

Are high-intensity long-duration continuous AE activity (HILDCAA) events substorm expansion events?

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Abstract

High-intensity, long-duration, continuous AE activity (HILDCAA) are magnetospheric/ionospheric events that occur during high-speed solar wind streams. The AE increases are caused by intermittent magnetic reconnection between southward components of interplanetary Alfvén wave fluctuations and magnetopause magnetic fields. During solar minimum, corotating interaction regions (CIRs) created by corotating stream interactions with slow-speed streams cause relatively short duration moderate to minor magnetic storms. These storms are followed by lengthy (days to weeks) of HILDCAA intervals characterized by low levels of enhanced ring current activity (D_{ST}). Shorter HILDCAA intervals are also noted following interplanetary coronal mass ejections (ICME)-related storm events. Two intervals were chosen to study in detail using POLAR UVI imaging data to identify substorms. The first was an interval not associated with a storm. The second was a short interval following an ICME-related magnetic storm. Although substorms were detected during the HILDCAA intervals, there was little or no relationship between substorm occurrences and AE ($-AL$) increases. One possible explanation is that prompt penetration of interplanetary electric fields associated with magnetic reconnection lead to enhanced ionospheric westward electrojet current densities ($-AL$ increases). These same dawn-to-dusk electric fields could lead to the convection of nightside outer magnetospheric/plasmasheet plasma, causing particle injection and D_{ST} decreases. Substorms must be caused by other processes, such as self-organized criticality.

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1. Introduction

Long stretches of continuous, high-intensity, AE intervals often follow major interplanetary events such as shocks and solar wind density enhancements. Tsurutani and Gonzalez (1987) defined high-intensity long-duration continuous AE activity (HILDCAA) events as intervals where: (1) AE peak values exceed 1000 nT, (2) the durations were greater than

2 days, and (3) the AE values never dropped below 200 nT for more than 2 h at a time. A further requirement was that: (4) HILDCAAs must occur outside of the main phases of magnetic storms. Tsurutani and Gonzalez (1987) (hereafter called TG87) stressed that the mechanism creating HILDCAAs must be separate from those creating magnetic storm main phases because no known physical hypothesis could explain storm “recoveries” that last for as long as days or weeks (unless of course, further particle injections are occurring). All major physical processes for ring current decay (charge exchange, Coulomb collisions, convection, and wave-particle interactions) have time scales of hours to fractions of days (Kozyra, et al., 1997, 2002).

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It should be noted that the original TG87 criteria set for HILDCAA events was arbitrary. Somewhat extreme criteria were imposed to illustrate the geophysical phenomena. Clearly the same physical process may occur where one or more of the four criteria are not strictly followed. It should also be noted that the definition of HILDCAA events contains the term “AE Activity”, and not necessarily substorm activity. The cautious wording was suggested by S.-I. Aka-sofu (personal communication, 1986) because in TG87, it was not known if the AE activity was due to auroral substorms or not (see also comments about AE usage in Rostoker et al., 1987; Kamide and Kokubun, 1996). This question is still an open one.

Tsurutani et al. (1990a), used IMP-8 solar wind plasma and magnetic field data and the AE indices to study HILDCAAs. High cross-correlation coefficients were noted between the southward component of IMF B_z (B_S) and the AE indices. The correlation coefficients were 0.49–0.64 for 12–24 h intervals and were up to 0.85 for shorter intervals. IMP-8 is an Earth-orbiting satellite. The maximum GSE- y and $-z$ distances for the 7 intervals of study were 32 and $24R_e$, respectively. Previous HILDCAA-AE analyses using ISEE-3 data (ISEE-3 was in orbit around the L_1 libration point) gave much poorer correlation coefficients. The above two results indicate that the spatial scale size of the causative Alfvén waves are often smaller than the ~ 60 – $100R_e$ scale sizes of the ISEE-3 orbit about the Sun–Earth line.

One thought is that the strong IMP-8 B_S –AE cross-correlation results demonstrate that HILDCAAs are a consequence of solar wind energy transfer to the magnetosphere caused by magnetic reconnection between southward components of interplanetary Alfvén waves and magnetospheric magnetic fields. The reconnection picture is the same as the Dungey (1961) mechanism. The reconnection intervals are short compared with that during storm main phases due to the oscillatory nature of the Alfvén waves. One possible interpretation of this result is that the AE increases are substorm expansion phases and the D_{ST} decreases are caused by plasma injections into the outer regions of the nightside magnetosphere. Other possibility exist, however. The enhanced AE could be due to enhanced magnetospheric/ionospheric convection and may not involve substorm onsets at all (Sergeev et al., 1996; Tsurutani et al., 2003; Zhou et al. 2003). Also inward (and outward) motions of the tail current system could cause the D_{ST} decreases (and increases) without plasma injections (Campbell, 1999; see Feldstein, et al. 2003, for comments on the role of the tail current during magnetic storms).

