Intense growth phase events of substorms

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Abstract. Over the past few decades, several events of the intense growth phase preceding the expansion onset of substorms were reported. We reexamine these events using an extensive set of data, including ground-based magnetograms at auroral latitudes, solar wind data from the Wind and IMP 8 satellites, and auroral UV images from the Polar and Viking satellites. Magnetograms show that the intense auroral electrojet is located in the early morning sector during these events. A common feature among the corresponding solar wind conditions for these events is the existence of a period of southward interplanetary magnetic field (IMF) preceded by a prolonged northward IMF. This intense growth phase, however, seems to be independent of the IMF $B_y$ polarity. Enhanced auroras in the early morning sector appear during the growth phase. These auroras are consistent with relatively large geomagnetic disturbances during these events, indicating that enhanced conductances, combined with enhanced electric field caused by southward IMF, play an important role in the auroral electrojet during these intense growth-phase events.

1. Introduction

An isolated substorm can be separated into three phases [e.g., McPherron, 1979]. The magnetotail begins to store the solar wind energy when the interplanetary magnetic field (IMF) turns southward. This phase is called the “growth phase.” The stored energy is then released during the “expansion” phase. Auroras are activated during the expansion phase. “Expansion onset” is referred to the time of the sudden release of the stored energy, generating auroral breakup. The auroral activities dim, and the magnetosphere begins to return to a quasi-quiet status of the “recovery” phase. A quite different view of the auroral substorm was presented by Elphinstone et al. [1996] where they introduced the view that the substorm process could be better understood as a set of interacting cycles, which may or may not activate depending on past and current conditions.

The auroral electrojet is one of the dominant signatures for substorms. The auroral electrojet consists of two basic components [Kamide and Kokubun, 1996; Akasofu and Kamide, 1998]. One is the directly driven component, which changes with solar wind conditions. This component usually creates the eastward electrojet on the duskside and the westward electrojet on the dawnside [Kamide and Kroehl, 1994]. The other is the unloading component. Substorms add an additional current system near midnight via the so-called current wedge [McPherron et al., 1973].

The auroral electrojet is commonly described by the $AU$ and $AL$ indices, which are derived from 10 to 13 magnetometer stations at auroral latitudes. The $AU$ ($AL$) index monitors the maximum intensity of the eastward (westward) electrojet. Kamide and Akasofu [1983], Akasofu et al. [1983], Feldstein et al. [1997], and Shue and Kamide [1998] cautioned that the standard $AE$ stations are not able to monitor the specifics of auroral electrojet activities associated with IMF variations and substorm activities. The auroral electrojet shifts, at times, outside the field of view of the stations.

The magnitude of the auroral electrojets during the growth phase is usually much smaller than that during the substorm expansion phase. Therefore a sub-
storm with the intense growth phase has been treated as an unusual event. To the authors' knowledge, five such events have been reported in the literature. These are the events of January 10, 1997; October 19, 1986; November 28, 1995; November 11, 1976; and July 24, 1986, which were studied independently by Tsurutani et al. [1998], Elphinstone et al. [1991], Sergeev et al. [1998], Pellinen et al. [1982], and Lui et al. [1995], respectively. They, however, did not focus on why electrojet activity was so high during the growth phase. To synthesize the consistent features of the auroral electrojets and the corresponding solar wind conditions, we reexamine the events in detail using magnetometer data from various chains and solar wind data. Brief reviews for these events are shown in the following five paragraphs.

A magnetic cloud arrived at Earth on January 10, 1997. The Wind satellite observed strong southward IMF and slowly rotated back to $B_z \sim 0$ over a period of 12 hours on January 10. The strong southward IMF resulted in enhanced auroral activity as seen from Polar auroral UV images. Tsurutani et al. [1998] reported that there was no significant substorm expansion activity during a 47-min interval of southward IMF. This may be because a prolonged northward IMF occurred before this interval of southward IMF. The magnetosphere could have been brought to a ground state during the prolonged northward IMF. In this event the substorm did not develop into a full depth [Shue and Kamide, 1998]. This event has attracted a large amount of attention both in the scientific community and the media. For more details on various aspects of this event, readers are referred to Fox et al. [1998].

Elphinstone et al. [1991] first studied the October 19, 1986, event using Viking auroral UV images. A substorm expansion onset occurred at 1132 UT during the event. This onset was preceded by prominent auroral activity in the early afternoon and early morning sectors. The westward electrojet had caused the $AL$ index to reach $\sim 340$ nT before the substorm onset. Since IMP 8 provided solar wind data over an extended period before and after the substorm onset, this event is suitable for purposes of global MHD simulations [Fedder et al., 1995; Wingace and Menietti, 1998].

