JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. A3, PAGES 3845–3857, MARCH 1, 2001

Plasmoid ejection and auroral brightenings

A. Ieda,[1] D. H. Fairfield,[1] T. Mukai,[2] Y. Saito,[2] S. Kokubun,[3] K. Liou,[4]
C.-I. Meng,[4] G. K. Parks,[5] and M. J. Brittnacher[5]

Abstract. Geotail plasma and magnetic field observations of 24 plasmoids between 21 and 29 R_E have been compared with Polar ultraviolet observations of auroral brightenings. Both single and multiple plasmoids almost always corresponded to brightenings, but the brightenings were sometimes weak and spatially limited and did not always grow to a global substorm. Even a case where a plasmoid event occurred with fast postplasmoid flow corresponded to a weak brightening but no substorm. Some brightenings did not correspond to plasmoids, but these brightenings were observed away from the longitude of Geotail, indicating that plasmoids have a small longitudinal extent in the near tail. The plasmoids were occasionally observed before the brightenings but more frequently were observed 0-2 min after the brightenings, with the delays probably due to the transit time to the observation point. It seems likely that formation of a near-Earth neutral line causes each brightening in the polar ionosphere, but these formations do not always lead to a full-fledged substorm. What additional circumstance causes development of a full, large-scale substorm remains an open question.

1. Introduction

Magnetotail plasmoids are spatially limited regions of tailward traveling hot plasmas containing helical magnetic field lines. The helical field lines and tailward motion are thought to be a direct consequence of magnetic reconnection. Plasmoids were observed about 10-30 min after the substorm onsets at distances ~60-230 R_E from the Earth, with typical tailward velocities of ~600 km/s [e.g., *Moldwin and Hughes*, 1993; *Slavin et al.*, 1993; *Nagai et al.*, 1994]. This observation suggests that reconnection occurs a few tens of Earth radii down the tail near the time of the onsets. Therefore there is a close association between reconnection and substorm onsets.

A critical question is whether reconnection is the triggering mechanism or a consequence of substorms. One way to answer this question is to determine whether reconnection occurs before or after the onsets. Such a detailed analysis cannot be done with distant tail plasmoids, because an assumption of constant velocity c each plasmoid is necessary to predict the ejection time In reality, the velocity varies as a plasmoid travels dow the tail [*Ieda et al.*, 1998], and this greatly affects th estimated ejection time of distant tail plasmoids. It i preferable to study plasmoids in the near tail that ar observed relatively soon after their ejection.

Earthward flows are also thought to accompany re connection events and relate to substorm processe earthward of the reconnection point [e.g., *Birn an Hesse*, 1996; *Shiokawa et al.*, 1997; *Fairfield et al.*, 199 1999]. Attempts to determine the time sequence of sul storm onset in the near tail have recently been pul lished. *Nagai et al.* [1998] statistically found earthwar flow earthward of 20-30 R_E and tailward flow beyon this region near the time of onsets. They also foun some earthward flows a few minutes before the onse an observation that supports reconnection as the tri gering mechanism for substorms. Similar results we obtained by *Machida et al.* [1999] and *Miyashita et a* [1999]. On the other hand, *Lui et al.* [1998a] statistical found no such global flow pattern and in fact conclude that fast flows were rarely observed around the onse They also suggested that the preceding fast flows th *Nagai et al.* [1998] found may be a consequence of pr vious substorm activity. The above controversy mig stem from different selection criteria in their identific tion of reconnection-associated flows.

The goal of this study is to clarify the tempor and spatial relationship between plasmoids and aur ral brightenings and then to apply the results to t association between reconnection and substorms. V

[1]Laboratory for Extraterrestrial Physics, NASA Goddard Space Flight Center, Greenbelt, Maryland.
[2]Institute of Space and Astronautical Science, Sagamihara, Kanagawa, Japan.
[3]Solar Terrestrial Environment Laboratory, Nagoya University, Toyokawa, Aichi, Japan.
[4]Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland.
[5]Geophysics Program, University of Washington, Seattle.

Paper number 1999JA000451.
0148-0227/01/1999JA000451$09.00

will first identify plasmoids in the tail as an indicator of reconnection. We will then compare them with auroral brightenings recorded by global ultraviolet images observed by the Polar spacecraft. Using global images, it is possible to determine the spatial association between plasmoids and brightenings. The global images also yield the timings of brightenings with no dependence on the time of day. Local time dependence is sometimes a problem when ground magnetic field data are used [*Liou et al.*, 1999]. Also, the only substorm onset indicators which can be observed promptly without significant propagation delays are auroral images and auroral kilometric radiation. Time delays associated with the drift of energetic particles to a geosynchronous spacecraft or the latitudinal movement of ionospheric electrojets until they pass over a ground stations can be some minutes [e.g., see *Slavin et al.*, 1992, 1993].

Auroral brightenings are often classified into localized "pseudobreakups" and global "substorms." Pseudobreakups seem to result from essentially the same physical process as a substorm expansion onset, but what causes the difference is unclear [*Pulkkinen et al.*, 1998; *Rostoker*, 1998]. In this study we will adopt the traditional definition of auroral substorm originally proposed by *Akasofu* [1964] that includes a poleward expansion of brightenings.

2. Data Set

2.1. Geotail and Polar

This study is based on simultaneous observations by the Geotail and Polar spacecraft. Geotail was launched on July 24, 1992. Polar was launched on February 24, 1996, after Geotail had finished its deep tail investigation and was continuing a near-tail study between 10 and 30 R_E.

The low energy particle (LEP) instrument on board Geotail measures three-dimensional plasma [*Mukai et al.*, 1994]. In this study we used 12-s (four-spin period) averages of velocity moments of ions from 32 eV/q to 39 keV/q. We calculated ion velocity moments on the assumption that all ion species are protons. We also used 3-s averages of the magnetic field data obtained by the magnetic field (MGF) experiment, which was described in detail by *Kokubun et al.* [1994].

The Polar ultraviolet imager (UVI) provides global imaging of the aurora borealis with a frame rate of ~36 s [*Torr et al.*, 1995]. A series of UVI images usually consists of two long (~1700 Å) Lyman-Birge-Hopfield (LBH) images (LBHL) and two short (~1500 Å) LBH images (LBHS). The integration times of the first and second of the two images are 18 and 36 s, respectively, for both long and short wavelengths. We first used LBHL data in determining auroral brightenings and subsequently referred to LBHS data when they could provide further information. UVI images will be shown in the altitude adjusted corrected geomagnetic (AACGM) coordinates [*Baker and Wing*, 1989].

2.2. Event Selection

To identify plasmoids, we have first visually scanned the data plots for candidate events and then used the criteria of *Ieda et al.* [1998]: (1) A total pressure enhancement in excess of 10% of the baseline value was required. (2) Only tailward moving plasmoids with a maximum tailward speed faster than 200 km/s were selected. (3) The existence of a B_z bipolar signature, with a peak to peak amplitude greater than 2 nT, was required. (4) A maximum ion density less than 1 cm^{-3} and a minimum ion temperature greater than 0.2 keV were required to guarantee the region as being inside the plasma-sheet-like region. (5) Short excursions of Geotail from the tail lobe into plasmoids were excluded by requiring $\beta_{i,x,\max} \geq 1$, where $\beta_{i,x,\max}$ is the maximum of the ratio of the ion thermal pressure to the X component of the magnetic pressure.

In the identification of plasmoids, we classified the plasmoids into clear and less clear events by visual inspection. The B_z bipolar signature was primarily used in the classification. We first selected 24 clear plasmoids out of 115 plasmoids from December 1996 to March 1997, 12 of which had simultaneous UVI data. Three of the 12 events were single plasmoid events. The rest were grouped into six multiple plasmoid events, in which other plasmoids (including less clear plasmoids not included in the original selection of clear plasmoids) were observed within 30 min of each other. As a result, 24 plasmoids were studied. Multiple plasmoid events are very common, as reported previously by *Moldwin and Hughes* [1992] and *Slavin et al.* [1993].

