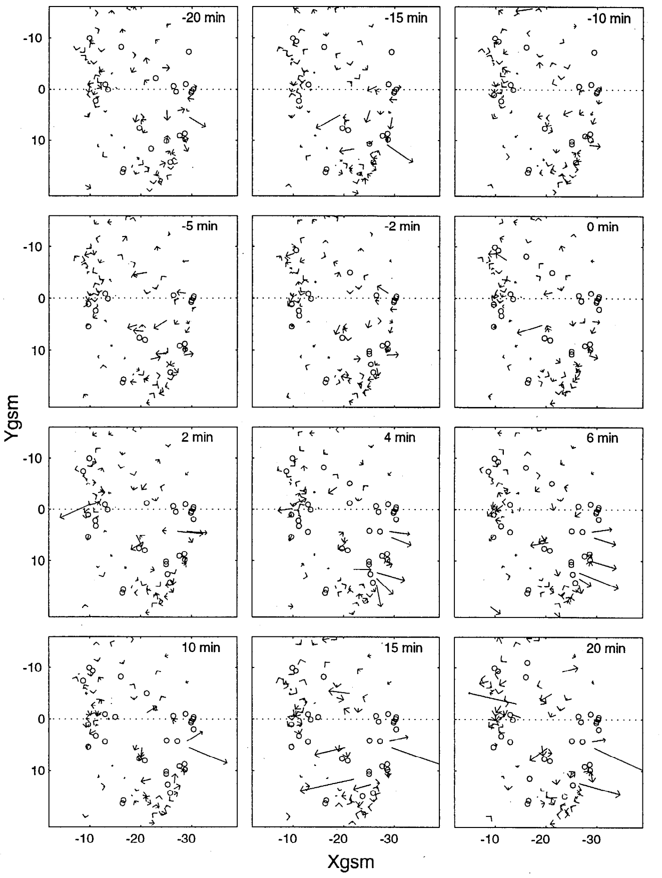

Figure 3. A temporal sequence of synoptic patterns of total plasma flow constructed from superposed epoch analysis of 102 substorm events. The scale is 100 km/s per R_E.

flux. We have therefore examined the time sequence for convective flows shown here in Figure 4. The results indicate (1) little earthward convective flow from the mid-tail to the near-Earth region before auroral breakups and (2) convective flow magnitudes substantially less than the total flow magnitudes. For example, the large earthward flow event in Figure 3 at (X, Y) ≈ (−18, 5) R_E at breakup (0 min) becomes a small earthward–duskward flow event in Figure 4, indicating that the event carries little plasma and magnetic flux inward.

Figure 5 is a synoptic pattern of changes in the B_z component of the magnetic field relative to the value averaged over 10 min before auroral breakup. This time sequence indicates dipolarization in the near-Earth region after auroral breakup with less significant dipolarization beyond X ≈ −20 R_E. Furthermore, comparison of Figures 3, 4, and 5 shows that near-Earth dipolarizations were not preceded by significant earthward flow transporting magnetic flux from the mid-tail region.

3. Summary and Discussion

Using global imaging of auroral breakups by POLAR UVI to identify substorm onsets, we investigated the behavior of the plasma sheet from 20 min before to 20 min after the onset time. We have found the following results:

(1) Strong plasma flows preceding or at substorm onsets are not always observed, even when GEOTAIL is well within the plasma sheet in the midnight sector, a result consistent with the findings of *Nagai et al.* [1988] (see their Figure 3).

(2) Some events of strong plasma flows seen just after substorm onset in the mid-tail exhibit strong flows even well before onset, suggesting that not all substorm onsets are isolated and/or that strong flows are always present but the probability of detecting one is merely enhanced during substorms.

(3) The time sequence of synoptic flow pattern suggests the plasma flow activity to be rather transient (duration of about a few minutes) and spatially localized in the plasma sheet.

(4) The accompanying changes in the B_z component show clear dipolarization in the near-Earth region but less significant dipolarization in the mid-tail region (beyond ~20 R_E).

The result of flow activity being temporally transient and spatially localized is consistent with predictions of the substorm synthesis model [*Lui*, 1991] and agrees with results from previous multi-satellite studies, which indicate fast bursty bulk flows to be spatially limited [e.g., *Angelopoulos et al.*, 1997]. The synoptic flow pattern bears remarkable similarity to the IMP 6 result [*Lui et al.*, 1977]. While the result rules out the occurrence of a large-scale (>10 R_E in the dawn–dusk direction) pattern of plasma flows of significant magnitude (>100 km/s) during substorms, it does not exclude the possibility of a flow pattern with a large-scale, slow (≤20 km/s) flow or with spatially localized large flows at auroral breakup. Although not shown here, we noted that most substorms in this study have onsets within 20–23 MLT. Furthermore, no substorm in this study shows development skewed abnormally in local times. Therefore, the variability in plasma sheet activity is likely to be typical for a substorm even though the synoptic flow pattern is constructed from different substorms.