The purpose of this paper is to illustrate the importance of HILDCAAs during the declining phase of the solar cycle, the relationship between the IMF B_S and AE and D_{ST} , and to determine the relationship between HILDCAAs and substorms expansive phases. We will use IMP-7 and -8 data to illustrate the HILDCAA relationship to high-speed streams

and Alfvén waves (in 1974) and the POLAR UVI imaging data to identify substorms and other auroral forms during intervals in 1997 and 1998. In the paper we will use not only the AE (auroral electrojet) indices, but also the AU and AL indices. AE is a summation of AU–AL. The latter two indices are measures of the eastward and westward electrojet current densities, respectively.

2. Results

Fig. 1 gives OMNI (IMP-7 and -8) interplanetary solar wind data and three geomagnetic activity indices (ap, AE, and D_{ST}) for the entire year of 1974. During 1974, there were two corotating high-speed solar wind streams (Sheeley et al., 1976, 1977; Tsurutani et al., 1995). These stream sequences are labeled “1” and “2”. The corotating streams caused moderate ($-100 \text{ nT} < D_{ST} < -50 \text{ nT}$) to weak ($-50 \text{ nT} < D_{ST} < -25 \text{ nT}$) recurring storms, and sometimes no significant ring current activity at all ($D_{ST} > -25 \text{ nT}$). The sequence 1 stream (see top panel) starts on day 25 and progresses at ~ 27 -day intervals, causing D_{ST} minimum values of -65 , -20 , -75 , -85 , -45 , -30 , “A”, -60 and -35 nT . The “A” event was the largest magnetic storm ($D_{ST} = -204 \text{ nT}$) that occurred during 1974. Three ICME fast streams created the strong storm (see Tsurutani et al., 1995), overshadowing the effects of the sequence 1 stream. Sequence 2 corotating streams start at day 15 and cause D_{ST} minima of -20 , -20 , -30 , -50 , -30 , -25 , -40 , -75 , and -35 nT .

The most dramatic geomagnetic responses to the corotating streams are HILDCAA events that occur after the storms. The HILDCAA events are found to be concurrent with the exceptionally long storm “recovery” phases after storm main phases. AE is generally most intense near the peak speed of the stream (where Alfvén waves have the largest amplitudes [not shown]) and it decreases with decreasing wave amplitude and stream speed. Each of the 27-day recurrent HILDCAA events can last 10 days or more. Some prime examples of this are found on days 25–35, 80–92 and 108–122 for the sequence 1 corotating stream, and on days 204–214, and 231–241 for the sequence 2 stream.

The presence of two stream events per solar rotation period causes the exceptionally large annual AE average for 1974 (283 nT). This is higher than either of the two annual average values for the following (dual peak) solar maximum values (221 nT in 1979 and 237 nT in 1981).

Fig. 2 shows the relationship between the Alfvén wave B_z fluctuations and AE and D_{ST} indices for a 4 day interval in 1974. This interval follows a storm main phase and is in the storm “recovery” phase (this interval is indicated by shading in the D_{ST} panel of Fig. 1). In Fig. 2, each increase in IMF B_S is accompanied by an AE increase and D_{ST} decrease. The GSM southward B_z (B_S) intervals are indicated by shading. Examples of IMF B_S events are found on day 135–1200 UT to ~ 1800 UT ($B_z \cong -9 \text{ nT}$), day 135–2000 UT