3. Observations

In this section we first present a single plasmoid event and then three multiple plasmoid events.

3.1. A Single Plasmoid event

Plate 1a shows a plasmoid event at GSM (X, Y, Z) = (-28, 8, -1) R_E at 0355 UT on January 12, 1997. From top to bottom, 20 min of the Geotail 3-s magnetic field and 12-s ion observations are shown. Detailed explanations of the plate are in the plate caption. A plasmoid is primarily characterized by a B_z bipolar signature and fast tailward flow. Plasma beta was much higher than unity, and this indicates that the plasmoid was observed deep in the central plasma sheet. A blue vertical line marks the center of a plasmoid at 0355:39 UT. In this paper we referred to the center of the plasmoid ($B_z = 0$) as a plasmoid arrival time, since the field line of this portion was originally located at the neutral line when reconnection began. We assume that plasmoids start to move tailward soon after reconnection is initiated. This motion occurs because of the additional magnetic tension force of the trailing half of plasmoids. The plasmoid velocity is probably slow when reconnection occurs on plasma sheet field lines because of slow Alfvén velocity

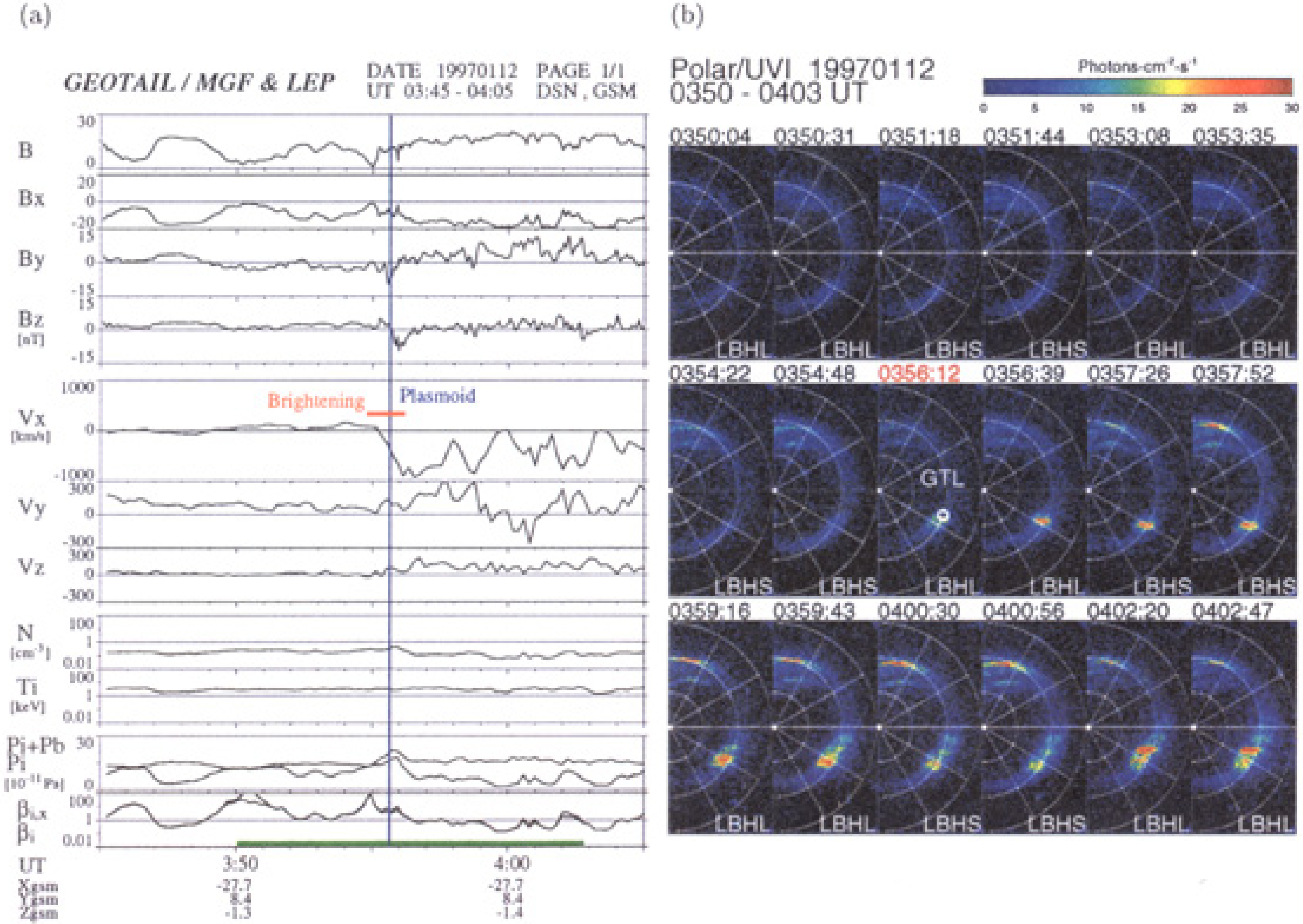

Plate 1. An example of (a) a plasmoid observed by Geotail and (b) an auroral brightening observed by Polar/UVI. In Plate 1a, 30 min of the magnetic field and ion velocity moments are shown in the geocentric solar magnetospheric (GSM) coordinates. A blue vertical line marks the center of the plasmoid. The top four panels show the 3-s magnetic field data: (from top to bottom) strength and the three components. The next five panels are 12-s averages of ion velocity moments: the three components of velocity, and ion density and temperature. The next panel is 12-s averages of the pressures (the ion pressure and the total pressure are superposed). The electron thermal pressure is neglected in the calculation of the total pressure. The bottom panel is ion beta (ratio of the ion thermal pressure to the magnetic pressure) and ion-beta-x (ratio of the ion thermal pressure to the x component of the magnetic pressure). A green line shown in the bottom panel indicates the interval of Polar/UVI images shown on the right.

