Ann. Geophys., 27, 525–535, 2009
www.ann-geophys.net/27/525/2009/

Annales Geophysicae

Vertical evolution of auroral acceleration at substorm onset

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Received: 1 October 2008 – Revised: 17 December 2008 – Accepted: 29 December 2008 – Published: 2 February 2009

Abstract. This study describes the onset process of auroral substorms in connection with the vertical evolution of auroral particle acceleration, on the basis of auroral kilometric radiation (AKR) dynamics. We show that the auroral acceleration process at substorm onset basically consists of two stages: (1) appearance/intensification of a low-altitude acceleration region at 4000–5000 km accompanied by initial brightening and (2) breakout of high-altitude field-aligned acceleration above the pre-existing low-altitude acceleration region at 6000–12 000 km, which is followed by auroral breakup and poleward expansion. It is also revealed that this two-stage evolution of auroral acceleration corresponds to the two-step reinforcement of field-aligned current.

Keywords. Magnetospheric physics (Auroral phenomena; Magnetosphere-ionosphere interactions; Storms and substorms)

1 Introduction

It has been widely accepted that auroral breakup and the related sharp negative bay are caused by auroral electron beams and field-aligned current (FAC), respectively (e.g. Akasofu, 1968; McPherron et al., 1973). They are driven in the field-aligned acceleration region at substorm onset. Thus, a sudden build-up of the field-aligned acceleration is essential to the onset of the magnetospheric substorm. Although the latitudinal and longitudinal development of an auroral substorm has been investigated on the basis of observations from the ground and space (e.g. Elphinstone et al., 1996, and references therein), the dynamic behavior of auroral acceleration, especially its vertical evolution at substorm onset, is not well understood, except for statistical features of the field-aligned auroral acceleration region drawn from in-situ observations by rocket and satellite (e.g. Evans, 1974; Mozer et al., 1977; Ergun et al., 2002).

Remote observation of AKR is a useful tool for detecting the dynamics of the auroral acceleration region (Kaiser and Alexander, 1977; Morioka et al., 1981; Liou et al., 1999; Hanasz et al., 2001; Janhunen et al., 2004). Recently, Morioka et al. (2007, 2008) derived the features of the sudden build-up process of field-aligned acceleration at substorm onset from remote AKR observations. A sudden expansion of the AKR spectra, typically from 30 to 800 kHz at substorm onset, was defined as AKR breakup. This frequency range corresponds to the altitude range of the AKR source (roughly from 16 000 to 2000 km) because the AKR radiates at the local electron cyclotron frequency along auroral field lines. Furthermore, the range of the AKR source can be roughly regarded as equivalent to that of the acceleration region because AKR is the result of wave-particle interaction with electron beams in the acceleration region (e.g. Ergun et al., 1998; Pottelette et al., 2001).

The onset of the magnetospheric substorm was first defined by Akasofu (1964) as the sudden brightening of the auroral arc (T=0–5 min) followed by rapid poleward motion (T=5–10 min) on the basis of ground-based all-sky camera observations. Subsequently, the terms "substorm onset", which means the start of a magnetospheric substorm, and "breakup", which means the start of an auroral substorm in the ionosphere, have been commonly used in substorm studies. However, the definitions of these terms are

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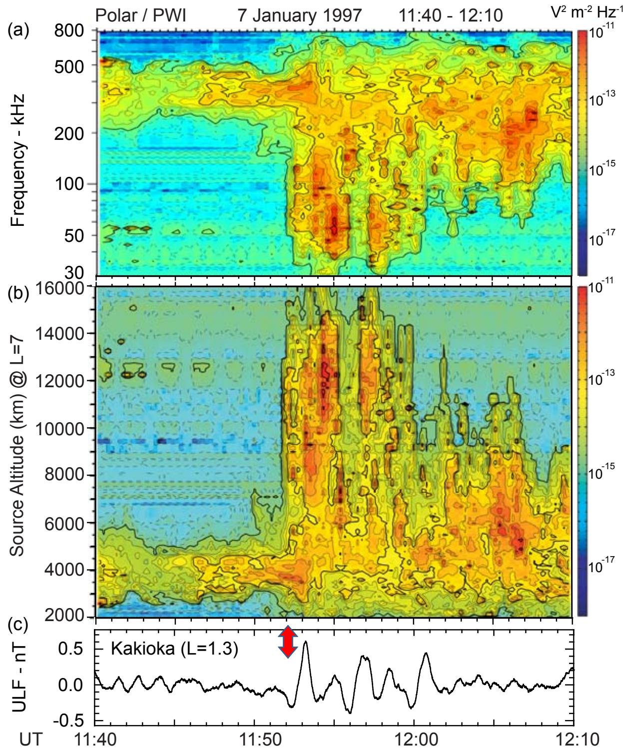

Fig. 1. AKR spectrogram and Pi2 pulsation on 7 January 1997. **(a)** $f-t$ (frequency-time) diagram of AKR from Polar/PWI. **(b)** $a-t$ (altitude-time) diagram of AKR; vertical axis indicates source altitude of AKR along L=7 field line. **(c)** Geomagnetic pulsation at low-latitude station, Kakioka (L=1.3); red arrow shows onset of Pi2 pulsation.

not always common and several terms have been used to depict auroral substorms (Rostoker et al., 1980), such as "initial brightening", "intensification", "brightening", "poleward expansion", "expansion onset", "expansive phase onset", and "full onset", partly because auroral substorms include several steps to complete the onset process and manifest various evolutions. Sometimes the term "initial brightening" is used as a synonym for "breakup" and/or "substorm onset". Voronkov et al. (2003) described three steps in auroral substorm development on the basis of a typical substorm event: intensification of 557.7-nm emission following cross-tail electric-field pulsation, breakup characterized by poleward expansion and Pi2 pulsation, and expansive phase onset followed by fast poleward expansion of energetic electron precipitation.