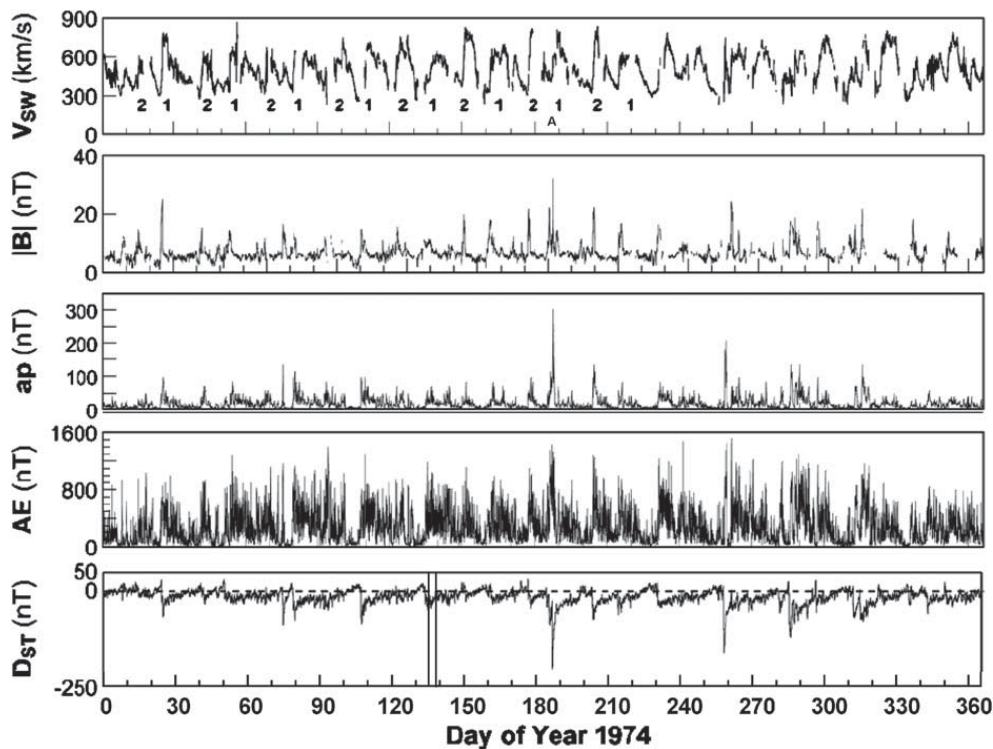


Fig. 1. The solar wind speed, the interplanetary magnetic field magnitude, and three geomagnetic indices (ap , AE and D_{ST}) for 1974. Corotating stream sequences 1 and 2 are indicated in the top panel. Each of the CIRs associated with the fast stream–slow stream interactions cause only moderate to weak D_{ST} events (the “A” event is due to a series of interplanetary CMEs and this overshadows the CIR effect). The streams themselves are related to HILDCAAs (noted in the AE indices) that last days to weeks. There are low level D_{ST} decreases during HILDCAA events. A 4 day HILDCAA interval that will be discussed later is indicated by shading.

to ~ 2200 UT ($B_Z \cong -9$ nT) and day 136–0500 UT to ~ 0900 UT ($B_Z \cong -8$ nT). The corresponding geomagnetic index increases and decreases were: ~ 1300 , ~ 650 and ~ 900 nT for AE and -40 , -50 and -35 nT for D_{ST} . There are two more major IMF B_S events on day 136–2200 UT to day 137–0100 UT ($B_Z \cong -8$ nT) and day 137–0200 UT to ~ 0430 UT ($B_Z \cong -8$ nT). There are corresponding AE increases and D_{ST} decreases, but delayed by ~ 1 h. The peak AE values are ~ 800 and ~ 1200 nT. The D_{ST} minimum are -35 and -45 nT.

Fig. 3 is an interval of intense and continuous AE activity (see bottom panel). This event was an isolated interval of geomagnetic activity. The event was moderately intense (up to ~ 500 nT) and lasts from 1600 to 2020 UT. The event does not meet the strict criteria of the $AE > 1000$ nT peak intensity, nor the 2 day duration limitation. However, because the event was relatively intense and continuous, we will examine this event assuming that it is part of the same phenomenon as HILDCAA events.

The AE , AL and AU indices in Fig. 3 were obtained from the Kyoto World Data Center (courtesy of T. Kamei, 2003). Superposed on the figure are vertical shadings indicating substorm intervals. We obtain these substorm intervals by examining Polar UVI images discussed next (in Fig. 4).

Fig. 4 contains the POLAR UVI images for the time interval of Fig. 3. The time cadence of the images is ~ 3 min. From the north polar auroral images, six clear substorm expansion and recovery phases can be identified. We use the Akasofu (1964) substorm morphology as the baseline. The substorms are present from: 1521 to 1533 UT, 1545 to 1604 UT, 1641 to 1653 UT, 1702 to 1724 UT, 1741 to 1808 UT and 1845 to 1910 UT. These events will be hereafter referred to as substorms 1–6 (see Table 1). The substorms are identified by the bright (red), near-midnight auroral UV intensifications, latitudinal and longitudinal expansions and fadings.

We now return to Fig. 3 to determine whether the HILDCAA AE intensifications are indeed substorms or not. Unfortunately there was no IMP-8 interplanetary data available for this event.

A comparison between substorm occurrence (shading) and AE enhancements can be made using Fig. 3. Substorm events 2 and 4 can be argued to be located at the leading edges of AE increases. Substorm events 1 and 3 are barely noticeable in the AE index. Substorm events 5 and 6 occur when the AE values are generally the highest and are noted to occur after AE had already reached local maximum values.