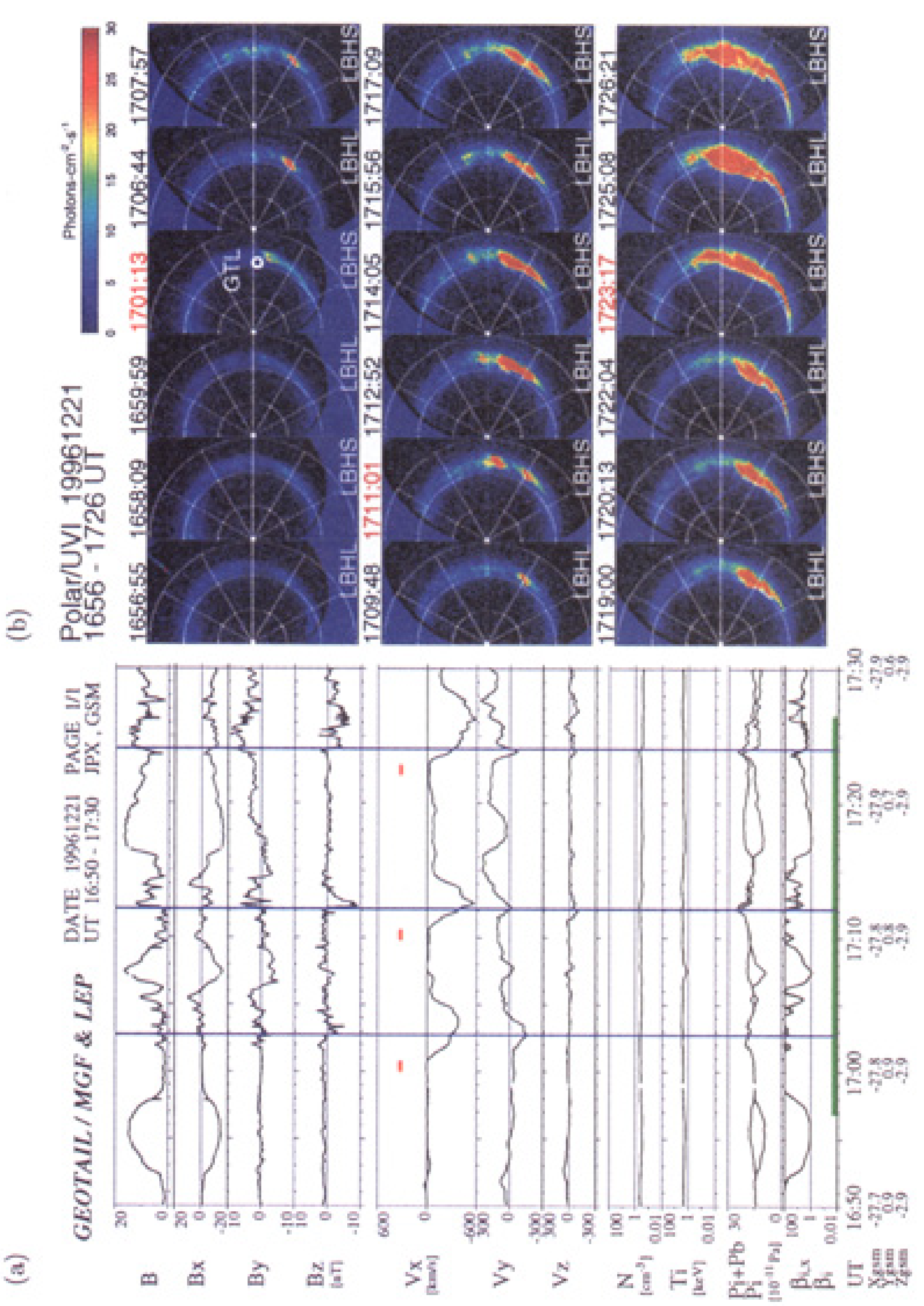

Plate 2. A multiple plasmoid event in the same format as Plate 1. Shown are (a) Geotail magnetic field and thermal ion parameters and (b) selected Polar/UVI images. This event shows that each plasmoid is associated with each auroral activity.

in the upstream region of reconnection. Plasmoids may be further accelerated as reconnection moves on lobe field lines. A red horizontal line in the V_x panel was made connecting the times of consecutive Polar/UVI images between which an auroral brightening occurred.

Plate 1b is a series of Polar UVI images of the nightside polar ionosphere from 60° to 90° magnetic latitudes shown in AACGM coordinates for the interval shown as a green line on the bottom panel of Plate 1a. The Polar images show a brightening at 0356:12 UT in Plate 1b. This is the center time of the interval over which the image was taken and is labeled with red letters on the top of the image. We define the onset time of the brightening (0355:30 UT) as the center time between the time the brightening was first identified (0356:12 UT) and the time of the previous image (0354:48 UT).

The time delay of the plasmoid arrival following the brightenings was 9 ± 42 s. Before the brightening occurred, there was a quiet interval of over 1 hour without brightenings, and thus it appears that the plasmoid and the brightening were associated and were observed simultaneously.

Spacecraft locations can be mapped to the polar ionosphere with magnetic field models, but during active times of changing field configuration there is apt to be considerable uncertainty in the latitude of the foot point. Mapping of the field lines is probably better in the longitudinal direction, especially when a satellite is located near the midnight region. In Plate 1b the Geotail location mapped to ~2240 MLT in the AACGM coordinates using a corrected Tsyganenko 89 model [*Tsyganenko,* 1989]. Note that simultaneous Geotail magnetic field data were not used in this mapping. This location is indicated as a white circle. This location was very near the brightening observed between 2200 and 2230 MLT and hence also supports the association of the plasmoid and the brightening.

The brightening had a slight poleward expansion, and this event might be considered a small substorm. Wind was located 102 R_E upstream from Earth, and the observed solar wind velocity was about 530 km/s (not shown), which yields a time delay of ~20 min for the solar wind to arrive at Earth. Interplanetary magnetic field (IMF) B_z had turned southward ~20 min before the shifted time of the plasmoid passage and was ~-3 nT until a northward turning around the nominal time of the plasmoid passage. This substorm may be triggered by the IMF northward turning. This weak and short B_z south interval seems to be consistent with the small substorm. During this interval, K_p was 2. IMF B_y was about 3 nT and was in the opposite direction of the core field of the plasmoid.

3.2. Multiple Plasmoids With Global Brightenings

Plate 2a shows a multiple plasmoid event accompanied by global auroral brightenings. Geotail was located in the midnight magnetotail at (X, Y, Z) = (-28, 1, -3) R_E at 1700 UT on December 21, 1996. Three plasmoids arrived at 1702:44, 1712:08, and 1724:03 UT, as indicated by vertical blue lines, the second and the last ones being identified as the clear plasmoids. These three plasmoids show the 10- to 20-min spacings typical of these multiple events [*Slavin et al.,* 1993]. Every other UVI image is shown in Plate 2b, but the three brightenings were identified from the complete image set as between 1659:59 and 1700:46, 1709:48 and 1710:35, and 1722:04 and 1722:51 UT. Each plasmoid was preceded by a corresponding brightening about 2 min earlier, whereas tailward flows seem to arrive almost simultaneously with the brightenings. These increasing tailward flowing plasmas ahead of plasmoids can originate just earthward of the satellite and be pushed by following plasmoids [*Nishida et al.,* 1994; *Ieda et al.,* 1998]. This simultaneity seems typical in our data set. The time delays between brightenings and plasmoid arrivals for these three events are 141 ± 24, 116 ± 24, and 95 ± 24 s, respectively.

Wind was located at 87 R_E upstream from Earth and observed a solar wind with a typical speed of 350 km/s. Around Earth, IMF B_z appeared to turn southward approximately 30 min before the first plasmoid passage and was about -5 nT through the whole interval of this event. A substorm was likely to occur under this situation. During this interval, K_p was 3-. IMF B_y fluctuated around 0 nT.

3.3. Multiple Plasmoids With Weak Brightenings

Plates 3a and 3b show a multiple plasmoid event with weak, localized brightenings. Geotail was located at (X, Y, Z) = (-29, 2, -2) R_E at 1950 UT on February 3, 1997, and observed continuous tailward fast flow with a typical velocity of 500 km/s from 1946 to 2008 UT. Two clear plasmoids were observed at 1947:51 and 1954:39 UT during the fast flow; while Polar/UVI observed two weak and localized brightenings between 1945:22 and 1946:46 and between 1954:34 and 1955:58 UT. The time delays of plasmoid arrivals were 107 ± 42 and -37 ± 42 s. During the event, Geotail was located at 2400 MLT, which coincided with the location of both brightenings. Thus it is very likely that those weak brightenings are triggered by reconnection that formed the plasmoid.

This prolonged tailward fast flow apparently emanated from the near-Earth neutral line since it includes plasmoids. The tailward flow continued after the passage of the second plasmoid, and this suggests that reconnection continued from the low-latitude field lines to the high-latitude field lines. According to the classical near-Earth neutral line model, we would thus expect a poleward expansion of the brightening, but it was not observed.

The brightenings in this event are weak, spatially localized, and only apparent in the virtual absence of previous auroral activities. Under more disturbed conditions it would be difficult to definitively associate plasmoids with weak brightenings.