The event of November 28, 1995, had been studied by Petrovovich et al. [1998] and Sergeev et al. [1998]. They showed two subsequent, short-duration increases in the westward electrojet in the postmidnight sector for the event. Characteristics of the substorm expansion onset, such as auroral breakup, PI2 pulsations, fast flows, current disruption, and plasmoid formation, were not observed until the recovery phase of the second increase of the electrojet. In this event the substorm did not develop into a full-scale substorm.

On November 11, 1976, a sudden southward IMF turning preceded by a prolonged northward IMF led to relatively large geomagnetic disturbances ($\sim 300$ nT) that were observed in the morning sector [Pellinen et al., 1982]. A very weak increase in the $|AL|$ index (100 nT), which was identified by them as the substorm expansion onset from all-sky camera data, was observed during the recovery of the relatively large disturbances in the midnight sector.

Elphinstone et al. [1995] used Viking auroral UV images to show an enhanced auroral activity called "azimuthally spaced auroral forms" prior to the substorm expansion onset. Their Figure 8 shows a histogram of the azimuthally spaced auroral forms showing a peak at a wavelength $\sim 200$ km in the ionosphere or having a peak in mode number of $\sim 100$. This distribution was very similar to that found for the ballooning instability. Lui et al. [1995] further studied one of the Elphinstone et al. [1995] events (July 24, 1986) and concluded that the substorm expansion onset was preceded by prominent auroral activities in the morning sector with spatial separations between adjacent bright regions ranging from 160 to 640 km. Their intensity was modulated at $\sim 3.2$-min intervals.

2. Observations

We collect data from ground-based magnetometers for the events of January 10, 1997, and October 19, 1986. We also collect solar wind data for the two events. Auroral UV images for the two events can be found in the works of Tsurutani et al. [1998] and Elphinstone et al. [1991], respectively. The magnetograms and the corresponding solar wind conditions for the other events (November 28, 1995, November 11, 1976, and July 24, 1986) had been presented by Sergeev et al. [1998], Pellinen et al. [1982], Elphinstone et al. [1995], and Lui et al. [1995]. We do not need to duplicate their efforts in collecting the data. Efforts have been made instead to synthesize and interpret these events.

2.1. January 10, 1997, Event

There occurred, at least, two substorms during the first half of January 10, 1997 [Shue and Kamide, 1998]. However, the first substorm is of particular interest in the present study. The expansion onset of this substorm was at 0334 UT, identified from Polar auroral UV images. Magnetometer data from 105 ground-based stations have been used for this event. Figure 1 shows the location of these stations above 60° corrected geomagnetic latitude (CGlat) at 0304 UT. Although there were not many magnetometer stations in the noon sector, this sparse distribution over the noon sector will not affect our results about electrojet activity in the dark sector.

We are interested in changes in geomagnetic disturbances and solar wind conditions prior to the substorm expansion onset. Thus we arrange plots of these parameters for an extended period prior to the substorm expansion onset, as shown in Figure 2. The quiet time variations (of January 8, 1997) have been removed from each of the magnetograms. Magnetograms were
IMF turned northward again 10 min later. The substorm expansion onset then occurred at 0334 UT.

Lyons et al. [1997] estimated the time delay between the arrival of a northward IMF turning at the magnetopause and the substorm expansion onset would be \( \sim 9 \pm 4.5 \) min. Thus the northward IMF may be a triggering factor for the present substorm. However, Lopez et al. [1998] took a closer look at this event and found that a pressure pulse preceded this northward turning. It should be noted that whether a northward IMF turning or a pressure pulse triggers a substorm expansion onset is beyond the scope of this study. For other solar wind parameters the IMF \( B_y \) was positive prior to the onset. The proton velocity increased slightly at the time of the southward IMF turning at 0224 UT.

**Figure 1.** Locations of magnetometer stations used for the January 10, 1997 (0304 UT), event. Only stations above 60° CGLat are shown. The auroral image from Polar is plotted over the stations. We also plot the fields of view of the Finland and Iceland East radars.

The Wind satellite was located at \( \sim 85 \text{ R}_E \) when this substorm was in progress. The solar wind data from Wind with a 18-min time shift are shown in the seven bottom panels of Figure 2. This time shift was estimated by Tsurutani et al. [1998] using Wind and Geotail data. Note that Geotail was skimming the dawnside magnetopause, mainly staying in the magnetosheath during the period [Shue and Kamide, 1998]. The low geomagnetic activity before 0230 UT was associated with a prolonged northward IMF. The vertical dotted line at 0224 UT marks the time of a southward IMF turning. This period was a few minutes earlier than the initiation of the geomagnetic activity. It is expected that the geomagnetic activity has a few minutes of time delay to respond to the southward IMF turning. The IMF turned northward at 0310 UT for a short period and then changed back to a southward orientation. The

**Figure 2.** Superposed \( X_m \) component plots and solar wind measurements from the Wind satellite (January 10, 1997). \( V_{th} \) is the thermal velocity of the solar wind. The solar wind data have been shifted 18 min for the propagation time. The vertical dotted and dashed lines mark the time of the southward turning and the expansion onset, respectively.
Figure 3a. Magnetic disturbances at individual stations in the early morning sector. The vertical dotted (dashed) line denotes the time of the southward IMF turning (the expansion onset). The local time of stations marked following the vertical dashed line is estimated at the time of the peak AL prior to the substorm expansion onset.

