Relationship between magnetotail variations and auroral activities during substorms

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[1] We have compared magnetotail variations with auroral activities during 8 substorms using GEOTAIL and Polar UVI data. In the 1737 UT substorm event on 15 December 1996, auroral breakups and intensifications were highly correlated with fast plasma flows with the variations in the north-south magnetic field and the total pressure in the magnetotail. GEOTAIL was located around $X \sim -21$ R_E, and several fast tailward flows were observed in the early expansion phase with the southward magnetic field and the total pressure enhancement, associated with plasmoids. These flows were observed simultaneously with or within about 1 min of auroral breakups or pseudobreakups. In the late expansion or recovery phase, some fast Earthward flows were observed with the northward magnetic field as well as the total pressure enhancement slightly earlier than small auroral intensifications. These observations imply that the activation and tailward retreat of the near-Earth neutral line is intermittent. Furthermore, including the other events, we found that the total pressure decrease in the magnetotail can be correlated with auroral activity better than the fast plasma flow. The total pressure in the magnetotail significantly decreases during auroral breakups or poleward expansions of the auroral bulge but slightly decreases during pseudobreakups. The duration of the expansion and the maximum size of the auroral bulge are closely correlated with the duration and amount of total pressure decrease in the magnetotail, respectively. These results imply that the magnitude of auroral activities associated with substorms depends on that of energy dissipation in the magnetotail. *INDEX TERMS:* 2788 Magnetospheric Physics: Storms and substorms; 2744 Magnetospheric Physics: Magnetotail; 2704 Magnetospheric Physics: Auroral phenomena (2407); 7835 Space Plasma Physics: Magnetic reconnection; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; *KEYWORDS:* substorms, auroral breakup, plasma flow, total pressure, GEOTAIL, Polar UVI

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1. Introduction

[2] Energy accumulates in the magnetotail by intrusion of the solar wind energy through the dayside magnetic reconnection. When an internal catastrophic instability is generated or external conditions change, the stored energy is released. The severe dissipation causes the substorm expansion.

[3] Various models have been proposed for the triggering mechanism of the magnetospheric substorm: the current disruption model [*Lui*, 1996], the near-Earth neutral line (NENL) model [*Hones*, 1976; *Baker et al.*, 1996], the magnetosphere-ionosphere coupling model [*Kan et al.*, 1988], the external triggering model [*Lyons*, 1995], and others. In the current disruption model, the ballooning instability [e.g., *Roux et al.*, 1991] or the kinetic drift instability [*Lui et al.*, 1990] causes the current disruption around $X \sim -10$ R_E. The dipolarization then occurs in a non-MHD manner [*Lui et al.*, 1999], and the current wedges are formed. On the other hand, some recent studies from the GEOTAIL data concluded that the magnetic reconnection plays an important role in the substorm triggering [*Nagai et al.*, 1998; *Machida et al.*, 1999; *Miyashita et al.*, 1999, 2000, 2001]. *Miyashita et al.* [2000] concluded that a substorm expansion onset is triggered by the magnetic reconnection, which initially takes place around $X \sim -20$ R_E in the premidnight sector. A few minutes later, the dipolarization occurs around $X \sim -10$ R_E simultaneously with the substantial plasmoid evolution in the region of $-23 > X > -30$ R_E. However, there is still much debate on the substorm triggering mechanism.

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[4] During substorms, various phenomena occur in the magnetosphere, in the ionosphere, and on the ground: dipolarization, formation of the current wedges, energetic particle injection around geosynchronous orbit, plasmoid, bursty bulk flow, auroral brightening, westward electrojet, and Pi2 pulsation. Quite similar phenomena can be observed at pseudobreakups as well, although they are weaker, more localized, and more short-lived [e.g., *Koskinen et al.*, 1993; *Ohtani et al.*, 1993; *Nakamura et al.*, 1994; *Petrukovich et al.*, 1998; *Aikio et al.*, 1999]. Pseudobreakups would be caused by the same physical process that causes substorms [*Nakamura et al.*, 1994; *Rostoker*, 1998]. However, there is no global development of activities at pseudobreakups, while activities develop globally at substorms: The auroral substorm has a poleward expansion of brightening [*Akasofu*, 1964]. The region of the tail current disruption expands tailward in the course of a substorm, although the spatial scale of the onset region of the current disruption is not different between substorms and pseudobreakups [*Ohtani et al.*, 1993].

[5] Other auroral activities include the poleward boundary intensification (PBI) [*Lyons et al.*, 1999; *Zesta et al.*, 2000], which is a nightside auroral signature moving equatorward from the poleward boundary of the auroral oval and is associated with processes different from substorms. The PBI occurs many times during time intervals of ~1 hour of all levels of geomagnetic activity. The typical duration of each activation is less than 10 min. The intensity of the PBI is generally not as bright as that of the substorm expansion aurora. Corresponding to the PBIs, earthward bursty flows with the northward magnetic field are seen in localized regions of the plasma sheet. Furthermore, the PBIs are associated with Pi2 pulsations and perturbations of the north-south magnetic field on the ground, and with weak injections of particles with a few tens of keV and oscillations of the north-south magnetic field near geosynchronous orbit. Unlike substorms, however, the source region of the bursty flows would be located in the distant tail, and the activations do not develop to a large-scale disturbance.

[6] A number of recent studies have investigated the relationship between auroral activities and transient fast plasma flows in the magnetotail. Fast Earthward flows, which are localized, can be observed, corresponding to substorm auroral breakups and pseudobreakups [e.g., *Angelopoulos et al.*, 1997; *Fairfield et al.*, 1999] as well as poleward boundary intensifications or north-south aligned structures [e.g., *Henderson et al.*, 1998; *Lyons et al.*, 1999; *Sergeev et al.*, 2000; *Zesta et al.*, 2000]. On the other hand, tailward moving plasmoids or magnetic flux ropes correspond to auroral brightenings associated with substorms or pseudobreakups [*Lui et al.*, 1998; *Ieda et al.*, 2001]. Most of these previous studies focused on either Earthward or tailward plasma flows in relation to magnetotail variations.

[7] In the present study, we investigated the correlation between variations in the magnetotail and auroral activities, i.e., auroral breakups and intensifications including pseudobreakups, based on our previous statistical results of *Machida et al.* [1999] and *Miyashita et al.* [1999, 2000, 2001]. We examined fast plasma flows which were first directed tailward and then turned Earthward. Furthermore, we focused on the total pressure variations in the magnetotail in particular, while much attention was paid to the plasma flow in the previous studies. We found that there is a good correlation between plasma flows in the magnetotail and auroral activities in some events, but the total pressure decrease in the magnetotail can be correlated with auroral activity better than the fast plasma flow. Also, we suggest that the magnitude of the auroral activities depends on that of the energy dissipation in the magnetotail.