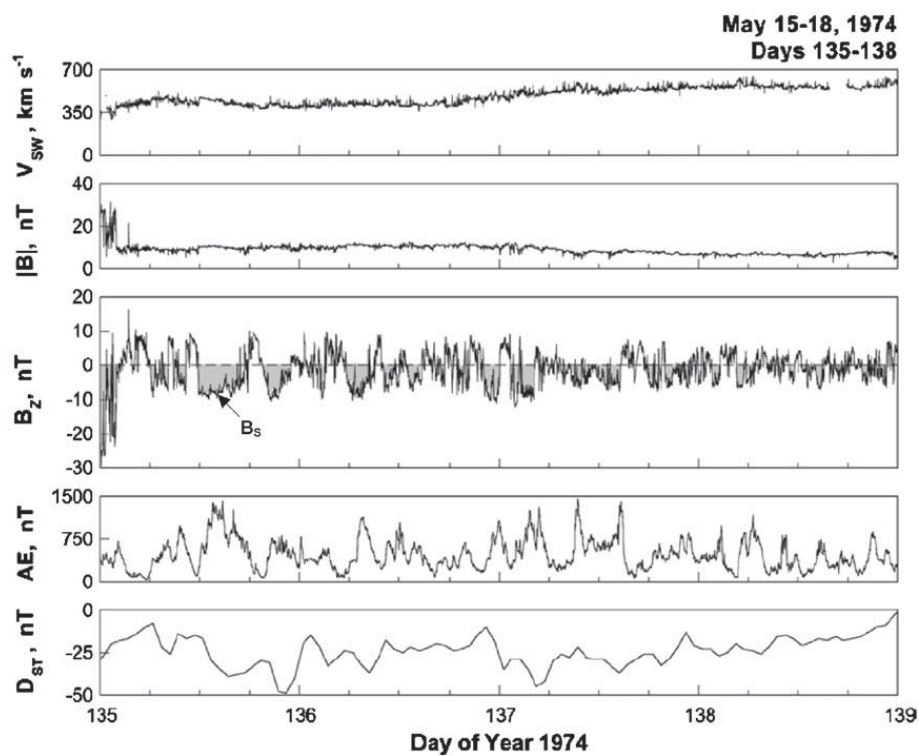


Fig. 2. A four day interval (May 15–18, 1974) during a magnetic storm recovery phase. Each IMF B_s event is accompanied by an AE increase and a D_{ST} decrease.

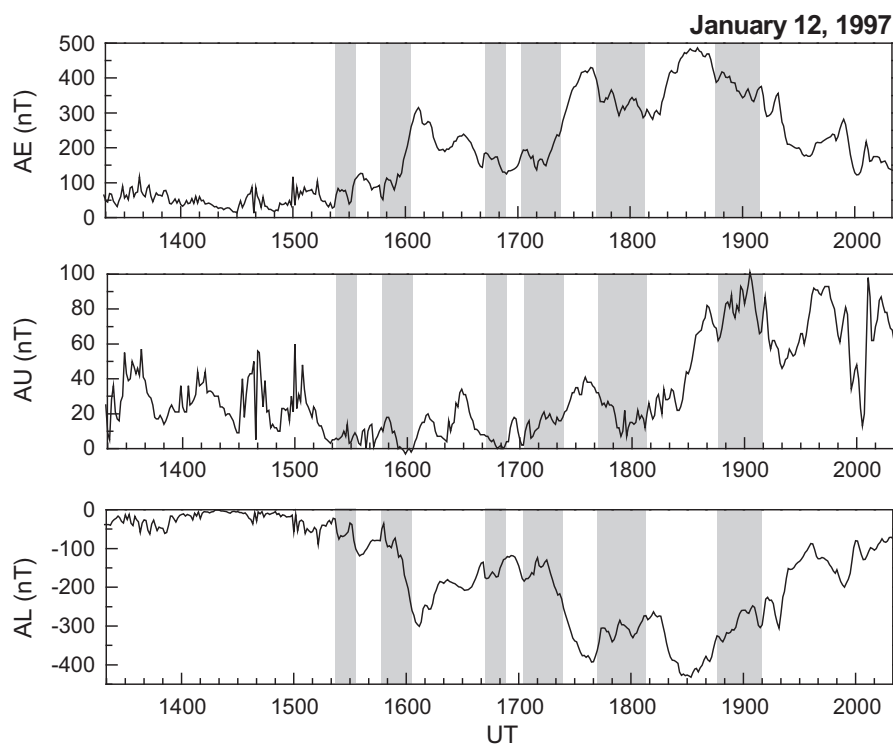


Fig. 3. An interval of continuous high AE values occurring on January 12, 1997. Substorm expansive phase intervals are indicated by the shading.