During this event, IMF magnitude was about 3 nT and B_z was about -2 nT around the Earth from 40 min before the first plasmoid passage until 15 min after the second plasmoid passage. During this interval, K_p was 1+. IMF B_y gradually varied from -1 to 1 nT.

3.4. Multiple Plasmoids Under Disturbed Condition

Plates 4a and 4b show a plasmoid event that occurred when significant aurora were already present. Geotail was at (X, Y, Z) = (-28, -9, -3) R_E at 1150 UT on January 13, 1997. Before an arrival of the first plasmoid at 1149 UT, there were a number of brightenings at times such as 1130:37 and 1139:22 UT. Geotail stayed in the plasma sheet but showed no significant fast flows at these times. This can be explained by noting that the Geotail location at 0122 MLT was well separated from the longitude of the brightenings that occurred around 2200-2300 MLT.

At later times, Geotail observed plasmoids when brightenings occurred in the postmidnight sector where Geotail was located. Plasmoids can be observed only when spacecraft are located near the longitude where brightenings occur. This observation confirms that plasmoids start in a local region and expand rapidly [*Ieda et al.,* 1998; *Slavin et al.,* 1999]. Plasmoids were observed at 1149:24, 1211:41, and 1224:36 UT, with the first one identified as a clear plasmoid. These events were associated with auroral brightenings between 1147:17 and 1148:34, 1207:25 and 1210:02, and 1220:55 and 1223:32 UT. The delay times of plasmoids were 91 ± 42, 187 ± 79, and 142 ± 79 s.

The third brightening in the postmidnight sector was quite weak, and we term this brightening a less clear association. This association is less clear because of the presence of a more intense brightening farther to the west. Of the 24 plasmoids we studied, four had a less clear corresponding brightening. The rest had clearly associated brightenings.

The fact that Geotail at 0122 MLT was able to see the first (1149:24 UT) plasmoid originating from 2350 to 0100 MLT can be explained by the expansion of the plasmoid [*Ieda et al.,* 1998]. This plasmoid had negative Y velocity, which indicates an expansion in the dawnward direction where Geotail was located. Alternatively, one might associate the brightening with downcoming electrons of the western edge of the current wedge, with the main part of the wedge to the east and nearer the Geotail position. In most cases, however, the Geotail locations mapped quite directly to the longitude of the brightenings, even when the brightenings were localized. Consequently, we think the separation is due primarily to the plasmoid expansion in this particular case. If this interpretation is correct and the plasmoid expands duskward as well as dawnward, the plasmoid was at least 2 hours or 15 R_E wide in the longitude, since Geotail was located about 1 hour duskside of the center of the brightening.

During this event, IMF magnitude was about 3 nT and B_z was about -1 nT. K_p was 1 between 0900 and 1200 UT and was 2+ between 1200 and 1500 UT. IMF B_y ranged from 2 to -1 nT.

4. Summary and Discussion

4.1. Association Between Plasmoids and Brightenings

In this work we have first identified plasmoids and then studied brightenings. In the single plasmoid event shown in Plates 1a and 1b a plasmoid and a brightening occurred simultaneously nearly in the same longitude following a more than 1-hour interval with no brightenings. In the multiple plasmoid event shown at Plates 2a and 2b, three successive plasmoids had corresponding brightenings about 2 min before each plasmoid arrival. These and other events strongly suggest a close association between plasmoids and brightenings.

The plasmoid-associated brightenings are sometimes weak and spatially limited as shown in Plates 3a and 3b. Such weak brightenings would be hard to recognize during disturbed intervals, as mentioned for the last plasmoid in Plates 4a and 4b. Of the 24 plasmoids studied, four did not have clearly associated brightenings, but the remaining 83% had corresponding brightenings within a few minutes. Although 17% of plasmoids only had less clear brightenings, we interpret this as due to disturbed background conditions in the polar ionosphere and conclude that each plasmoid has a corresponding brightening.

4.2. Why Are Plasmoids and Brightenings Associated?

Plasmoids are known to often have strong fields at their centers, which makes them three-dimensional structures that are known as flux ropes [e.g., *Hughes and Sibeck,* 1987]. These core fields are usually in the cross-tail or Y direction, with their polarity statistically determined by the Y component of the interplanetary magnetic field. Flux ropes will connect to the Earth unless further reconnection, say, on the flanks of the magnetosphere, disconnects the field lines.

Shown in Figure 1 are two hypotheses on how brightenings and plasmoids/flux ropes are associated: Hypothesis 1 is that brightenings mark the foot points of flux ropes which may map to longitudes different than those of the observing spacecraft [*Kivelson et al.,* 1996; *Lui et al.,* 1998b]. Hypothesis 2 is that earthward flow from the reconnection producing the plasmoid/flux rope may initiate auroral processes on field lines earthward of the spacecraft which map to low altitudes near the longitude of the reconnection [*Birn and Hesse,* 1996; *Birn et al.,* 1999].

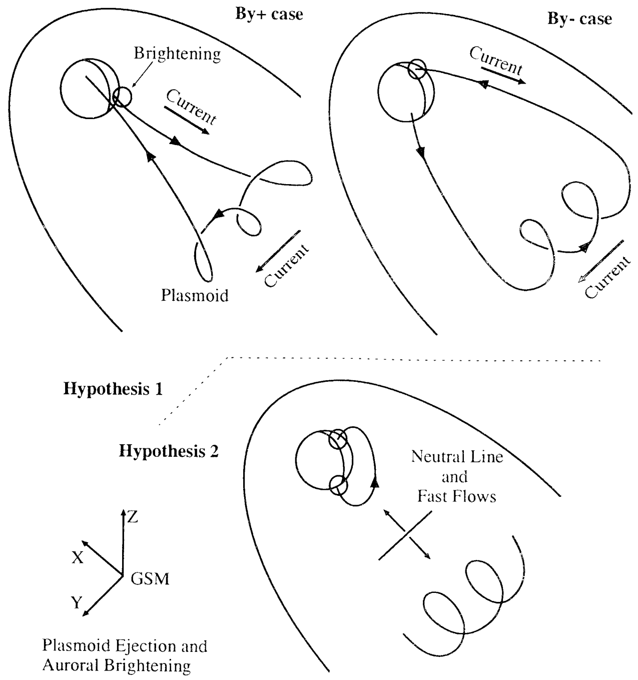

Figure 1. Two hypotheses of how brightenings and plasmoids/flux ropes are associated. Hypothesis 2 is supported by observations.

When the core field is in the dawn to dusk (positive) direction, the field lines of the flux rope will connect from the southern dawn hemisphere to the northern dusk hemisphere, as shown in the upper left of Figure 1. The current in plasmoids/flux ropes is always in the dawn to dusk direction, consistent with the polarity of the looped field lines. *Kivelson et al.* [1996] considered the current closure path of flux ropes and suggested that a significant current flows from the polar ionosphere into flux ropes.

If electrons carrying this current are those that produce the aurora [*Lui et al.,* 1998b], brightening will be produced in the southern dawn when the core field is positive. With a negative core field, the field line will connect from southern dusk to northern dawn, and the brightenings will be in the northern dawn, as shown in the upper right of Figure 1.

The events discussed in this paper do not support hypothesis 1 because our Northern Hemisphere brightenings are found to be associated with all plasmoid events. This association excludes the possibility that there were brightenings occurring only in the Southern Hemisphere that were not observed by the spacecraft (i.e., the third plasmoid in Plate 2). In addition, they do not map to a longitude away from the spacecraft. If current from the flux ropes connects to the ionosphere, it is probably weak.