2. Data Set

[8] To investigate magnetotail variations, we used the ion moments and the magnetic field data obtained from the low-energy particle experiment (LEP) [*Mukai et al.*, 1994] and the magnetic field experiment (MGF) [*Kokubun et al.*, 1994], respectively, on board the GEOTAIL spacecraft. The time resolution of these data is 12 s. The ion moments were calculated from ions from a few tens of eV/q to ~40 keV/q under the assumption that all ions are protons.

[9] For auroral activities we examined the Polar ultraviolet imager (UVI) data [*Torr et al.*, 1995]. The global auroral images used in this study were obtained at two bands of the N_2 Lyman-Birge-Hopfield (LBH) emission, i.e., a shorter wavelength band (LBHS, 1400–1600 Å) and a longer wavelength band (LBHL, 1600–1800 Å). The integration periods of the first and second images are 18 s and 36 s, respectively, for both LBHS and LBHL data. Note that the LBHL-to-LBHS intensity ratio varies with energies of precipitating particles [e.g., *Strickland et al.*, 1983]. The UVI image data are shown in the altitude adjusted corrected geomagnetic (AACGM) coordinates [*Baker and Wing*, 1989].

[10] We selected eight substorm events, as listed in Table 1. In these events, tailward flows were first observed, and then Earthward flows were observed in the magnetotail. Here we did not necessarily require that GEOTAIL remain in the high-β (>1) plasma sheet throughout the substorm events. GEOTAIL was located in $-18 > X > -28\ R_E$ in the premidnight sector except for one event in which GEOTAIL was around $X \sim -13\ R_E$ in the postmidnight sector.

3. Case Studies

3.1. 15 December 1996 Substorm

[11] The substorm event that occurred at ~1737 UT on 15 December 1996 is a good example of correlation between fast plasma flows in the magnetotail and auroral activities in the ionosphere. The fast plasma flows were first directed tailward and then turned Earthward. GEOTAIL was located around $(X, Y) \sim (-21, 7)\ R_E$ in geocentric solar magnetospheric (GSM) coordinates. Figure 1 shows 2-hour Pi2 and GEOTAIL data from 1720 UT to 1920 UT. These data include the Pi2 pulsations at Kakioka (0220–0420 LT), three components of the plasma flow and the magnetic field, the total magnetic field, the total (upper line) and ion (lower line) pressures, and the ion β. Since the X component of the magnetic field B_x was mainly directed tailward throughout the time interval, GEOTAIL was in the southern part of the magnetotail except for several excursions to the northern part. The Z component of the magnetic field B_z decreased until ~1735 UT, corresponding to plasma sheet thinning, which started at ~1615 UT. The total pressure increased from ~1630 UT, corresponding to the energy storage during the substorm growth phase. After 1742 UT, several fast

Table 1. Auroral Breakups and Intensifications during Selected Substorm Events[a]

				Onset Location		GEOTAIL Location	
Event	Date	UT	O/I[a]	MLT, hour	MLat, deg	X, R_E	Y, R_E
1	96/12/04	2140:18 ± 19	O	23.0	68	−18.5	7.5
		2157:11 ± 37	O	21.5	70	−18.9	7.3
2	96/12/15	1737:00 ± 60	O′	1.0	?	−20.9	7.7
		1808:02 ± 18	O	22.5	65	−21.3	7.5
		1816:56 ± 148	I			−21.5	7.3
3	96/12/15	2052:07 ± 37	O	21.0	65	−23.0	6.0
		2100:23 ± 18	I			−23.1	6.0
		2107:27 ± 37	I			−23.1	6.0
4	96/12/16	0002:33 ± 18	O	23.0	68	−24.6	4.3
		0040:16 ± 37	O	0.5	70	−24.8	4.0
		0049:28 ± 37	I			−24.9	3.8
5	96/12/21	1700:36 ± 19	O	23.5	66	−27.8	0.9
		1722:04 ± 18	I			−27.9	0.9
6	97/03/24	1028:10 ± 18	O	21.0	66	−22.2	8.9
7	97/03/29	1308:46 ± 18	O	22.0	66	−20.9	14.6
		1329:20 ± 37	I			−21.0	14.2
		1438:56 ± 18	O	20.5	65	−21.1	13.3
8	97/10/10	2134:50 ± 18	O	21.5	59	−13.1	−1.8

[a]Times and onset locations were determined from Polar UVI images except for 1737 UT substorm onset on 15 December 1996, which was determined from ground magnetic field data. O and I denote onset (auroral breakup) and intensification (further expansion of the auroral bulge), respectively.

tailward flows were observed in association with the plasmoids, which had the southward magnetic field and the total pressure enhancement and sequent decrease in them. Most of the tailward flows had duskward and equatorward components. In particular, a very fast tailward flow of ∼1400 km/s was seen with a equatorward flow component of more than 600 km/s and B_z of ∼14 nT at 1823 UT. After that, some fast Earthward flows were observed with the northward magnetic field, or dipolarization. These flows accompanied the total pressure enhancement and sequent decrease.

[12] We examined Polar UVI data to compare the magnetotail variations with auroral activities. The times of auroral breakups (substorm onsets) and intensification (further expansion of the auroral bulge) are indicated by O and I at the top of Figure 1, respectively, with numbers and vertical solid lines; those of maximum auroral bulges are indicated by M with vertical dotted lines. The times of pseudobreakups or small intensifications are indicated by P with vertical dashed lines. Figure 2 shows examples of pseudobreakups, auroral breakup, and intensifications. Only the selected nightside images are shown here, although we examined all LBHL and LBHS nightside images. The magnetic midnight and dawn are plotted to the right and top, respectively. The contours of AACGM magnetic latitudes are drawn from 90° with an increment of 10°. The time indicated at the top of each panel is the center of data integration period. The times of the auroral activities indicated by the vertical lines in Figure 1 were determined as the center of the interval between the end time of the data in which an auroral activity started and the end time of the previous data [see *Liou et al.*, 2000].

[13] The panels in the top row of Figure 2 show a pseudobreakup that occurred at ∼22.0 MLT and ∼67° MLat at 1757:37 UT ±18 s (P5). In the postmidnight sector the aurora activity was high owing to the previous first auroral breakup that occurred at ∼1737 UT (O′1). The exact onset time and location of O′1 could not be determined from the UVI data, since the data were not available before 1726 UT and this onset probably occurred out of view of the UVI instrument. However, this onset time of O′1 could be determined from positive bays at low- and midlatitude ground stations of Beijing Ming Tombs, Lunping, and Phu Thuy (∼1 MLT). The pseudobreakup P5 was very large and most intensified at 1759:46 UT ±37 s (labeled 1800:14), but it did not develop globally. The middle two rows show the second auroral breakup and the further poleward expansion of the auroral bulge. The auroral intensity started to become stronger at ∼22.5 MLT and ∼65° MLat at 1808:02 UT ±18 s (O2), and then the intensified region expanded westward.