Figure 3a (3b) shows magnetograms from individual stations in the early morning sector (evening and afternoon sectors). The local time information at the time of the peak AL value prior to the substorm expansion onset for each station is shown following the vertical dashed line. In Figure 3a, BJN (Bear Island) at (71.5° CGlat, 5.3 MLT) is found to have the maximum westward electrojet. NAQ (Narsarsuaq) and LRV (Leirvogur) also showed high activity before the expansion onset occurred; and had a significant increase in the westward electrojet after the substorm expansion onset. This latter increase is attributed to an enhanced current system which was added to the midnight sector at the expansion phase. NAL (Ny Alesund) observed small $X_m$, but relatively large positive $Y_m$. The Z perturbation at NAL indicates that the center of the electrojet was located in the south of the station. At BJN the Z component was positive, but small, suggesting that the center of the westward electrojet was near the south of BJN. SCO (Scoresby) and LRV are located at nearly the same meridian. SCO observed a positive Z, while LRV observed a negative Z, indicating that the electrojet was between the two stations. NAQ observed a transition from a negative Z to a positive Z. In Figure 3b one finds that stations FSM (Fort Smith), GIL (Gillam), YKC (Yellowknife), and RAB (Rabbit Lake) recorded relatively high activity in the eastward electrojet. Comparing to the magnitude of the eastward electrojet, however, the westward electrojet in the evening and afternoon sectors was much weaker.

One may argue that the expansion onset can be identified as 0230 UT, which is the time when the time BJN began to record a relatively large geomagnetic disturbance. However, BJN was located at dawn, and midnight stations measured only very weak activity, indicating that the possibility of the expansion onset at 0230 UT is slim. In fact, Tsurutani et al. [1998] used a series of Polar auroral UV images (see their Fig-
Figure 3b. Magnetic disturbances at individual stations in the evening and afternoon sectors, in the same format as Figure 3a.

Figure 3b) to demonstrate that no auroral breakup at midnight occurred until 0334 UT. A form of enhanced aurora appeared prior to the expansion onset: this auroral form extended azimuthally, with a gap at noon. They found that from 0312 to 0334 UT, the enhanced aurora became asymmetric, with the dawnside far brighter than the duskside, and the dawnside brightness changing with time. The relatively large westward electrojet was peaked at 5.5 MLT, coinciding with the peak in auroral luminosity. These auroral images clearly show that an enhanced aurora appears in the early morning sector during the intense growth phase event.

With these images it is possible to estimate the instantaneous distribution of the ionospheric conductances [Kamide et al., 1986; Lummersheim et al., 1991]. As a first approximation, the pattern of the auroral emissions can be regarded as the conductances pattern. The contour plot of the Polar UV image for 0304 UT, January 10, 1997, is overlapped on the location plot of the magnetometer stations (see Figure 1). It is important to realize that the latitudinal width of the enhanced aurora is of the order of a few degrees and that the westward electrojet flows over BJN (near 0600 MLT) and passes through the region bounded SCO and LRV (near 0300 MLT). The Z perturbations are consistent with this estimation.

To confirm that the electrojet distribution was determined primarily by the conductivity distribution and the scale size of the electric field is much wider than that of the enhanced conductivity, we have also examined the electric field data. Fortunately, convection data from Super Dual Auroral Radar Network (SuperDARN) radars located in Finland and Iceland East were available for this event. The fields of view of the two radars cover the early morning sector, as shown in Figure 1.

There are 16 beams for each radar. In the field of view of the Finland radar, Beam 0 (15) corresponds to the most western (eastern) one. For the Iceland East
Plate 1. Range-time plots of line-of-sight velocity observed at the (top) Finland and (bottom) Iceland East radars. The gray area indicates ground scatter region.
radar the most northern beam is Beam 0, and the most southern beam is Beam 15 [Greenwald et al., 1995]. The radars were operating with a discretionary mode on January 10, 1997: only Beams 5 to 14 for the Finland radar and Beams 0 to 9 for the Iceland East radar were available. Plate 1 shows range-time velocity plots of Beam 9 for the Finland radar and Beam 9 for the Iceland East radar. The reason we choose these beams is that the directions of Beams 9 for Finland and Iceland East radars cross over BJN where the magnetic perturbations and the corresponding auroral emissions are available.