Fig. 4. POLAR UVI images for the interval of Fig. 3. Six clear substorms are noted in the interval.

Conversely, there are 3 clear AE local maximum intervals in the figure: ~ 1605 UT, ~ 1735 – 1740 UT, and ~ 1825 – 1842 UT. AL had maxima at the same times. The peak AE (–AL) values for the three intervals are ~ 315 nT (~ 300 nT) at 1605 UT, ~ 430 nT (~ 370 nT) at 1735 UT and ~ 490 nT (~ 420 nT) at 1830 UT, respectively. Substorm 2 was present during the first AE/–AL rise, but not at the peak (~ 315 nT). For the second

AE/–AL peak, substorm 4 was present during the initial rise, and substorm 5 after the peak. There were no substorms at the peak AE/–AL. For the third AE/–AL event, there was no substorm during the AE/–AL rise. Substorm 6 occurred well after the peak AE/–AL interval.

It should be noted in Fig. 3 that the major contribution to the AE increases are AL decreases. The AU index is a minor

Table 1
Substorms occurring in Fig. 4

Date: January 12, 1997		
Event no.	Substorm onsets (UT)	Substorm terminations (UT)
1	1521	1533
2	1546	1604
3	1641	1653
4	1702	1724
5	1741	1808
6	1845	1910

factor. This implies that HILDCAAs are due to westward electrojet intensifications.

We return to Fig. 4 to examine the auroral forms during the three peaks AE/–AL intervals. At ~ 1605 UT, the very intense aurora had already decreased, but precipitation over a broad region was still present. Aurora was present from 63° to 75° magnetic latitude and from ~ 22 local time (LT) to ~ 02 LT.

The second AE/–AL peak, from ~ 1735 to ~ 1740 UT is again characterized by precipitation over a broad latitudinal and longitudinal extent. The aurora again appears to be characterized by a featureless and diffuse nature. At ~ 1738 UT

the aurora is broadest in latitudinal extent between midnight and ~ 03 LT (the limit of POLAR viewing is ~ 03 LT) and extends from $\sim 63^\circ$ to $\sim 72^\circ$ magnetic latitude. It is possible that the precipitation extends to an even broader LT extent (see the image at 1733 UT where the intense precipitation extends to ~ 06 LT, the limit of UVI viewing at that time).

The third AE/–AL peak occurs from ~ 1825 to 1842 UT. Prior to this, there was a weak, poleward moving structure. At 1805 UT, the auroral brightness is localized to 70 – 72° magnetic latitude at ~ 22 LT. By 1818 UT this weak feature developed into a poleward bulge extending up to 75° magnetic latitude at ~ 23 LT. However from 1827 to 1839 UT, the interval of interest, the aurora had faded significantly. Throughout this interval, the midnight to dawn aurora was continuous and relatively intense. Again POLAR viewing limitations prevented knowledge concerning auroral energy deposition at other local times.

2.1. March 11, 1998

The March 11, 1998 HILDCAA event is shown in Fig. 5. The geomagnetic indices (AU, AL, AE and D_{ST}) are given from top to bottom of the figure. The HILDCAA event occurs in the recovery phase of an intense magnetic storm