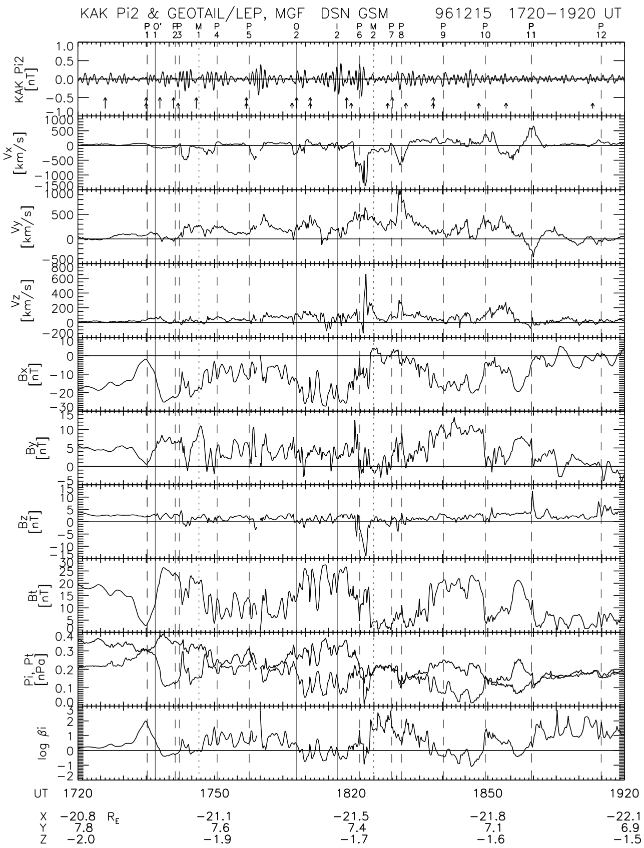

Figure 1. From top to bottom, the Pi2 pulsations at Kakioka (0220–0420 LT), three components of the plasma flow and the magnetic field, the total magnetic field, the total (upper line) and ion (lower line) pressures, and the ion β observed by GEOTAIL from 1720 UT to 1920 UT. The times of auroral breakups (substorm onsets) and intensification (further expansion of the auroral bulge) are indicated by O and I, respectively, at the top of the figure, with vertical solid lines; those of maximum auroral bulges are indicated by M with vertical dotted lines. The times of pseudobreakups or small intensifications are indicated by P with vertical dashed lines. These times were determined from Polar UVI images except for the substorm onset O′1 which was determined from ground magnetic field data. Pi2 onset times at Kakioka and Hermanus are indicated by long and short arrows in the top panel, respectively.

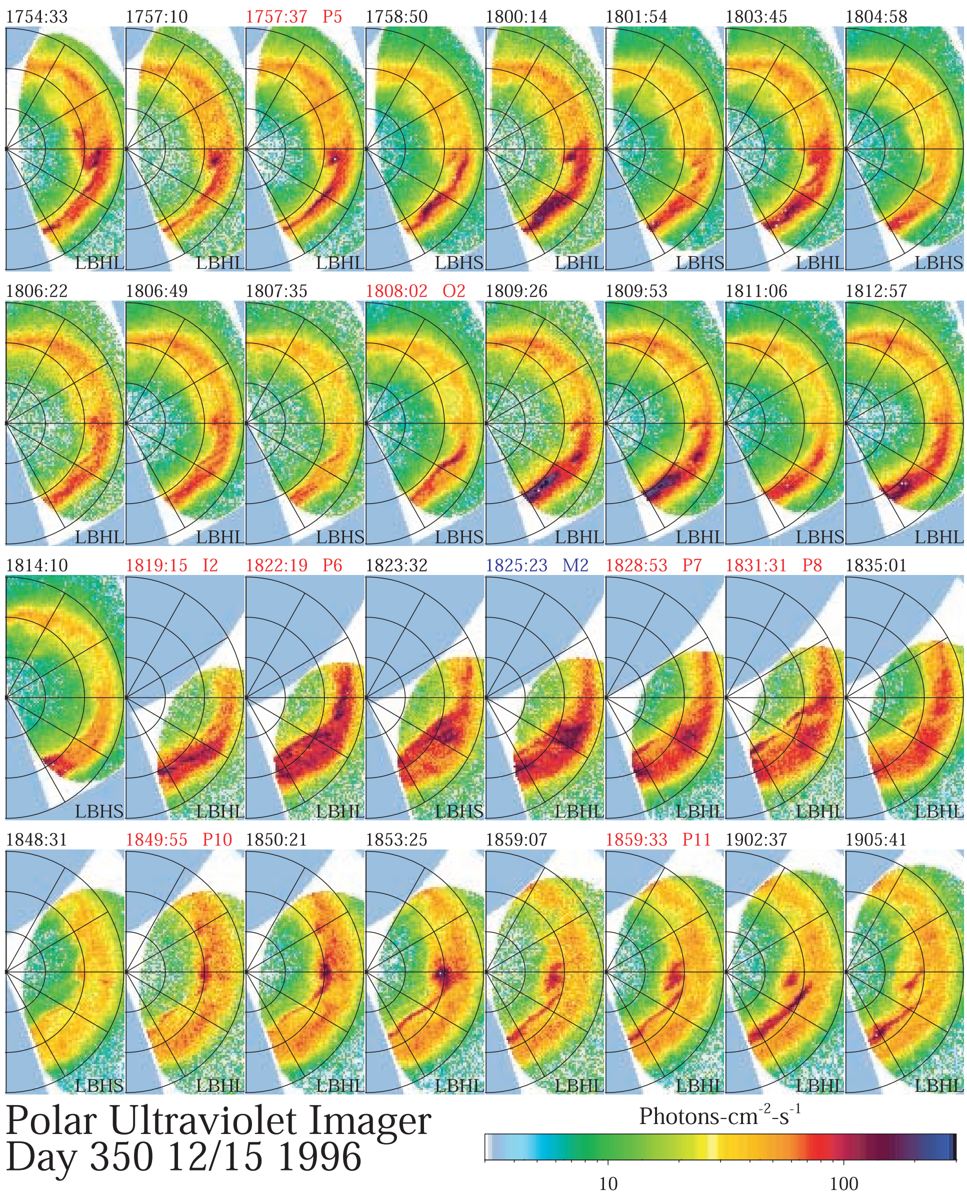

Figure 2. Selected nightside images from Polar UVI on 15 December 1996, showing examples of pseudobreakups, auroral breakup, and intensifications. The magnetic midnight and dawn are plotted to the right and top, respectively. The contours of AACGM magnetic latitudes are drawn from 90° with an increment of 10°. The time indicated at the top of each panel is the center of data integration period in universal time. The panels with red time tag show the auroral breakup (substorm onset, O), intensification (further expansion of the auroral bulge, I), or pseudobreakup or small intensification (P), while that with blue time tag shows the maximum auroral bulge (M).