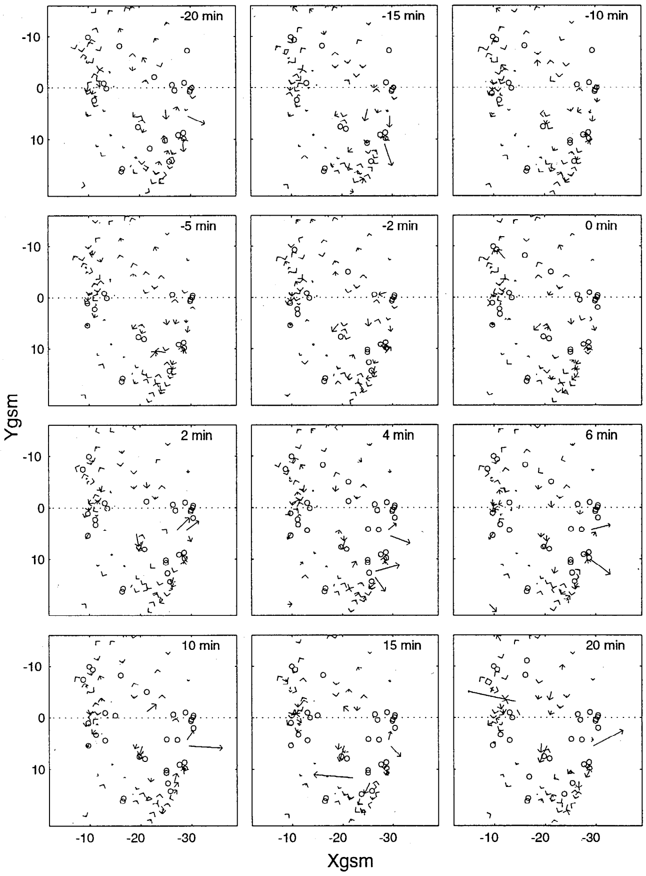

Figure 4. A temporal sequence of synoptic patterns of plasma flow perpendicular to the magnetic field.

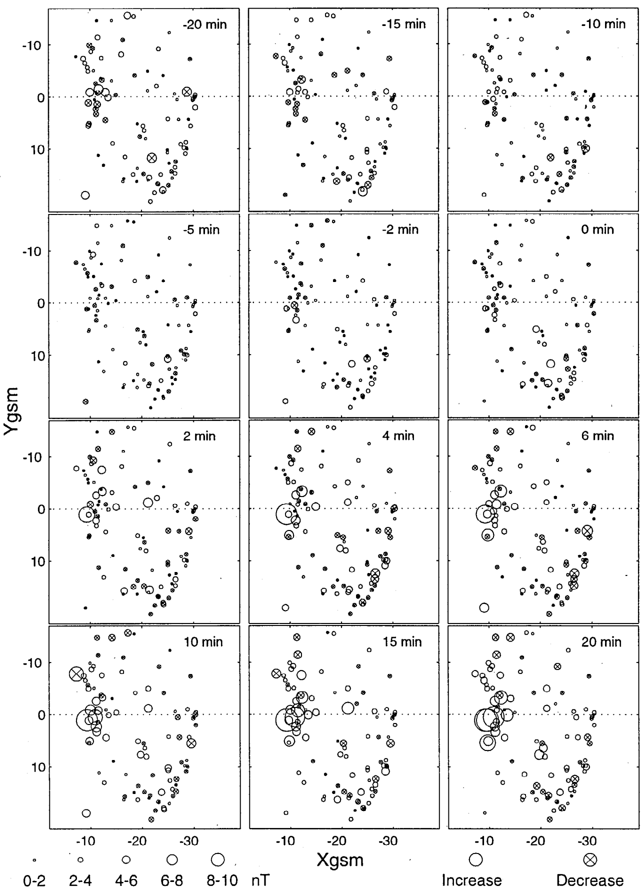

Figure 5. A temporal sequence of magnetic field changes in the B_z component relative to the averaged value within 10 min before auroral breakups. Symbol size represents amount of change; open circles represent increases over the reference value (i.e., dipolarization); closed circles represent decreases.

Although some agreements exist between our results and those of *Nagai et al.* [1998], our methodology is different. Nagai et al. used the maximum flow within a 20-min time window around the Pi2 onset to classify the flow signature in the plasma sheet, differentiating the events only by the sign of the V_x flow component. Our study differs from the previous one in three important ways: (1) the auroral breakup from global auroral imaging is used to mark the onset time for the superposed epoch analysis; (2) the full plasma flow vector on the equatorial plane is shown (as was done in *Lui et al.* [1977]) to reveal any significant dawn–dusk flow component; and (3) the time sequence of plasma flows is provided to indicate the flow duration and variability. We believe these improvements allow more insight into plasma transport during substorms.

There is also a major difference between the conclusion of Nagai et al. and the implication of the present result. Based on the occurrence of some events in which onsets of tailward flows and southward B_z beyond ~20 R_E precede the Pi2 onset, Nagai et al. concluded that substorms are initiated by magnetic reconnection at mid-tail. The present result using auroral breakups to mark substorm onsets does not show indication of strong flows substantially (≥2 min) preceding substorm onsets and therefore does not support the conclusion reached by Nagai et al. We note from their individual event example (their Figure 2) that Pi2 onset precedes onsets of magnetic reconnection signatures for the first event, but the order is reversed for the later two events. Therefore, it is possible that Pi2 onset precedes mid-tail reconnection for the first substorm in a substorm series, whereas the later ones may involve reconnection before the subsequent substorm onsets/intensifications because the tail is already disturbed by the first substorm in the series. Further work is necessary to examine this possibility.

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