The observations presented above indicate that the plasmoids, and presumably the associated earthward flows, occur at the same longitudes as the brightenings. Therefore it seems more likely that the earthward flows initiate processes on field lines earthward of the spacecraft (hypothesis 2, as illustrated at the bottom of Figure 1 and described by *Birn and Hesse* [1996] and *Birn et al.* [1999]). These processes create the current wedge and are associated with low-altitude particle acceleration that produces the aurora.

4.3. Interpretation of the Temporal Relationship Between Plasmoids and Brightenings

Figure 2 shows the time delay between brightenings and 20 plasmoids with clearly corresponding brightenings. Plasmoids were observed 0-2 min after brightenings in most cases. However, ejection of a plasmoid should occur before the arrival of the plasmoids, because there is a separation in the downtail direction between their originating region and the satellite location in order that the initial required positive B_z be observed. The earliest observed plasmoids should correspond to satellite locations very near the reconnection region.

Plate 5a shows a plasmoid that was observed before a brightening. Geotail was located in the magnetotail at (X, Y, Z) = (-27, 7, -1) R_E at 0900 UT on February 25, 1997. The leading half of the plasmoid has a relatively weak enhancement of the northward field, which is likely to indicate that this is a "young" plasmoid that has just been formed. The plasmoid arrived at 0900:27

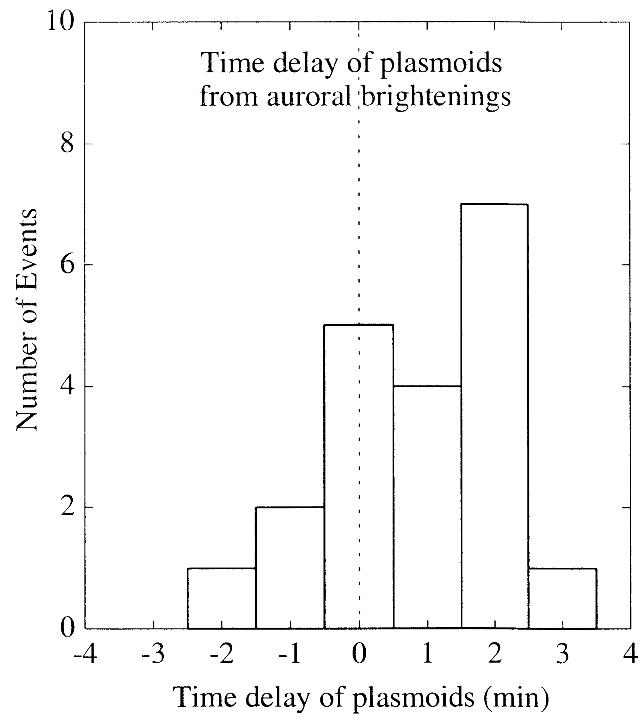

Figure 2. Time delays of plasmoid arrivals relative to auroral brightenings. It is important to realize that the figure does not reflect the important travel time from the reconnection point to the observation point. When this additional delay is considered, it appears that reconnection precedes brightenings.

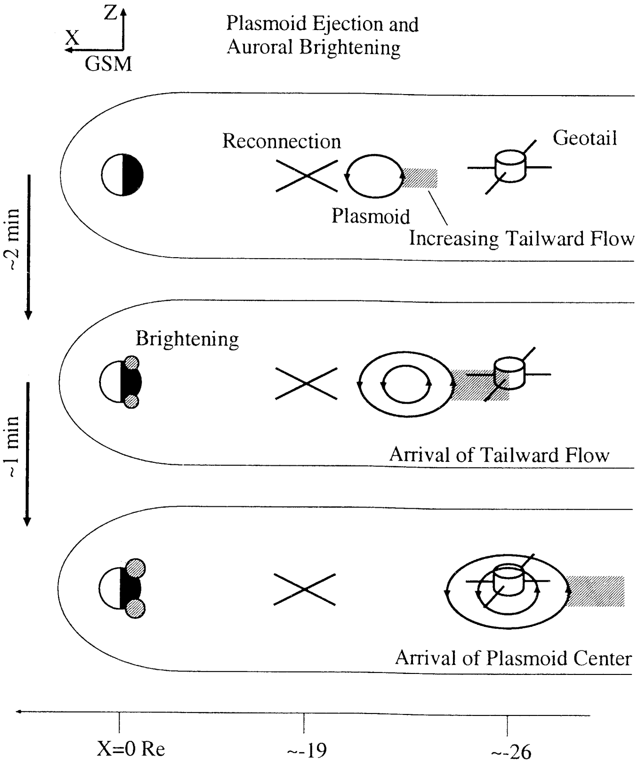

Figure 3. Schematic illustration of plasmoid and brightening evolution from top to bottom on the midnight meridian plane.

UT, as indicated by a vertical blue line. The Polar images in Plate 5b show a localized brightening between 0901:52 and 0903:16 UT. The time delay of the plasmoid arrival from the brightenings is -127 ± 42 s. The mapped location of Geotail was 2244 MLT, coinciding with the brightening.

The temporal relationship between plasmoid ejection and brightenings is illustrated in Figure 3. The earliest plasmoid we observed was ~2 min before the brightening, when we presume the neutral line happened to be near the satellite location. Typically, we observed plasmoids 0-2 min after the brightenings, since they take time to move to the observation point. By combining these numbers, we conclude that the plasmoids were typically observed ~3 min after they were formed by reconnection. The downtail velocities of the plasmoids studied in this paper were 300-600 km/s, or about 3-6 R_E/min at the average distance of 26 R_E down the tail. Near-tail plasmoids are accelerating [*Ieda et al.*, 1998], and an assumption of constant acceleration rate yields a separation distance between the neutral line and satellite location of 7 R_E, which leads to a location of the neutral line at about 19 R_E down the tail. The average location may be more tailward because we only studied tailward moving plasmoids and not earthward flows.

Our interpretation is that reconnection occurs before the corresponding brightening and that a "young" plasmoid is observed before a brightening if the satellite is located near the neutral line, as illustrated on the top panel of Figure 3. We conclude this because some plasmoids were observed before brightenings and because reconnection is likely to occur a few minutes earlier than plasmoid arrivals at 26 R_E. In the middle panel of Figure 3, a brightening occurs ~2 min after the reconnection. This is often simultaneous with the arrival of increasing tailward flow, where plasma is pushed by an approaching plasmoid. Finally, the center of the plasmoid arrives at Geotail around 26 R_E another 1 min later, as illustrated in the bottom panel of Figure 3.

4.4. Association Between Reconnection and Substorms

Our study finds that plasmoids are associated with individual auroral brightening, just as *Fairfield et al.* [1999] found that earthward flow bursts are closely associated with auroral brightenings. Plasmoids are convincing signatures of reconnection, and earthward flow bursts (and associated as bursty bulk flows) are, in a similar manner, thought to be the earthside consequence of reconnection. Both this earlier work and the present paper support the idea that reconnection in the tail causes an auroral brightening in the polar ionosphere. However, in view of the weakness of some brightenings, the question remains concerning the relation between reconnection and global substorms.

The temporal relationship between plasmoids in the distant tail and substorm onsets has been extensively surveyed, and a close relationship between reconnection and substorms was concluded [e.g., *Moldwin and Hughes*, 1993; *Slavin et al.*, 1993; *Nagai et al.*, 1994]. However, it now appears that plasmoid ejection can be associated with weak and localized brightenings as well as with global substorms. Since global images were not used in the earlier papers just cited, the poleward expansion of brightenings was not a concern in their identifications of substorms, and pseudobreakups may be included. Therefore it is not surprising that these earlier studies did not associate plasmoids with pseudobreakups. Also, with the greater distances and the assumption of constant tailward speed, the accuracy of these earlier plasmoid-substorm association studies was less than in this analysis of near-tail plasmoids.