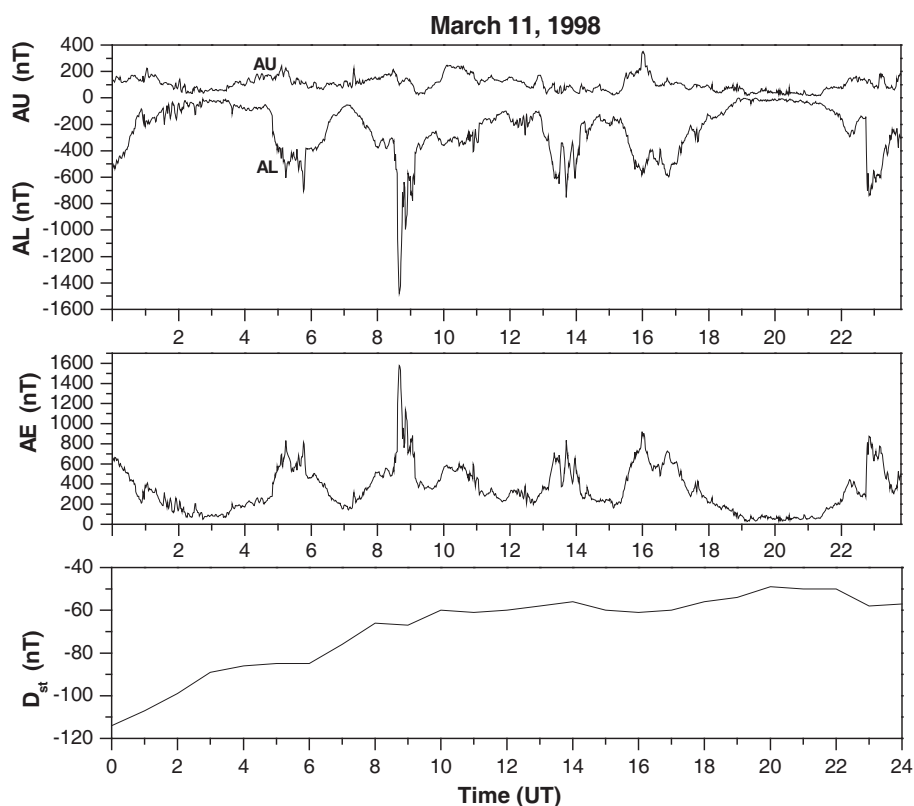


Fig. 5. A HILDCAA interval detected on March 11, 1998. From top to bottom are the 1 min average AU and AL indices, the AE index and D_{ST} .

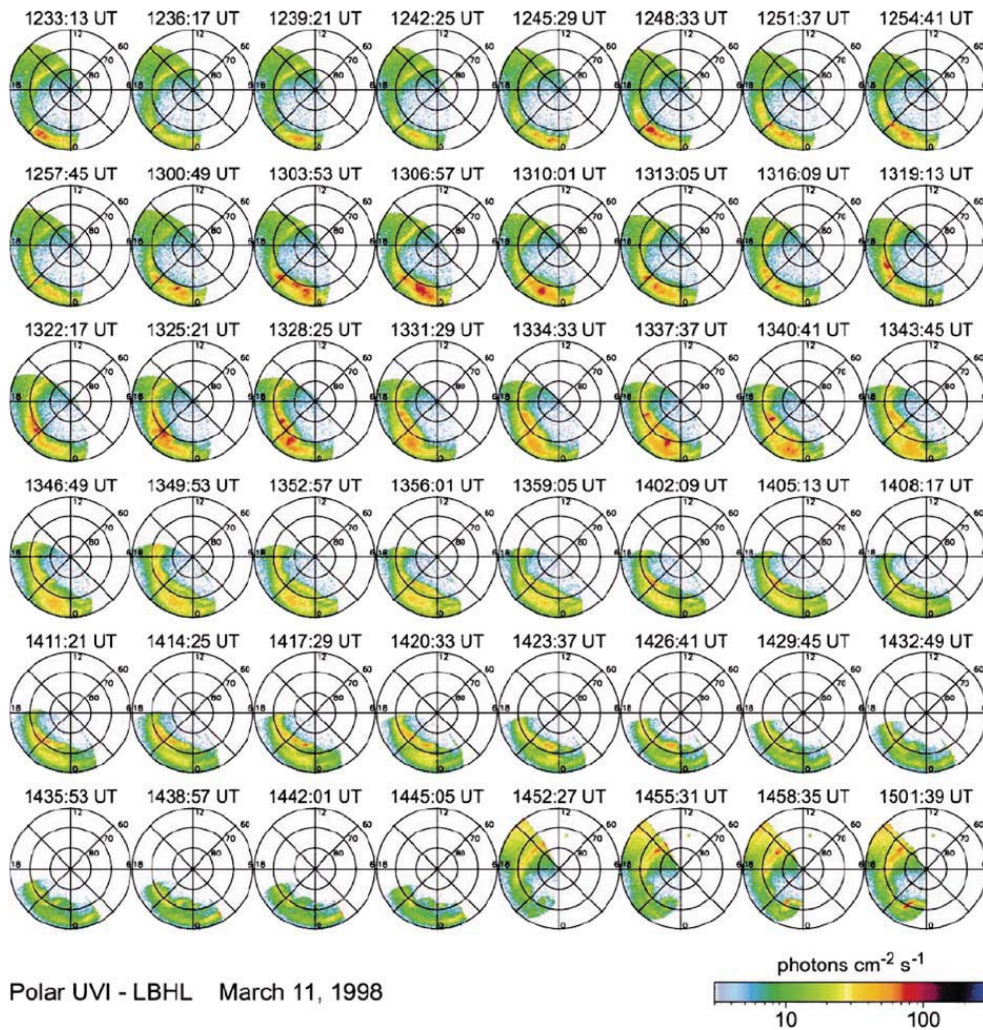


Fig. 6. POLAR UVI images from 1233:13 UT to 1501:39 UT. This is a short portion of Fig. 5 HILDCAA interval. Substorms are identified using these images.