The auroral bulge, however, did not significantly develop until 1814:10 UT ±18 s. At 1816:56 UT ±148 s (this large uncertainty is due to the unfortunate data gap from 1814:29 UT to 1819:05 UT), the auroral bulge started to further expand poleward around 21.0 MLT (labeled 1819:15 I2) and became largest at 1824:55 UT ±37 s (labeled 1825:23 M2). The range (maximum width) of the auroral bulge was 19.5–0.0 hours (4.5 hours) in MLT and 62–74° (12°) in MLat, where the values of MLT and MLat were determined with accuracies of 0.5 hours and 1°, respectively. Unfortunately, the western edge of the auroral bulge could not be identified due to the UVI view, so the width in MLT may be larger. Small intensifications were also observed at ~22.5 MLT and ~68° MLat at 1821:51 UT ±37 s (labeled 1822:19 P6), at ~20.0 MLT and ~74° MLat at 1828:53 UT ±18 s (P7), and at ~23.0 MLT and ~70° MLat at 1831:03 UT ±37 s (labeled 1831:31 P8). P8 may be a poleward boundary intensification (PBI) which is accompanied by a north-south aligned structure. The bottom row shows auroral activities during the late expansion phase or the recovery phase. The small intensification occurred at ~0.0 MLT and ~70° MLat at 1849:27 UT ±37 s (labeled 1849:55 P10). At 1859:33 UT

±18 s, two small intensifications were seen simultaneously at ~23.0 MLT and ~71° MLat and at ~20.0 MLT and ~73° MLat (P11). These activities occurred near the poleward boundary of the auroral oval and are possibly PBIs.

[14] The plasma flows in the magnetotail were closely correlated with the auroral activities that include the auroral breakups, the pseudobreakups, and the intensifications. The fast tailward flow at ~1742 UT was observed 1 min after the small intensification at 1741:22 UT ±37 s (P2) or simultaneously with the pseudobreakup at 1742:17 UT ±18 s (P3), although it is not clear which activity corresponds to the plasma flow. The tailward flow at ~1745 UT was observed 3 min after the pseudobreakup P3 or 6 min before the small intensification at 1750:34 UT ±37 s (P4), and was intensified at ~1747 UT. There seems to be a small intensification at 1744:26 UT ±37 s, which may correspond to this tailward flow. The next fast tailward flow was observed at ~1758 UT, which was simultaneous with the pseudobreakup at 1757:37 UT ±18 s (P5). The second substorm onset at 1808:02 UT ±18 s (O2) corresponds to the tailward flow at ~1807 UT, or 1 min earlier. The further auroral intensification at 1816:56 UT ±148 s (I2) may correspond to the very fast tailward flow at ~1820 UT. Since the uncertainty of the timing of the intensification is very large owing to the data gap, relative timing is also very ambiguous, i.e., 0–6 min. Also, since GEOTAIL was in the plasma sheet boundary layer in most of the interval from 1809 UT to 1820 UT, it is possible that the tailward flow associated with the plasmoid around the auroral intensification was not observed. The tailward flow at ~1820 UT is possibly related to the small intensification at 1821:51 UT ±37 s (P6), or 2 min later. The tailward flow at ~1829 UT was simultaneous with the small intensification at 1828:53 ±18 s (P7). The next two small intensifications at 1831:03 ±37 s (P8, possibly the PBI) and 1840:15 ±37 s (P9) did not have clear correlations with fast plasma flows. During the late expansion or recovery phase, the fast flows turns Earthward. The fast earthward flows at ~1848 UT, 1858 UT, and 1913 UT corresponded to the small intensifications at 1849:27 UT ±37 s (P10), 1859:33 UT ±18 s (P11), and 1914:53 UT ±18 s (P12), respectively, which occurred 1 or 2 min after the fast flows. The auroral activity that corresponds to the fast tailward flow at ~1852 UT was not observed.

[15] For the 1737 UT substorm event on 15 December 1996, several fast tailward flows were first observed in good correlation with the auroral activities during the early expansion phase. Then, during the late expansion or recovery phase, the fast plasma flows turned Earthward and were observed about 1 min before the small auroral intensifications. These observations imply that the near-Earth neutral line was first located Earthward of GEOTAIL, $X \sim -21\ R_E$, and then it retreated tailward. We will discuss this later.

[16] We also investigated the correspondence between the total pressure decrease in the magnetotail (TPD) and the auroral activity. The total pressure is a good indicator of the unloading process in the magnetotail [*McPherron and Baker*, 1993]. Although the pressure balance in the Z direction would be broken in association with substorms [*Petrukovich et al.*, 1999], the TPD occurs and propagates in all regions of the plasma sheet, the plasma sheet boundary layer, and the lobe around substorm onsets [*Miyashita et al.*, 1999, 2000]. In the plasma sheet the total pressure enhancement is often observed with the fast plasma flow, and then the TPD occurs after the passage of the front of the flow. Even if a spacecraft is out of the plasma sheet, the TPD can be observed after the passage of the traveling compression region.

[17] We found that the TPD was also closely correlated with the auroral activity. From Figure 1 the enhancement and sequent decrease of the total pressure was observed in the tail, corresponding to the auroral breakups as well as the pseudobreakups or the small intensifications. Most of the pressure variations were accompanied by the plasmoid-associated fast tailward flows in the early expansion phase or the fast Earthward flows in the late expansion or recovery phase. The variations in the total pressure were rather complicated in this event, but some clear correspondence could be seen: for example, the TPD at 1757 UT corresponds to P5, that at 1830 UT to P7, that at 1848 UT to P10, and that at 1857 UT to P11. Some TPDs were not accompanied by the fast flows, probably due to the spacecraft locations, but were correlated with the auroral activities: the TPD at 1739 UT corresponds to O′1 and that at 1840 UT to P9. The pseudobreakup P1 did not seem to correspond to a TPD.