The brightenings associated with plasmoids can be the initial one, the second one, or an intensification of a previous brightening, as shown in the multiple plasmoid event in Plates 2a and 2b. This suggests that stepwise development of auroral brightenings may be associated with multiple formation of neutral lines, not with an intensification of the reconnection rate of a single neutral line. Reconnection seems to be associated with each brightening, rather than with the onsets of global substorms only.

4.5. Difference Between Global Substorms and Pseudobreakups

A fundamental question is, What in the magnetosphere determines whether a pseudobreakup or a full

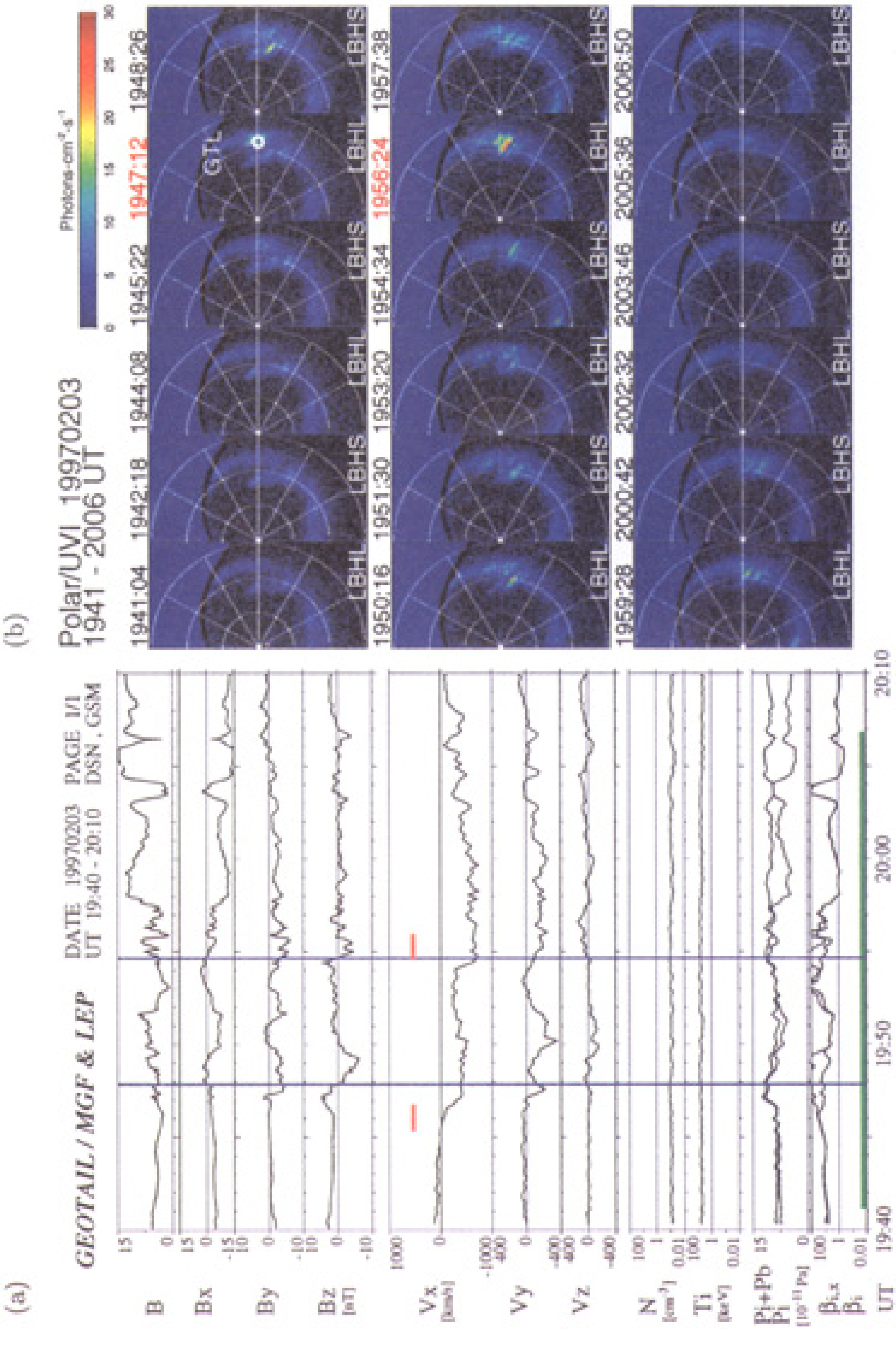

Plate 3. A multiple plasmoid event with weak brightenings in the same format as Plate 1. Shown are (a) Geotail magnetic field and thermal ion parameters and (b) selected Polar/UVI images. This event shows that plasmoids followed by fast tailward flows are not necessarily associated with substorms but with small brightenings.