caused by southward IMF B_z fields within a magnetic cloud (note the recovery of the D_{ST} index in the figure). The magnetic cloud was part of an ICME. The 1 min AU, AL and AE indices were created at Nagoya Univ. STELab and the D_{ST} indices are 1 h values. The strict criterion for a HILDCAA event are not met for this event. Although the peak AE value was ~ 1580 nT ($-AL = 1480$ nT) at 0840 UT, the continuous intense AE interval lasted only from ~ 450 UT to ~ 1845 UT. We will consider this interval to be of the same type as a HILDCAA event for the purpose of this study.

An interval where reasonably good POLAR UVI viewing was present is given in Fig. 6, a smaller segment of the above interval. Imaging is taken at a ~ 3 min cadence and extends from 1233 UT to 1501 UT. A blowup of the geomagnetic indices for this ~ 3 h interval is given in Fig. 7. The substorms are indicated by shading.

From Fig. 6, a substorm expansion phase onset can be noted at ~ 1300 UT. There is a brightening from ~ 21 to ~ 24 LT and $\sim 65^\circ$ to $\sim 70^\circ$ magnetic latitude. This brightening is more apparent in the subsequent image at 1303 UT. The brightest auroras begin to fade by 1310 UT. During this interval, both AE and $-AL$ increase slightly (see Fig. 7). AE increased from ~ 300 to ~ 360 nT and $-AL$ from 100 to 300 nT.

At 1322 UT a second auroral expansion phase begins. Auroral brightening can be noted at ~ 21 LT and 70° magnetic latitude. This general region of the auroral zone brightens and expands by 1328 UT. Although the aurora has faded from its previous brightest levels by 1343 UT, the spatial coverage of the aurora is at a maximum at this time. The broad auroral expanse extends from ~ 19 to ~ 24 LT and at 22 LT, from $< 60^\circ$ to 75° magnetic latitude.

Fig. 7 is examined for these intervals. The AE and $-AL$ indices increases begin at ~ 1317 UT prior to the substorm

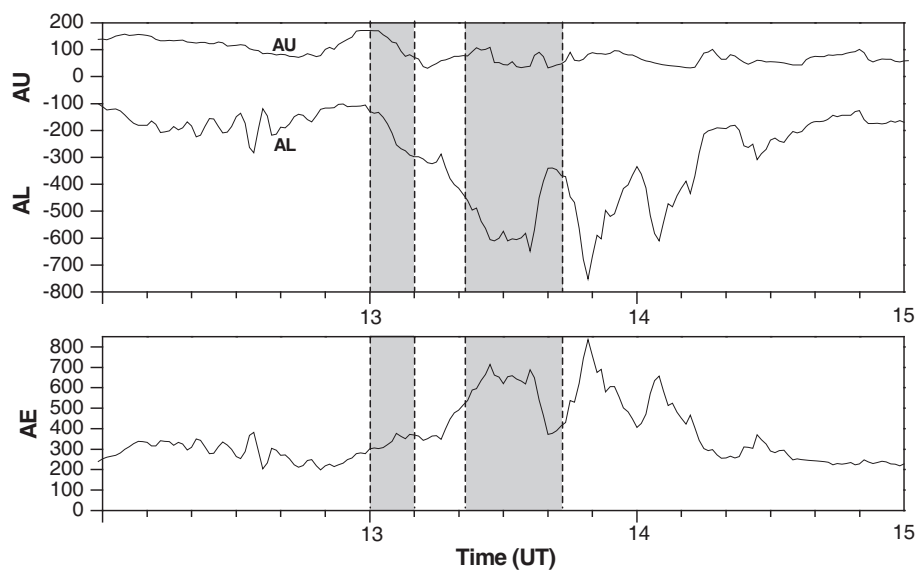


Fig. 7. A blowup of Fig. 5. Three clear AE and AL enhancements are detected. Substorms intervals are indicated by shading.

expansion phase onset. AE increases from ~ 350 nT and reaches a maximum of ~ 700 nT at ~ 1327 UT. The $-AL$ value increases from ~ 300 nT and increases to a maximum value of ~ 600 nT in the same time interval. Thus, there is generally good agreement between the AE and $-AL$ indices and the auroral expansion data.

The sharpest AE and $-AL$ increases occur from 1340 UT to 1349 UT. AE reaches a peak value of ~ 830 nT and $-AL \sim 750$ nT (both at 1349 UT). Examining the POLAR UVI images from Fig. 6, there is nothing particularly noteworthy. The extent of the nightside aurora remains broad and somewhat featureless. The only exception to this is the appearance of a higher latitude auroral band at $\sim 73^\circ$ magnetic latitude at 22 LT. The band has a width of $\sim 2^\circ$, and extends from 21 LT (72° magnetic latitude) to 2 LT at $\sim 67^\circ$ magnetic latitude.