[18] Furthermore, the total pressure had a large decrease in association with the auroral breakup or the further poleward expansion of the auroral bulge. The total pressure decreased by ~40% from ~1739 UT for ~11 min, associated with the auroral breakup O′1. The duration of the auroral bulge expansion seems to be comparable to that of the TPD, although the exact time of O′1 was rather ambiguous. Associated with the auroral breakup O2, at which the auroral bulge did not significantly develop poleward immediately, the total pressure did not decrease much, and it continued to have a tendency to increase. However, associated with the intensification I2, at which the further expansion of the auroral bulge started, the total pressure decreased by ~52% from ~1819 UT for ~4 min. Although the time of I2 has the ambiguity of ~2.5 min, the duration of the bulge expansion, ~8 min, may be regarded as being comparable to that of the TPD. At the pseudobreakups or small intensifications, the total pressure decreased slightly and shortly. However, the TPD seemed to be relatively large when the intensity of the pseudobreakup was large, as seen at P5 and P11.

[19] For the Pi2 pulsations, we examined ground magnetic field data taken at the low-latitude stations of Kakioka (26.94° geomagnetic latitude and 208.29° geomagnetic longitude) and Hermanus (−42.58° geomagnetic latitude and 82.20° geomagnetic longitude). Kakioka was located in the postmidnight sector (2.4–4.3 MLT), and Hermanus in the premidnight sector (18.1–20.0 MLT) between 1720 UT and 1920 UT. The top panel in Figure 1 shows the H component at Kakioka for the Pi2 period range of 40–150 s. Long and short arrows indicate Pi2 onset times at Kakioka and Hermanus, respectively, which were determined with an accuracy of 1 min. We identified 15 Pi2 onsets where, if the difference between the onset times at the two stations was 1 min, we regarded the onsets as being due to the same event. Most of the Pi2 onsets had good correspondence to the onsets of the auroral activities, including the pseudobreakups. Out of 15

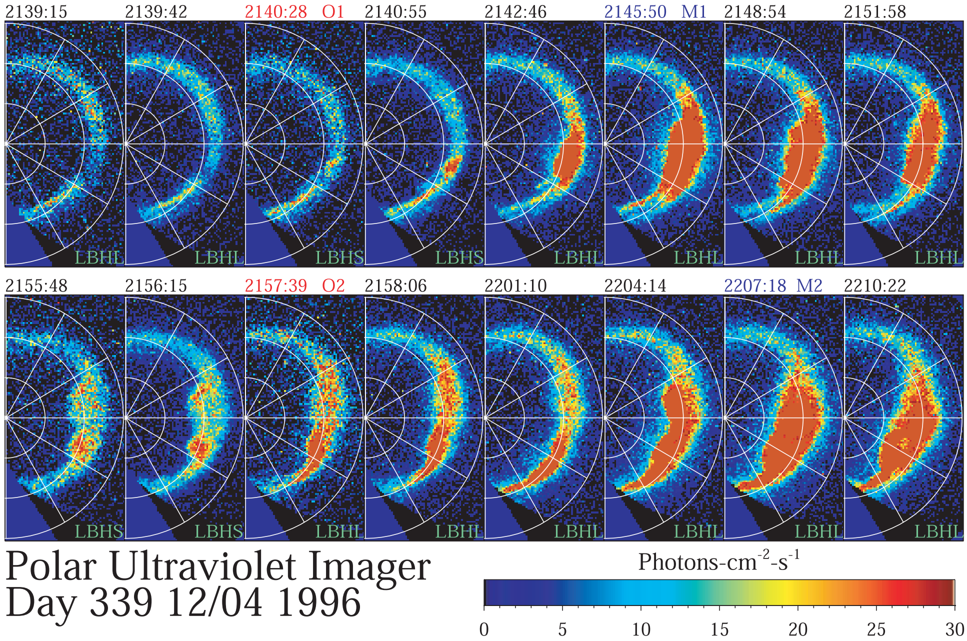

Figure 3. Selected nightside images from Polar UVI on 4 December 1996, showing two auroral breakups and expansions of the auroral bulge.

Pi2 onsets, 10 occurred within 2 min of the auroral onsets, 7 of which occurred within 0–1 min of the auroral onsets.

3.2. 4 December 1996 Substorm

[20] We also paid attention to variations in the total pressure in the magnetotail. The substorm event that occurred at ~2140 UT on 4 December 1996 shows that the total pressure decrease in the magnetotail can be correlated with auroral activity better than the fast plasma flow. This event also shows the clear difference in the TPD between the auroral breakup and the pseudobreakup.

[21] As shown in Figure 3, the auroral breakups occurred twice in this event. The first breakup occurred at ~23.0 MLT and ~68° MLat at 2140:18 UT ±19 s (labeled 2140:28 O1), and the auroral bulge had a maximum size at 2145:50 UT ±18 s (M1) ~5.5 min after the breakup. The second breakup occurred at ~21.5 MLT and ~70° MLat at 2157:11 UT ±37 s (labeled 2157:39 O2), and the auroral bulge had a maximum size at 2207:18 UT ±18 s (M2) ~10 min after the breakup. Pseudobreakups or small intensifications were observed at ~22.0 MLT and ~73° MLat at 2110:34 UT ±37 s (P1), at ~20.5 MLT and ~70° MLat at 2123:45 UT ±18 s (P2), at ~21.0 MLT and ~71° MLat at 2134:10 UT ±19 s (P3), at ~23.0 MLT and ~71° MLat at 2151:03 UT ±37 s (P4), and at ~0.0 MLT and ~75° MLat at 2217:43 UT ±18 s (P5) (not shown).

[22] Figure 4 shows 2-hour Pi2 and GEOTAIL data from 2100 UT to 2300 UT in the same format as Figure 1, where the Pi2 pulsations at Hermanus (21.5–23.4 MLT) are shown. GEOTAIL was located around (X, Y) ~ (−19, 7) R_E. The Z component of the magnetic field was decreased from ~2040 UT until the first auroral breakup O1, corresponding to the plasma sheet thinning. After several southward excursions of B_z, the dipolarization took place about 1 min before the second breakup O2. The total pressure increased from ~1950 UT until ~2045 UT, although a substorm seemed to occur before 2030 UT. Then the total pressure remained nearly constant until O1 except for decrease and increase from 2040 UT to 2058 UT. As shown in Figure 4, the total pressure in the tail had large decreases at both breakups, while it decreased only slightly (P2, P4, and P5) or did not decrease (P1 and P3) at the pseudobreakups. The first large decrease occurred about 1 min before O1 with the southward B_z, although the tailward plasma flow started to be observed after O1, probably due to the location of GEOTAIL. The total pressure was decreased by ~30% for ~5 min. The second large decrease occurred simultaneously with O2, which was accompanied by the dipolarization, and the total pressure decreased by ~65% for ~11 min. The duration of the poleward expansion of the auroral bulge was comparable to that of the TPD for both breakups.