A positive velocity denotes the direction toward a radar. For the Finland radar the data show mostly the north-south component, whereas for the Iceland East radar, the data show mostly the east-west component. In Plate 1 the echoes below 65° latitude (range $\leq 700$ km) are considered to be E region scatters and should be ignored. The line-of-sight velocity of E region echoes may be sound speed, limited to a maximum of $\sim 300$ to 400 m/s, therefore not reliable [e.g., Hanuise et al., 1990].

In the range-time plot of the Finland radar the color of the region at range 1600 km at around 0304 UT is yellow or light green, indicating the existence of enhanced northward velocities. Beam 9 of the Iceland East radar points to BJN. The beam is aligned with the region of the enhanced aurora in the early morning sector. The color at range 1300 km at around 0304 UT is also yellow or light green, indicating that enhanced eastward convection. The eastward convection was reduced as time lapsed. This change is consistent with a change in IMF from southward to northward. The ground magnetic variations also changed accordingly (see Figure 2).

2.2. October 19, 1986, Event

The event of October 19, 1986, had been studied in detail by Elphinstone et al. [1991] and Elphinstone et al. [1996] in terms of whether the dayside aurora was a precursor to the nightside aurora. The number of ground magnetometer stations they were referred to was not extensive enough to discuss the global nature of the auroral electrojets. Since an intense growth phase is our major concern in the present study, it is worth reexamining this event using more ground-based magnetometer data. Data from 37 ground magnetometer stations at high latitudes have been collected for this event. The locations of these stations above 60° CGLat at 1127 UT are shown in Figure 4. As will be shown later, 1127 UT was the time when the westward electrojet reached its maximum value at FCC (Fort Churchill). Although very few stations were located along the evening sector, the station distribution did not substantially affect our study since the main focus of this study is placed on the westward electrojet in the early morning sector.

As in our analysis of the January 10, 1997, event, we remove quiet time variations (1200 UT October 17 to 1200 UT October 18) from each of magnetograms and generate superposed $X_m$ component plots from the stations over 60°-75° CGLat. These are shown in the first panel of Figure 5. According to the plots, the large $AL$ value was seen by only one station during the event. The other stations exhibited relatively low activity. The vertical dashed line at 1132 UT denotes the expansion onset time. Elphinstone et al. [1996] examined other sources of information; Pi2 pulsations and particle injections at geosynchronous orbit, reconfirming a causal relationship between the precursor activity and the substorm expansion onset occurred at 1132 UT. It is important to point out that this substorm expansion added only a small amount of $X_m$ (−100 nT) to the westward electrojet.

The IMP 8 satellite was in the solar wind 30 RE upstream from the Earth during the event. A detailed timing analysis suggests that the auroral electrojet was associated with a period of southward IMF preceded by a prolonged northward IMF, a period of large negative IMF $B_y$, and two velocity jumps in the solar wind, as shown in Figure 5. The solar wind density was nearly constant. The first velocity jump did not generate much of the auroral electrojet because of the northward IMF at the time. Although we are not totally certain because of the data gaps, the second velocity jump and southward IMF seems to result in geomagnetic distur-
enhanced aurora in the early morning sector. As seen in Figure 6b, the eastward electrojet was highly enhanced at 16.8 MLT at DIK (Dixon Island). AMD (Amderma) also experienced the effect of a relatively high electrojet activity.

Plate 3 of Elphinstone et al. [1991] showed a large-scale auroral distribution from 1117 to 1134 UT. The auroral activity in the afternoon sector began to brighten in the early stage of this period. A few minutes later, auroral forms with beads appeared in the morning and evening sectors. The auroras in the two sectors were connected at the time of the expansion onset, leaving an gap in the prenoon sector. This auroral form is similar to the one for the January 10, 1997, event in the sense of the azimuthal distribution. In contrast to the January 10, 1997, event, the auroral emission of this event on the duskside was much brighter than that on the dawnside. The auroral images show no emissions at midnight, resulting in the low conductances of the ionosphere, and hence low electrojet activity. This is consistent with the fact that FYU, TLK, and AVI observed almost no geomagnetic activity prior to the expansion onset.

2.3. November 28, 1995, Event

Sergeev et al. [1998] presented observations of two subsequent, short-duration increases of the westward electrojet in the postmidnight sector of the November 28, 1995, event. They described the second electrojet as an “incomplete” current system with a well-developed dawn electrojet but in the absence of a dusk electrojet. They superposed $H$ components from standard magnetometer stations only (see their Figure 1). The first electrojet increase demonstrates localized behavior of the westward electrojet. By examining individual magnetograms from their Figures 1 and 3, we find that the localized electrojet occur at FCC. The strength of the electrojet reached its maximum value (−180 nT) at 1044 UT. The local time of the station was at 3.8 MLT at that time. GIL and RAB also experienced relatively high westward electrojet activity. DIK, which was located at (68.5° CGlat, 16.1 MLT), experienced ~50 nT strength of eastward electrojet.