The AE and $-AL$ indices rapidly decrease from ~ 1349 UT to ~ 1400 UT. By ~ 1400 UT, the index values are ~ 410 and ~ 340 nT, respectively. The nightside aurora dims from 1356 UT to 1402 UT. Beyond that time, the aurora is still present at an approximately constant level of intensity. More rapid dimming of the aurora occurs from 1420 UT to 1429 UT.

There is a subsequent AE/ $-AL$ increase from 1359 UT to 1405 UT. AE increases from ~ 400 to ~ 650 nT and $-AL$ from ~ 350 to ~ 605 nT. There is nothing of particular noteworthy in the imaging data. The aurora consists of broad moderately intense forms and the intensity generally decreases from 1359 UT to 1408 UT. The POLAR UVI images are restricted to local times less than ~ 02 UT and it is possible that morningside auroral activity was taking place. However, there is nothing in the nightside aurora that would strongly imply such a possibility.

3. Summary and discussion

The purpose of this paper was to examine the importance and interplanetary cause of HILDCAAs and to determine if HILDCAAs are a continuous series of substorms or not. For the imaging part of the analyses, due to the limited viewing of the POLAR UVI imager, we have selected intervals of continuous AE where the strict HILDCAA criteria were not totally met. Both intervals selected (one in 1997 and a second in 1998) did have continuous, elevated AE indices for lengthy periods of time and both intervals were outside the main phase of magnetic storms. Other 1998 HILDCAA intervals were also examined but are not discussed here.

The results of the analyses indicate that substorm expansion phases are present within HILDCAA events, but there was little or no relationship between substorms and AE ($-AL$) intensifications (the analyses of the other HILDCAA intervals yielded the same results). Some substorms occurred with little or no changes in AE and $-AL$. Other substorms occurred with dramatic changes in AE and $-AL$ (but not peak-to-peak correlated). At still other times, AE and $-AL$ had significant changes with little or no apparent auroral variations. In general, one must conclude that there is little or no correspondence between AE/ $-AL$ increases and substorm expansive phases and substorm expansive phases during HILDCAA and/or HILDCAA-like intervals.

4. Conclusions

HILDCAAs are caused by magnetic reconnection associated with the southward B_z components of interplanetary Alfvén waves present in high-speed streams. In some intervals in the declining phase of the solar cycle (1974), the

annual average of AE can be higher than that during solar maximum years. If one assumes that the AE index can be used as a proxy for the auroral energy deposition and Joule heating, then one can conclude that greater energy deposition into the ionosphere can and does occur outside of solar maximum.

Auroral expansion phases are present during HILDCAA events. However, there is a lack of a one-to-one correspondence between substorm expansion phases and AE/–AL enhancements. One likely explanation is that the southward component of the interplanetary magnetic field (of Alfvén waves) cause magnetic reconnection and drive enhanced westward auroral electrojets evidenced by the correlation between the IMF B_s and AE shown in Fig. 2 (see Sergeev et al., 1996; Tsurutani et al., 2003; Zhou et al., 2003, for other examples under different conditions). Substorm expansions, on the other hand, might be of a stochastic nature, perhaps driven by self-organized criticality (Tsurutani et al., 1990b; Freeman and Watkins, 2002, and references therein).

Although the relationship between HILDCAAs and substorms have been clarified, the relationship between D_{ST} decreases and AE (–AL) increases is not obvious. Soraas et al. (2003) have shown that the small D_{ST} decreases during HILDCAA events are due to particle injections into the outer regions ($L > 4$) of the magnetosphere. Thus the apparent “long decays” of D_{ST} after some storms is due to continuous sporadic injection of ring current particles. The Soraas et al. (2003) hypothesis is that plasma injection into the magnetosphere is due to magnetic reconnection between interplanetary fields and the magnetopause fields. Our results strongly support this idea. Convection of plasma in the outer regions of the magnetosphere/plasmasheet towards the Earth due to the dawn-to-dusk electric fields is indeed the most likely source of particle injection (see discussion in Gonzalez et al., 1994, for the role of interplanetary electric fields during magnetic storms and Tsurutani and Gonzalez, 1997). Additionally the role (major or minor) of substorms in particle injections during HILDCAA events needs to be established.

All of the ideas/hypotheses presented here are easily testable. We hope that readers/coauthors will take up some of the challenges in the near future.

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