3.3. 24 March 1997 Substorm

[23] The substorm event that occurred at ~1028 UT on 24 March 1997 is another example for the relationship between the TPD and the auroral activities. In Figure 5 the auroral breakup occurred at ~21.0 MLT and ~66° MLat at 1028:10 UT ±18 s (O1), and the auroral bulge immediately expanded poleward and had a maximum size at 1057:36 UT ±18 s (M1) ~30 min after O1. The postmidnight part of the auroral bulge also substantially developed from ~1050 UT and had a maximum at 1112:56 UT ±18 s (M2). Pseudobreakups were observed at ~0.5 MLT and ~68° MLat at 0947:04 UT ±18 s (P1) and at ~22.0 MLT and ~68° MLat at 1006:42 UT ±18 s (P2).

[24] Figure 6 shows Pi2 pulsations at Kakioka (18.8–20.8 MLT) and GEOTAIL data from 0940 UT to 1140 UT. GEOTAIL was located around (X, Y) ~ (−22, 9) R_E. The total pressure in the magnetotail did not decrease at the

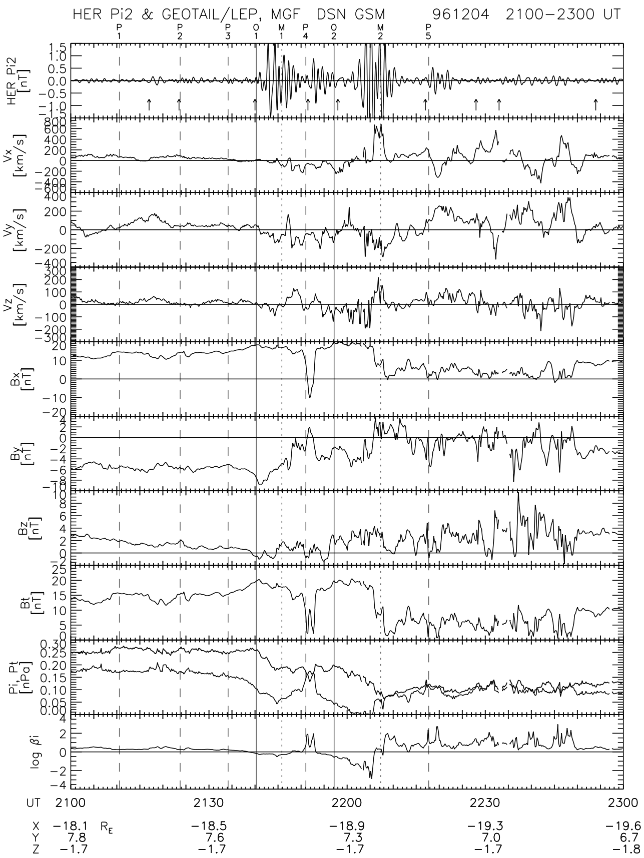

Figure 4. Two-hour Pi2 and GEOTAIL data from 2100 UT to 2300 UT on 4 December 1996, in the same format as Figure 1, except for showing Pi2 pulsations at Hermanus in the top panel.

pseudobreakup P1. After P2 the enhancement and sequent decrease of the total pressure were observed in association with the earthward flow with the northward B_z in the plasma sheet, and then the total pressure was nearly constant until the auroral breakup O1. Slightly after O1, the total pressure was enhanced owing to the tailward flow associated with the plasmoid. Then GEOTAIL moved away from the main part of the plasmoid to the low-β PSBL or lobe, and the southward B_z corresponding to the traveling compression region was observed, which lasted for ~6 min. The total pressure, however, decreased by ~65% for ~27 min, which is comparable to the duration of the poleward expansion of the auroral bulge. After that, the enhancement of the total pressure was observed at ~1058 UT, but its association with the expansion of the postmidnight part of the auroral bulge is not clear.

4. Auroral Bulge and Total Pressure Decrease

[25] In this section we show statistical results of the relationship between the development of auroral bulges and the TPD associated with auroral breakups or intensifications.

[26] Figures 7a and 7b show the correlations of the amount of TPD in the magnetotail in percentage with the maximum sizes of the auroral bulge in magnetic local time (MLT) and in magnetic latitude (MLat), i.e., the maximum longitudinal and latitudinal sizes, respectively. The number of auroral bulges is 13, including those associated with the second breakups. (A list of auroral breakups and intensifications is shown in Table 1.) Here, we used 1-min averaged values of the total pressure to remove rapid fluctuations. Also, we determined the bulge sizes in MLT and MLat with accuracies of 0.5 hours and 1°, respec-

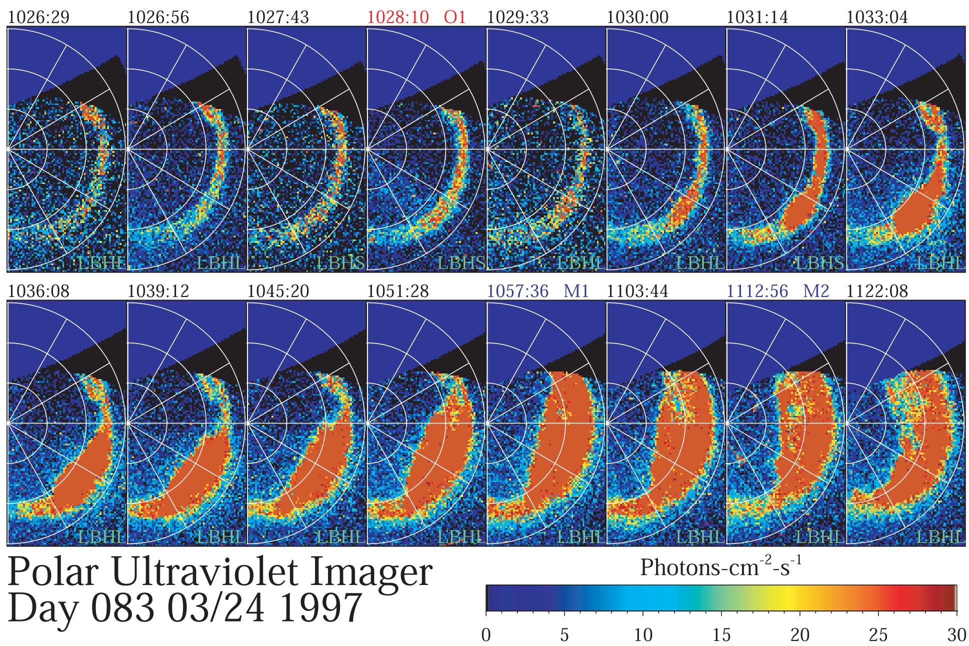

Figure 5. Selected nightside images from Polar UVI on 24 March 1997, showing the auroral breakup and expansion of the auroral bulge.