The Wind satellite was located in the duskside magnetosheath on November 28, 1995, while the IMP 8 satellite was located on the duskside of the magnetosheath (see Figure 9 of Sergeev et al. [1998]). As shown in their Figure 8, there was a period of strong southward IMF in the IMP 8 data, however, no such IMF structure was observed by the Wind satellite, indicating the localized characteristics of the IMF structures. It is reasonable to choose the IMP 8 data as the corresponding solar wind conditions for the localized westward electrojet on the duskside because the IMP 8 satellite was in the duskside magnetosheath. The IMP 8 data show a southward IMF preceded by a prolonged period of northward IMF. The IMF $B_y$ was negative throughout the event. Unfortunately, there

**Figure 5.** Superposed $X_m$ component plots, and solar wind measurements from the IMP 8 satellite on October 19, 1986. The solar wind data have been shifted 3 min for the propagation time. The vertical dotted and dashed lines denote the time of the southward turning and the expansion onset, respectively.
Figure 6a. Magnetic disturbances at individual stations in the early morning and midnight sectors. The vertical dotted (dashed) line denotes the time of the southward IMF turning (the expansion onset). The local times of stations marked following the vertical dashed line is estimated at the time of the peak AL prior to the substorm expansion onset.

were no global auroral images available to be examined regarding whether the similar auroral form reported in the January 10, 1997, and October 19, 1986, events occurred during the November 28, 1995, event. However, the meridional scanning photometer (5577 Å) at Poker Flat showed the existence of auroral emissions at 60° CGlat in the midnight sector prior to the expansion onset (see Plate 1 of Sergeev et al. [1998]). Note that this event was not so isolated as the other event shown in this paper. We can see electrojet activity (from Figure 1 of their paper), intense auroral activity (from Plate 1 of their paper), and burst flows in the plasma sheet (from Figure 7 of their paper) prior to the growth phase.

Figure 6b. Magnetic disturbances at individual stations in the evening sector, in the same format as Figure 6a.
Table 1. Summary of Events With Large Growth Phase

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Date</th>
<th>Peak AL Time</th>
<th>Onset Time</th>
<th>Peak AL</th>
<th>Peak AL Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Jan. 10, 1997</td>
<td>0304 UT</td>
<td>0334 UT</td>
<td>200 nT</td>
<td>BJJ (71.5° CGlat, 5.3 MLT)</td>
</tr>
<tr>
<td>2</td>
<td>Oct. 19, 1986</td>
<td>1127 UT</td>
<td>1132 UT</td>
<td>-340 nT</td>
<td>FCC (69.5° CGlat, 4.3 MLT)</td>
</tr>
<tr>
<td>3</td>
<td>Nov. 28, 1995</td>
<td>1044 UT</td>
<td>1119 UT</td>
<td>-180 nT</td>
<td>FCC (69.5° CGlat, 3.8 MLT)</td>
</tr>
<tr>
<td>4</td>
<td>Nov. 11, 1976</td>
<td>2042 UT</td>
<td>2102 UT</td>
<td>-300 nT</td>
<td>DIK (68.5° CGlat, 2.1 MLT)</td>
</tr>
<tr>
<td>5</td>
<td>July 24, 1986</td>
<td>2237 UT</td>
<td>2205 UT</td>
<td>-230 nT</td>
<td>DIK (68.5° CGlat, 4.0 MLT)</td>
</tr>
</tbody>
</table>

2.4. November 11, 1976, Event

Pellinen et al. [1982] reported an intense growth phase with a maximum disturbance of \( \Delta H = -300 \) nT. The maximum disturbance was measured at DIK during the event, as shown in their Figure 2. The electrojet at DIK reached its peak at 2042 UT (2.1 MLT). The electrojet increased its strength at the midnight stations after the expansion onset, while other stations in the morning and midnight sector observed much smaller electrojet strength. This indicates the localized feature of the westward electrojet of this event. In the evening sector, FCC and NAQ also observed relatively high activity of the eastward electrojet.

Figure 3 of Pellinen et al. [1982] shows IMF data recorded in the dawnside magnetosheath by the IMP 8 satellite. It is obvious that large geomagnetic disturbances occurred during a period of southward IMF, which was preceded by a prolonged northward IMF. The IMF \( B_y \) was positive throughout the growth phase. As in the November 28, 1995 event, no global auroral images for the event were available. However, the all-sky camera data from Ivalo shows that some auroral activity existed in the midnight sector prior to the substorm expansion onset.

2.5. July 24, 1986, Event

Figure 4 of Elphicxone et al. [1995] shows relatively high electrojet activity at DIK (Dixon Island), MMK (Murmansk), and SOD (Sodankyla). The maximum value \((-230 \) nT) was obtained from DIK (68.5° CGlat, 4.0 MLT). The strength of the disturbance at MMK (1.2 MLT) and SOD (0.8 MLT) was only one half of that at DIK. The westward electrojet near midnight increased its strength after the substorm onset (2305 UT) (see Figure 5 of Lui et al. [1995]). Note that the time of the expansion onset was identified using the Viking auroral UV images and geosynchronous particles flux [Elphicxone et al., 1995; Lui et al., 1995].