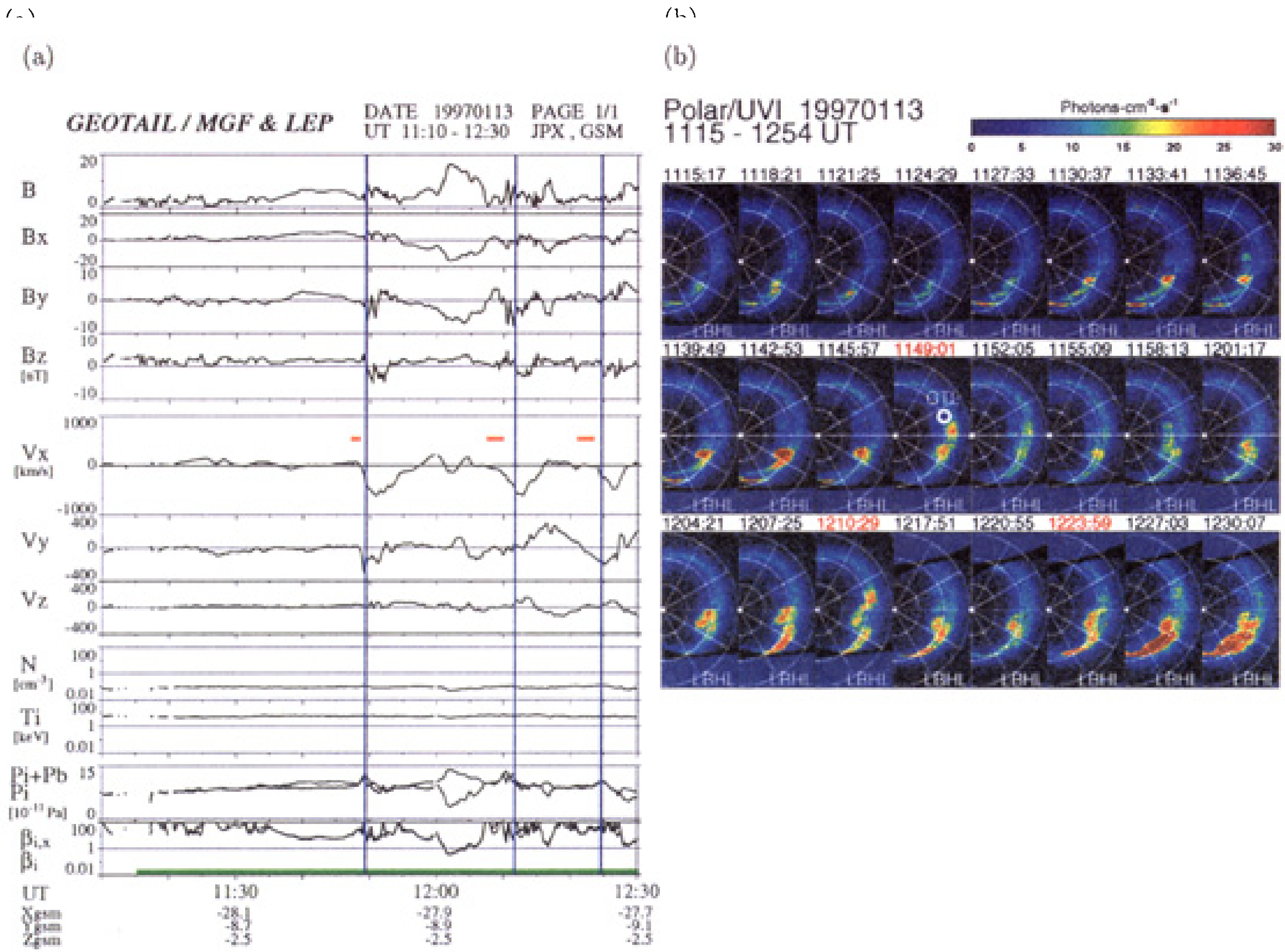

Plate 4. A multiple plasmoid event under disturbed condition in the same format as Plate 1. Shown are (a) Geotail magnetic field and thermal ion parameters and (b) selected Polar/UVI images. The brightening observed nearly simultaneous with the first plasmoid was somewhat separated in longitude from mapped plasmoid location. This can be understood by an expansion of the plasmoid because both V_y and Y locations of Geotail are negative. The third brightening represents a less clear event.

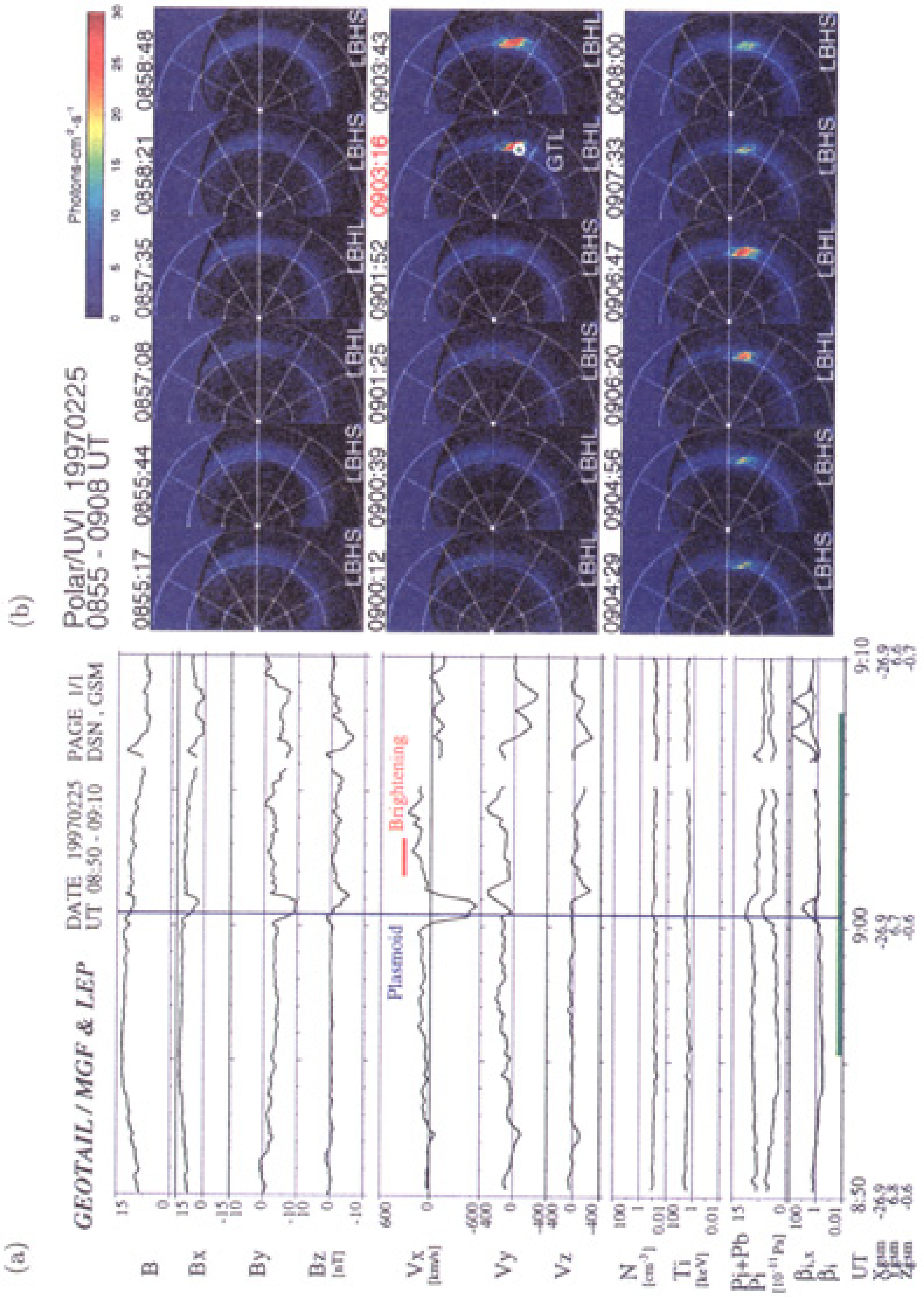

Plate 5. A plasmoid observed earlier than a brightening in the same format as Plate 1. Shown are (a) Geotail magnetic field and thermal ion parameters and (b) Polar/UVI images.

substorm will occur, particularly if they are both due to reconnection, as our results suggest? Reconnection initiates on closed field lines in the plasma sheet and creates the helical field lines that make up the plasmoid. The process then begins reconnecting higher-latitude lobe field lines and creates postplasmoid fast tailward flows. It is sometimes thought that pseudobreakups might correspond to reconnection on closed field lines and substorms to times when reconnection proceeds to lobe field lines. The lobe reconnection would tap the lobe energy and also produce the poleward motion of aurora that is characteristic of substorms.

Examples such as the multiple plasmoids in Plate 3 seem to contradict this idea because the extended interval of rapid tailward flow following the plasmoids seems to imply lobe reconnection but the aurora seems to clearly indicate a minimal pseudobreakup without poleward expansions. Thus these poleward expansions seem to be associated with secondary disturbances earthward of neutral lines rather than with reconnection itself. Resistive MHD simulations show that it is the earthward flow well earthward of the reconnection site that produces the field line currents and presumably the aurora breakup [*Birn and Hesse,* 1996; *Birn et al.,* 1999].

It is also possible that multiple or more extended reconnection regions must be activated to produce a substorm. A definitive answer to this problem must await further work.

5. Conclusion

We have studied brightenings in the polar ionosphere when plasmoids were observed between 21 and 29 R_E down the tail. It was found that plasmoids are invariably associated with auroral brightenings. After considering the transit time of the plasmoid to the spacecraft, we conclude that plasmoid formation precedes the auroral brightening, with both events instigated by reconnection near 20 R_E. We discussed that there is such an association because reconnection yields both plasmoids and brightenings. These brightenings, however, did not always develop into global substorms, which indicates that the formation of a near-Earth neutral line may be necessary but is not a sufficient condition to trigger a full-fledged substorm. The above result poses the unanswered question of what circumstances lead to a fully developed substorm.

Acknowledgments. This work was performed while A.I. held a National Research Council-NASA/GSFC research associateship. Research by K. Liou and C.-I Meng is supported by the NASA grant NAG5-7724 to the Johns Hopkins University Applied Physics Laboratory. The Polar UVI research at the University of Washington is conducted under a NASA grant NAG5-7732. Wind magnetic field and solar wind data were provided by the Wind magnetic field and solar wind data processing teams. A.I. thanks J. A. Slavin, A. T. Y. Lui, A. Nishida, T. Nagai, S. Machida, M. Nosé, A. J. Klimas, T. Takeuchi, and Y. Miyashita for useful discussions.