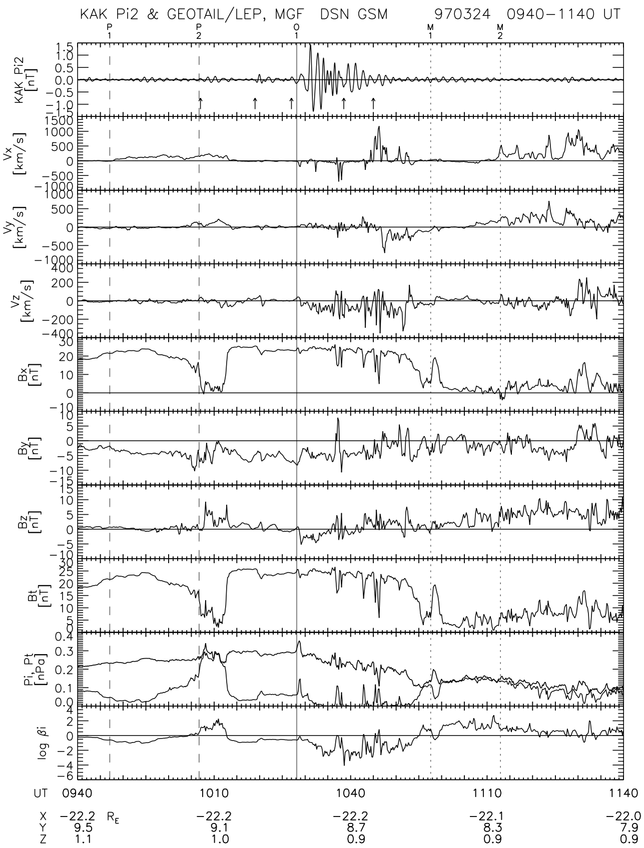

Figure 6. Two-hour Pi2 and GEOTAIL data from 0940 UT to 1140 UT on 24 March 1997, in the same format as Figure 1.

tively. Solid circles indicate events where the entire auroral bulge was observed. On the other hand, solid triangles indicate events where either the eastern or western edge (Figure 7a) and the equatorward edge (Figure 7b) could not be determined accurately due to the view of the UVI instrument; the bulge sizes may actually be larger for these events. From Figures 7a and 7b, the maximum size of the auroral bulge is closely correlated with the TPD in the magnetotail; the correlation coefficients are 0.64 for Figure 7a and 0.57 for Figure 7b.

[27] Figure 7c shows the amount of TPD as a function of the maximum bulge sizes in MLT and MLat, where the radii of the circles are proportional to the amount of TPD, as indicated in the upper-left corner of the panel. There is a tendency for the maximum size of the auroral bulge to become large if the total pressure in the magnetotail has a large decrease.

[28] Furthermore, the duration of the poleward expansion of the auroral bulge is closely correlated with that of the TPD, as shown in Figure 7d. Here, the duration of the bulge expansion was defined as the interval from when the bulge started to substantially expand poleward to when it was maximized. The correlation coefficient is 0.61.

5. Discussion

[29] We found that the development of the auroral bulge is closely correlated with the TPD, which implies that the magnitude of auroral activities associated with substorms depends on that of energy dissipation in the magnetotail. The intensity of substorms can be determined by various ionospheric or magnetospheric parameters [*McPherron and Baker*, 1993; *Lui*, 1993]: for example, the auroral electrojet, the total current in the westward auroral electrojet, the latitude of initial brightening, the amount of precipitating particles, the area of bright auroras, the maximum poleward advance of the auroral bulge, and the duration of auroral activities. The maximum size of the auroral bulge that we adopted is one of the ionospheric parameters of the sub-

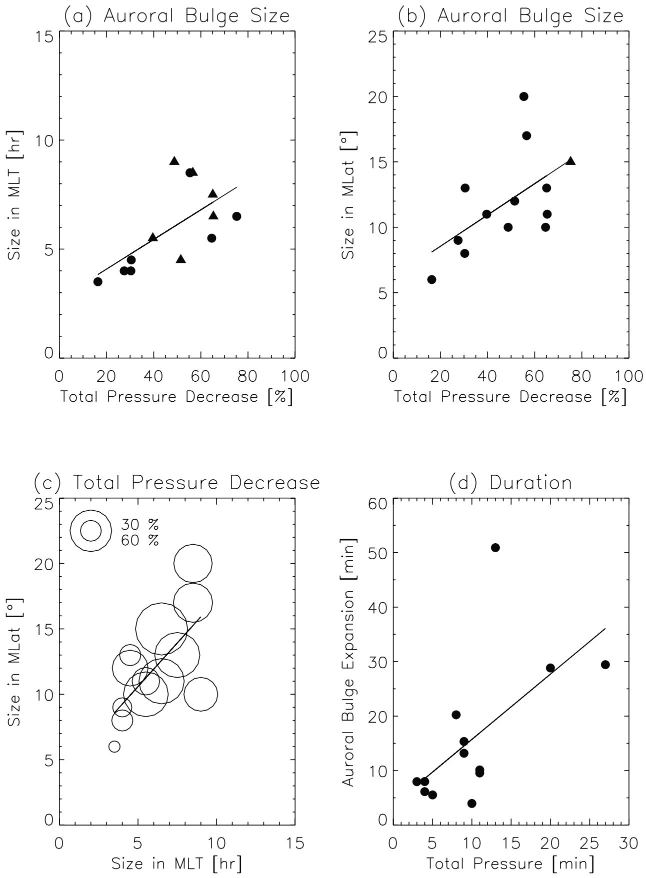

Figure 7. Correlations between the total pressure decrease in the magnetotail and the maximum size of the auroral bulge (a) in magnetic local time and (b) in magnetic latitude. Solid circles indicate events where the entire auroral bulge was observed, while solid triangles indicate events where the whole edge of the auroral bulge could not be determined accurately due to the view of the UVI instrument. (c) Total pressure decrease in the magnetotail as a function of the maximum sizes of the auroral bulge in magnetic local time and magnetic latitude. The radii of the circles are proportional to the amount of total pressure decrease, as indicated in the upper-left corner of the panel. (d) Correlation between the duration of the total pressure decrease in the magnetotail and that of the poleward expansion of the auroral bulge. The straight lines were derived from linear regression: (a) $Y = 0.07X + 2.72$, (b) $Y = 0.12X + 6.16$, (c) $Y = 1.33X + 3.92$, and (d) $Y = 1.20X + 3.75$.

storm intensity; the total pressure in the magnetotail is a good measure of energy stored and released in the lobe. Therefore we can deduce that the magnitude of auroral activities depends on the energy release in the magnetotail. The duration of the poleward expansion of the auroral bulge is closely correlated with that of the TPD. Also, the total pressure in the magnetotail has a large decrease at auroral breakups and intensifications, while it slightly decreases at pseudobreakups, when the auroral activity is often localized and short-lived. These observational results also support the idea of the dependence on behavior of the energy release in the magnetotail.