Figure 2 of Lui et al. [1995] shows solar wind conditions for the July 24, 1986 event, demonstrating that the event occurred during a period of extremely strong southward IMF \((-18 \) nT) preceded by a prolonged northward IMF. The IMF \( B_y \) changed from negative to positive during the growth phase. The strong southward IMF created enhanced auroral emissions on the duskside after the southward IMF turning (see their Plate 1). Some beads form of aurora appeared in the morning sector. Later, a sudden activation in the morning sector occurred, leaving the midnight sector relatively undisturbed. During this event, strong southward IMF moved the auroral oval equatorward to 60° CGlat. By examining the magnetograms in the evening sector (not shown), we found that PDB (Poste-de-la-Baleine) and FCC observed high activity of the eastward electrojet at ~300 nT.

3. Summary of the Observations

Tables 1-4 summarize the characteristics of auroral electrojet activity and the corresponding solar wind conditions for the five events discussed in section 2. These events show a strong westward electrojet in the early morning sector based on the AL index. We provide each event with an event number, as shown in the first column of Table 1. The times of the substorm expansion onset for these events had been determined from auroral emissions, Pi2 pulsations, particle fluxes at geosynchronous orbit, and plasma data in the magnetotail, whenever available, from Tsurutani et al. [1998], Elphicxone et al. [1991], Sergeev et al. [1998], Pellinen et al. [1982], and Lui et al. [1995]. We identified the peak AL value and the time of the peak AL from superposed \( X_m \) or \( H \) component plots for each event. The

Table 2. Corresponding Interplanetary Magnetic Field Conditions for the Events Listed in Table 1

<table>
<thead>
<tr>
<th>Event No.</th>
<th>IMF ( B_y )</th>
<th>IMF ( B_y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>southward ((-6.7 ) nT) after prolonged northward ((7.7 ) nT)</td>
<td>positive</td>
</tr>
<tr>
<td>2</td>
<td>southward ((-1.9 ) nT) after prolonged northward ((5.3 ) nT)</td>
<td>negative</td>
</tr>
<tr>
<td>3</td>
<td>southward ((-8.0 ) nT) after prolonged northward ((2.0 ) nT)</td>
<td>negative</td>
</tr>
<tr>
<td>4</td>
<td>southward ((-6.0 ) nT) after prolonged northward ((5.0 ) nT)</td>
<td>positive</td>
</tr>
<tr>
<td>5</td>
<td>southward ((-18.0 ) nT) after prolonged northward ((10.0 ) nT)</td>
<td>transition from negative to positive</td>
</tr>
</tbody>
</table>
Table 3. Stations With Relatively High Westward Electrojets in the Early Morning Sector

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BJN (71.5° CGlat, 5.3 MLT), NAQ (66.5° CGlat, 1.0 MLT), LRV (65.2° CGlat, 2.6 MLT)</td>
</tr>
<tr>
<td>2</td>
<td>SCO (71.8° CGlat, 3.0 MLT)</td>
</tr>
<tr>
<td>3</td>
<td>FCC (69.5° CGlat, 4.5 MLT), YKC (69.7° CGlat, 2.3 MLT)</td>
</tr>
<tr>
<td>4</td>
<td>FCC (69.5° CGlat, 3.8 MLT), GIL (68.9° CGlat, 3.8 MLT), RAB (67.5° CGlat, 2.9 MLT)</td>
</tr>
<tr>
<td>5</td>
<td>DlK (68.5° CGlat, 2.1 MLT), MMK (64.6° CGlat, 1.2 MLT), SOD (64.9° CGlat, 0.8 MLT)</td>
</tr>
</tbody>
</table>

latitude and local time information of the stations with peak AL is summarized in the last column of Table 1. Note that their local times are indicated for the time of the peak AL values.

Table 2 summarizes the corresponding IMF conditions for the five intense growth-phase events. A common feature of the corresponding IMF B_z among these events is that the intense growth phase was occurring during a period of southward IMF after a prolonged northward IMF. The average values of the IMF after and before the southward IMF turning have been estimated and shown in the second column of Table 2. Note that the solar wind monitor was in the magnetosheath for events 3 and 4; therefore the real values of the northward and southward IMF should be smaller than those listed in Table 2. Event 5 occurred under a strong southward IMF: the auroral oval should move much equatorward than in the other events. In the third column we find no systematic IMF B_y polarity.

In addition to the station providing the peak AL value for each event, it is worth examining other stations with relatively high electrojet activity. Stations with relatively high auroral electrojet, including the peak AL station listed in Table 1, have been summarized in Table 3. The local time for these stations was estimated at the time of the peak AL during the growth phase. Table 4 is similar to Table 3, but for the eastward electrojet in the evening and afternoon sectors.