Janet G. Luhmann thanks William J. Burke and another referee for their assistance in evaluating this paper.

References

Akasofu, S.-I., The development of the auroral substorm, *Planet. Space Sci., 12,* 273-282, 1964.

Baker, K. B., and S. Wing, A new magnetic coordinate system for conjugate studies at high latitudes, *J. Geophys. Res., 94,* 9139-9143, 1989.

Birn, J., and M. Hesse, Details of current disruption and diversion in simulations of magnetotail dynamics, *J. Geophys. Res., 101,* 15,345-15,358, 1996.

Birn, J., M. Hesse, G. Haerendel, W. Baumjohann, and K. Shiokawa, Flow braking and the substorm current wedge, *J. Geophys. Res., 104,* 19,895-19,903, 1999.

Fairfield, D. H., et al., Geotail observations of substorm onset in the inner magnetotail, *J. Geophys. Res., 103,* 103-117, 1998.

Fairfield, D. H., et al., Earthward flow bursts in the inner magnetotail and their relation to auroral brightenings, AKR intensifications, geosynchronous particle injections, and magnetic activity, *J. Geophys. Res., 104,* 355-370, 1999.

Hughes, W. J., and D. G. Sibeck, On the three-dimensional structure of plasmoids, *Geophys. Res. Lett., 14,* 636-639, 1987.

Ieda, A., S. Machida, T. Mukai, Y. Saito, T. Yamamoto, A. Nishida, T. Terasawa, and S. Kokubun, Statistical analysis of the plasmoid evolution with Geotail observations, *J. Geophys. Res., 103,* 4453-4465, 1998.

Kivelson, M. G., K. K. Khurana, R. J. Walker, L. Kepko, and D. Xu, Flux ropes, interhemispheric conjugacy, and magnetospheric current closure, *J. Geophys. Res., 101,* 27,341-27,350, 1996.

Kokubun, S., T. Yamamoto, M. H. Acuña, K. Hayashi, K. Shiokawa, and H. Kawano, The Geotail magnetic field experiment, *J. Geomagn. Geoelectr., 46,* 7-21, 1994.

Liou, K., C.-I. Meng, T. Y. Lui, P. T. Newell, M. Brittnacher, G. Parks, G. D. Reeves, R. R. Anderson, and K. Yumoto, On relative timing in substorm onset signatures, *J. Geophys. Res., 104,* 22,807-22,817, 1999.

Lui, A. T. Y., K. Liou, P. T. Newell, C.-I. Meng, S.-I. Ohtani, T. Ogino, S. Kokubun, M. J. Brittnacher, and G. K. Parks, Plasma and magnetic flux transport associated with auroral breakups, *Geophys. Res. Lett., 25,* 4059-4062, 1998a.

Lui, A. T. Y., et al., Ionospheric signature of a magnetic flux rope in the magnetotail, *Geophys. Res. Lett., 25,* 3733-3736, 1998b.

Machida, S., Y. Miyashita, A. Ieda, A. Nishida, T. Mukai, Y. Saito, and S. Kokubun, Geotail observations of flow velocity and north-south magnetic field variations in the near and middistant tail associated with substorm onsets, *Geophys. Res. Lett., 26,* 635-638, 1999.

Miyashita, Y., S. Machida, A. Nishida, T. Mukai, Y. Saito, and S. Kokubun, Geotail observations of total pressure and electric field variations in the near and middistant tail associated with substorm onsets, *Geophys. Res. Lett., 26,* 639-642, 1999.

Moldwin, M. B., and W. J. Hughes, On the formation and evolution of plasmoids: A survey of ISEE 3 geotail data, *J. Geophys. Res., 97,* 19,259-19,282, 1992.

Moldwin, M. B., and W. J. Hughes, Geomagnetic substorm association of plasmoids, *J. Geophys. Res., 98,* 81-88, 1993.

Mukai, T., S. Machida, Y. Saito, M. Hirahara, T. Terasawa, N. Kaya, T. Obara, M. Ejiri, and A. Nishida, The Low

Energy Particle (LEP) experiment onboard the Geotail satellite, *J. Geomagn. Geoelectr., 46*, 669-692, 1994.

Nagai, T., K. Takahashi, H. Kawano, T. Yamamoto, S. Kokubun, and A. Nishida, Initial Geotail survey of magnetic substorm signatures in the magnetotail, *Geophys. Res. Lett., 21*, 2991-2994, 1994.

Nagai, T., M. Fujimoto, Y. Saito, S. Machida, T. Terasawa, R. Nakamura, T. Yamamoto, T. Mukai, A. Nishida, and S. Kokubun, Structure and dynamics of magnetic reconnection for substorm onsets with Geotail observations, *J. Geophys. Res., 103*, 4419-4440, 1998.

Nishida, A., T. Mukai, Y. Saito, T. Yamamoto, H. Hayakawa, K. Maezawa, S. Machida, T. Terasawa, S. Kokubun, and T. Nagai, Transition from slow flow to fast tailward flow in the distant plasma sheet, *Geophys. Res. Lett., 21*, 2939-2942, 1994.

Pulkkinen, T. I., et al., Two substorm intensifications compared: Onset, expansion, and global consequences, *J. Geophys. Res., 103*, 15-27, 1998.

Rostoker, G., On the place of the pseudobreakup in a magnetospheric substorm, *Geophys. Res. Lett., 25*, 217-220, 1998.

Shiokawa, K., W. Baumjohann, and G. Haerendel, Braking of high-speed flows in the near-Earth tail, *Geophys. Res. Lett., 24*, 1179-1182, 1997.

Slavin, J. A., M. F. Smith, E. L. Mazur, D. N. Baker, T. Iyemori, H. J. Singer, and E. W. Greenstadt, ISEE 3 plasmoid and TCR observations during an extended interval of substorm activity, *Geophys. Res. Lett., 19*, 825-828, 1992.

Slavin, J. A., M. F. Smith, E. L. Mazur, D. N. Baker, E. W. Hones Jr., T. Iyemori, and E. W. Greenstadt, ISEE 3 observations of traveling compression regions in the Earth's magnetotail, *J. Geophys. Res., 98*, 15,425-15,446, 1993.

Slavin, J. A., et al., Dual spacecraft observations of lobe magnetic field perturbations before, during, and after plasmoid release, *Geophys. Res. Lett., 26*, 2897-2900, 1999.

Torr, M., et al., A far ultraviolet imager for the international solar-terrestrial physics mission, *Space Sci. Rev., 71*, 329-383, 1995.

Tsyganenko, N. A., A magnetospheric magnetic field model with a warped tail current sheet, *Planet. Space Sci., 37*, 5-20, 1989.

M. J. Brittnacher and G. K. Parks, Geophysics Program, University of Washington, Seattle, WA 98195. (britt @geophys.washington.edu; parks@geophys.washington.edu)

D. H. Fairfield and A. Ieda, Laboratory for Extraterrestrial Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771. (u2dhf@lepdhf.gsfc.nasa.gov; Aki.Ieda@gsfc.nasa.gov)

S. Kokubun, Solar Terrestrial Environment Laboratory, Nagoya University, Toyokawa, Aichi 442, Japan. (kokubun@stelab.nagoya-u.ac.jp)

K. Liou and C.-I. Meng, Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723. (kan.liou@jhuapl.edu; ching.meng@jhuapl.edu)

T. Mukai and Y. Saito, Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229, Japan. (mukai@stp.isas.ac.jp; saito@stp.isas.ac.jp)

(Received December 17, 1999; revised February 18, 2000; accepted March 22, 2000.)