[30] The total pressure in the magnetotail only slightly decreased or did not decrease in some pseudobreakups or small intensifications such as P1-3 on 4 December 1996 and P1 on 24 March 1997. A possible interpretation is that the total pressure decreased only a little in a localized region away from the spacecraft, but the magnitude of the decrease declined as the decrease propagated to the surrounding regions. Namely, the TPD associated with pseudobreakups may be localized and have a small magnitude. In contrast, the total pressure increases during the substorm growth phase and severely decreases during the expansion phase, corresponding to the loading-unloading process, even in small substorms [*Petrukovich et al.*, 2000]. *Nakamura et al.* [1994] inferred that the amount of energy released in the magnetotail is an important factor in determining whether the substorm expansion onset or the pseudobreakup occurs. From the GEOTAIL observations, we revealed the difference in the energy release in the magnetotail between the substorm and the pseudobreakup.

[31] The TPD occurred at or after auroral breakup in some events. From the statistical results of *Miyashita et al.* [1999, 2000], the TPD first occurs around $X \sim -20\ R_E$ in the premidnight tail a few minutes before onset on average. This location is a possible initial location of the near-Earth neutral line (NENL). Then the TPD propagates to the surrounding regions; the total pressure decreases after onset around $X \sim -10\ R_E$ and $X \sim -30\ R_E$. Hence it is possible for the TPD to be observed after auroral breakup if the propagation time of the TPD from the NENL to the spacecraft is longer than that of the information on the occurrence of the magnetic reconnection from the NENL to the ionosphere. Namely, the timing of the TPD can be subject to the location of the spacecraft relative to the location of the NENL.

[32] We selected the substorm events in which GEOTAIL was expected to be located first tailward and then Earthward of the NENL, so most of the observed TPDs would have occurred tailward of the NENL. However, the TPD can occur at both sides of the NENL from the statistical results [*Miyashita et al.*, 1999, 2000]. We examined the total pressure data from other spacecrafts in the magnetotail and confirmed that the TPD was observed Earthward of GEOTAIL in the substorm events where the Interball-Tail spacecraft was in the tail lobe. But, it is important to select events independent of particular characteristics to obtain general results. We would like to address it in a future work.

[33] We found that the duration of the TPD is comparable to that of the poleward expansion of the auroral bulge. In contrast, fast plasma flows do not always continue to be observed during the auroral expansion; the plasma flows were intermittent and turned their direction, but the total pressure continued to decrease after the second onset O2 on 4 December 1996 and the onset O1 on 24 March 1997, for example. The observations of the plasma flow can suffer from its intermittency and localization, or the exit of the spacecraft from the plasma sheet. Hence the duration of the TPD can be correlated with that of the substorm expansion phase better than that of the fast plasma flow.

[34] In the 1737 UT substorm event on 15 December 1996, described above, GEOTAIL observed several plasmoid-associated tailward flows and then Earthward flows, each of which lasted for several minutes. Similar characteristics were observed in substorm events such as the 2052 UT event on 15 December 1996 and the 1700 UT event on 21 December 1996. Also, the relative timings between the arrival of the fast tailward flow and the onset of auroral activity were different among the plasmoids, i.e., some tailward flows were observed before the auroral onset, and others after the auroral onset. The following is a possible interpretation of the intermittency of the flows, the turning of the flow direction, and the relative timings of the flows.

[35] The NENL stayed Earthward of the GEOTAIL position of $X \sim -21\ R_E$ during the expansion phase in the 1737 UT event on 15 December 1996. Taking into account the different relative timings of the flows, the magnetic reconnection may intermittently occur at different sites with respect to X and Y. The duration of each magnetic reconnection is less than 10 min. Although it is difficult to determine where the reconnection site was located, the plasmoid can be observed after auroral onset if the reconnection occurs at a more earthward site far from the spacecraft, and vice versa. The relative timing could suffer from the Y location of the reconnection site. The NENL retreats tailward in the late expansion/recovery phase or after ~1833 UT. The reconnection site may appear at different locations not continuously but intermittently, as suggested by *Angelopoulos et al.* [1996], while the classical NENL model predicts that the magnetic reconnection continuously occurs during a substorm [e.g., *Hones*, 1984].

[36] The formation of the NENL or the plasmoid can correspond to an auroral brightening, but it does not always develop as a large-scale substorm, as seen in the 15 December 1996 event. Namely, a plasmoid can be observed even during a pseudobreakup [*Petrukovich et al.*, 1998; *Aikio et al.*, 1999; *Ieda et al.*, 2001]. The magnetic reconnection precedes the dipolarization by a few minutes [*Machida et al.*, 1999; *Miyashita et al.*, 2000], but *Ieda et al.* [2001] suggested that the formation of the NENL is a necessary condition, not a sufficient condition, for the development into a large-scale substorm. A possible scenario is that the process of the current disruption or the dipolarization in the near-Earth region is triggered by the magnetic reconnection that occurs at a larger distance and play a crucial role in the development of the substorm, as suggested by *Ohtani et al.* [1999]. Further studies, however, are needed for the understanding of the relationship between the magnetic reconnection and the current disruption. It is also a future study to investigate what external, magnetospheric, and ionospheric conditions control the onset and development of the substorm.

6. Conclusions

[37] We compared the magnetotail variations with the auroral activities during eight substorms using the GEOTAIL and Polar UVI data. In the 1737 UT substorm event on 15 December 1996, auroral breakups and intensifications were highly correlated with fast plasma flows with the variations in the north-south magnetic field and the total pressure in the magnetotail. The fast plasma flows were first directed tailward and then turned Earthward. This event implies that the activation and tailward retreat of the near-Earth neutral line is intermittent.

[38] Furthermore, including the other events, we found that the total pressure decrease in the magnetotail can be correlated with auroral activity better than the fast plasma flow. The total pressure in the magnetotail has a large decrease in association with auroral breakups or poleward expansions of the auroral bulge, while the total pressure slightly decreases at pseudobreakups. The duration of the expansion and the maximum size of the auroral bulge are closely correlated with the duration and amount of the total pressure decrease in the magnetotail, respectively. These results imply that the magnitude of auroral activities associated with substorms depends on that of energy dissipation in the magnetotail. It should, however, be determined in a future study what controls the difference in the total pressure decrease in the magnetotail, i.e., what external, magnetospheric, and ionospheric conditions control the onset and development of the substorm.

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