In Figure 7 we superpose the stations listed in Table 3 on the contour plots of the Viking auroral UV emissions for 1127 UT, October 19, 1896 (in solid contours), and of Polar UV images for 0304 UT January 10, 1997 (in dotted-dashed contours). Note that auroras drastically change their locations on the duskside between the two auroral data, but not on the dawnside. The black circles with event numbers represent the locations of the stations for the different events. It is evident that the distribution of the stations is strikingly consistent with that of auroral emissions in the early morning sector, indicating that the intense growth phase events are associated with the auroral emissions.

For the evening and afternoon sectors, Figure 8 shows a plot for superposing the locations of the stations listed in Table 4 over the contours of the auroral emissions which are the same as in Figure 7. The black circles seem to be inconsistent with the enhance auroral emissions. Two possible reasons may contribute to the inconsistency. First, the electric field in the evening sector might dominate the eastward electrojet. Unfortunately, the electric field data were not available to check this point. Second, sources of the ionospheric conductances are not only from precipitating particles [Robinson et al., 1987; Hardy et al., 1987] but also from solar EUV radiation [Vickrey et al., 1981; Rasmussen et al., 1988], and the inconsistency may be due to higher conductances from solar EUV than from precipitating particles. Furthermore, the auroral oval was moving equatorward as the southward IMF was increasing, such that the black circles with number 5 might in fact match the auroral emissions. This result is supported by the observations that PDB and FCC saw a large eastward electrojets, up to 300 nT.

4. Discussion

The southward IMF has been known to be a very important parameter with respect to the transfer of solar wind energy into the magnetosphere. The growth phase develops after a turning of southward IMF, resulting in weak electrojet activity at auroral latitudes [McPherron, 1970]. The magnitude of the corresponding positive and negative H components perturbations during

Table 4. Stations With Relatively High Eastward Electrojets in the Evening and Afternoon Sectors

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FSM (67.8° CGlat, 18.4 MLT), GIL (66.8° CGlat, 20.1 MLT), YKC (69.6° CGlat, 18.0 MLT)</td>
</tr>
<tr>
<td>2</td>
<td>RAB (67.5° CGlat, 19.2 MLT)</td>
</tr>
<tr>
<td>3</td>
<td>DlK (68.5° CGlat, 16.8 MLT), AMD (64.8° CGlat, 15.6 MLT)</td>
</tr>
<tr>
<td>4</td>
<td>FCC (69.5° CGlat, 13.8 MLT), NAQ (69.5° CGlat, 18.6 MLT)</td>
</tr>
<tr>
<td>5</td>
<td>PDB (66.0° CGlat, 17.5 MLT), FCC (69.5° CGlat, 15.7 MLT)</td>
</tr>
</tbody>
</table>
the growth phase is usually much smaller than that during the substorm expansion phase. The events shown in this paper, however, have large $AL$ values prior to the expansion onset. Although no $AL$ threshold existed which defined an intense growth phase, the $AL$ values listed in Table 1 are large for the growth phase, comparing to that for the substorm expansion phase under the same event.

In this study, we have found that auroral westward electrojet was enhanced at only one or a very few stations, indicating a localized characteristic of the westward electrojet. The latitude and local time information of the stations which have relatively high electrojet activity seems to display a systematic pattern. Stations at "higher" latitudes observed relatively high electrojet activity in the "early morning" sector. Also, stations at "lower" latitudes observed relatively high electrojet activity in the "postmidnight" sector. Owing to a sparse distribution of ground-based magnetometer stations, stations located directly under the electrojet are able to measure the effect of the intense westward electrojet.

These intense growth phase events are shown to be associated with a period of southward IMF preceded by a prolonged northward IMF. It is important to point out that the prolonged northward IMF, which we have examined in the present paper, did not occur during the recovery phase of previous substorm activity. It is also important to note that the southward turning of IMF that followed the prolonged northward IMF had driven the auroral electrojet in the ionosphere, which is one of the typical signatures for the substorm growth phase. It is not our intention, however, to generalize that every southward IMF preceded by a prolonged northward IMF will produce an intense growth phase, but we would only like to point out that these intense growth-phase events did occur following changes of this type of the IMF orientation.

A possible interpretation of these intense growth phase events is that, if the IMF is northward for a prolonged interval, the magnetosphere becomes extremely quiet, reaching a balanced ground state and having the auroral oval at its highest latitude, near 75° [Akasofu and Kamide, 1976]. If the IMF turns southward abruptly from that northward condition, the magnetosphere-ionosphere system is not quite ready for having a ground substorm expansion. The "balance" of the system may be broken partially or locally, creating these intense growth phase events, which are not intense on a global scale, but intense in local auroral luminosities and the corresponding westward electrojet. The corresponding IMF $B_y$ shows no systematic feature for these events, indicating that an intense growth phase can appear in either a positive or negative $B_y$.

In Figure 7 we compare the location of the stations listed in Table 3 with the pattern of the auroral emissions. It is found that the location of the stations systematically matches with the pattern of the auroral emissions. This consistency demonstrates that the intense westward electrojet is associated with enhanced

Figure 7. Comparisons between the location of stations in the early morning sector and contours of the auroral emissions prior to the substorm expansion onset. The solid and dotted dashed contours of auroral emissions are the same as those plotted in Figures 1. The black circles with event numbers denote the location of the stations listed in Table 3.

Figure 8. Comparisons between the location of stations in the evening and afternoon sectors and the contours of auroral emissions used in Figure 7. The black circles with event numbers represent the locations of the stations listed in Table 4.
auroral emissions. It also indicates that the reported large westward electrojet is conductance-generated, i.e., enhanced conductances play a very important role in creating large westward electrojets prior to the expansion onset for these events. One may ask the reason why the magnetograms contain localized characteristics of the westward electrojet. One reason is that the stations are sparsely distributed in the regions. A station should be at the right position to observe the right magnitude of the narrow and large westward electrojet. Another reason is that the intensity of auroral emissions is temporally and spatially variable [Elphinstone et al., 1995, Lui et al., 1995]. Even though a station is located under the electrojet, the station might miss large geomagnetic disturbances due to changing emissions.

The solid contours of the auroral emissions in Figure 7 are for the October 19, 1986, event which is marked as event number 2. The black circle at 4.5 MLT (FCC) was located directly over the center of the auroral emissions in the north-south direction, explaining why FCC observed large geomagnetic disturbances. The black circle at 2.3 MLT (YKC), on the other hand, was located near the edge of the auroral emissions. Thus it is expected that YKC observed relatively high westward electrojet. The magnetogram for YKC supports this expectation. MEA (62.2° CGlat, 2.8 MLT) was also near the region of the auroral emissions. In fact, MEA observed a portion of the electrojet, but much smaller than that at FCC and YKC. Had a station been located near the peak of the auroral emissions, we would have observed intense electrojets, probably more intense than the magnitude observed at FCC. In Table 2 the magnitude of the corresponding southward IMF for event 5 (July 24, 1986) was about –18 nT. Such an extremely strong southward IMF must move the aura equatorward to 60° CGlat in the early morning sector, resulting in the auroral coverage beyond the scope of the stations (see Plate 4 of Elphinstone et al. [1995]). During this event the electric fields observed from an extremely strong southward IMF are believed to have been quite large.

The convection data from the SuperDARN radars for the January 10, 1997, event enable us to examine if the electrojet is electric field dominant or conductance dominant. We assume that the scale of the electric field is much wider than that of the auroral enhancement. From an examination of this period of the data it is found that the enhanced convection occurred at latitudes where the auroral emissions were enhanced. Thus a combination of the electric field and conductance led to the intense electrojet.

Finally, we note that the auroras in the early morning shown in this study did not accompany poleward expansion. One may believe that what we have shown is a pseudobreakup. However, the brightening lasted 15 min (40 min) for the October 19, 1986 (for January 10, 1997), event before the substorm expansion onset occurred near midnight. Although there are no clear def-

initions of pseudobreakups, McPherron [1991], Pullkinen [1996], and Atko et al. [1999] have shown pseudobreakups to be associated with short-lived, highly localized, weak ground magnetic perturbations. Thus the events we have shown are not pseudobreakups.

5. Conclusions

In this study, we have reexamined five events of the intense growth phase using ground based magnetometer data, solar wind data, and auroral UV images. These events have enabled us to understand further the processes behind what were observed in common. We provide the following findings from these data:

1. It is generally believed that the magnitude of the westward electrojet is smaller during the growth phase than that during the substorm expansion. However, each of the events that we have examined shows intense westward electrojet activity during the growth phase, comparing to the strength of the substorm expansion phase for the same event.

2. Only one or a very few stations which are located in the early morning sector observed large geomagnetic disturbances, resulting in a large AL value during the growth phase. This means a localized characteristic of the westward electrojet for these events.

3. These events occurred during a period of southward IMF preceded by a prolonged northward IMF. However, no systematic patterns in IMF $B_y$ among these events have been found. The period of southward IMF increases the electric field and hence the electrojet.

4. Enhanced aurora occurred during the growth phase of these events. The auroral features include enhanced dayside activity and early morning activity. The latter takes the form of azimuthally spaced auroral forms. Its luminosity changed both spatially and temporally, but enhanced auroral emissions are matched with the intense auroral electrojet, indicating that the ionospheric conductance further enhances the auroral electrojet.

5. We do not suggest that every southward IMF preceded by a prolonged northward IMF will produce such auroral emissions. However, stations can observe large geomagnetic disturbances when such auroral emissions exist and the stations are in the proper positions.

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