The steps in the evolution of auroral substorms could be significant manifestations of the magnetospheric substorm onset process that have not yet achieved a common understanding (e.g. Ohtani, 2004; Angelopoulos, 2008). The M-I coupling process in the course of substorm onset is an important element of this issue. The field-aligned acceleration in the M-I coupling region plays a key role in the dynamic connection of the near earth plasma sheet and the auroral onset site in the ionosphere. In this paper we describe the auroral substorm process in connection with the vertical evolution of the field-aligned acceleration by investigating the dynamic behavior of AKR sources at substorm onset. Four typical substorm events are analyzed in detail.

We used AKR observations by the Polar satellite. Polar Plasma Wave Instrument (PWI) observations (Gurnett et al., 1995) provide high-time resolution data for the electric field up to 800 kHz, which enabled analysis of the vertical structure of the M-I coupling region and its dynamics at substorm. Polar Ultraviolet Imager (UVI) data (Torr et al., 1995) were used to examine global auroral development during substorms. Geomagnetic pulsation data from auroral (from WDC, NIPR), sub-auroral (from SAMNET), and low-latitude (from Kakioka Observatory through WDC, Kyoto University) stations were used to identify substorm onset.

2 Observations

2.1 AKR breakup and substorm

Figure 1a shows a color-contoured spectrogram of AKR in the frequency range from 30 to 800 kHz for 30 min on 7 January 1997. Banded AKR in the 300 to 500 kHz appeared from the beginning of the frequency-time spectrogram ($f-t$ diagram), and the AKR suddenly expanded at ~11:52 UT. Since AKR is generated at the local electron cyclotron frequency along the auroral field lines, the AKR frequency can be converted into the source altitude along the field lines. Figure 1b shows the topside down spectrogram of panel (a) in which the vertical axis is a linear plot with respect to the AKR source altitude along the L=7 field line; that is, it is an altitude-time ($a-t$) diagram of the AKR source. Using this plot, we can discuss the AKR source dynamics along the magnetic field lines which corresponds to the temporal evolution of the field-aligned acceleration. A rather stable "low-altitude AKR" appeared from 3000 to 5000 km. Almost simultaneously with the low-latitude Pi2 pulsation onset at Kakioka (L=1.3, midnight (MLT)=15:04 UT) around 11:52 UT (Fig. 1c), a new AKR source appeared explosively at a higher altitude (7000–16 000 km). This new AKR source was not a simple extension of the pre-existing low-altitude AKR but an independent evolution at the higher altitude. We call it "high-altitude AKR", and the term "AKR breakup" is defined as the sudden appearance of a new AKR source above the pre-existing low-altitude AKR source. AKR breakup suggests the abrupt formation of a new high-altitude field-aligned acceleration region at substorm onset. It should be noted that AKR spectra provide no information on the horizontal distribution of AKR sources and related acceleration regions, although AKR radiates above the auroral oval.

The low-altitude AKR is emitted from the inverted-V type acceleration region, which is quasi-static and surrounds the auroral latitudes above the auroral oval (e.g. Frank and Ackerson, 1971), because the emission shows a close relationship with the oval activity (Morioka et al., 2007). On the other hand, the high-altitude AKR is emitted at the local onset site of the auroral substorm because the emission was simultaneously observed with the auroral expansion (Morioka et al., 2007, 2008).

Figure 2 illustrates the detailed relationship of AKR evolution and ground-based ULF pulsation. Panel (a) shows the $a-t$ diagram of AKR for 15 min on 16 April 1996. AKR breakup occurred around 23:13 UT (indicated by the vertical rectangle), with an explosive growth in intensity (up to 1000 times) within 30 s and an expansion to an altitude of 6000 to ~12 000 km. The moment of AKR breakup would be the instant when the local onset site in the auroral ionosphere is connected to the magnetosphere through a suddenly formed parallel acceleration region. For 2 to 3 min prior to the breakup, the low-altitude AKR showed gradual intensification from ~23:10 UT. Apparently, increasing low-altitude AKR is a necessary condition to ignite the high-altitude AKR.

The mid-latitude magnetogram at Kvistaberg (L=3.3, midnight (MLT)=21:50 UT) is shown in panel (b) of Fig. 2. Pi2 pulsation appeared simultaneously with the AKR breakup around 23:13 UT. Panel (c) shows the pulsation (*dH/dt*) data at auroral station, Tjornes (L=6.4). Around this time, Tjornes was at a premidnight location (midnight (MLT)=23:45 UT). The *dH/dt* signal began to negatively decrease (quasi-DC variation) almost simultaneously with the gradual intensification of the low-altitude AKR. This negative excursion of the derivative of the geomagnetic H-component (*d/dt* (*dH/dt*)$<$0) suggests an exponential increase in the westward electrojet current in the ionosphere, which was likely induced by the exponential increase in the upward FAC.

Figure 2d and e shows shorter period components (period of 2–10 and 10–20 s, respectively) of the Tjornes pulsation. The fluctuations gradually increased in amplitude (blue areas in panels (d) and (e)) starting almost simultaneously with both the start of negative excursion of *dH/dt* and the gradual intensification of the low-altitude AKR. A hodograph of the T=2–10 s component before 23:12:30 UT (not shown) indicated no polarization characteristics, so it can be concluded that these short period components were not hydromagnetic wave but were associated with the fluctuating component of the increasing FAC. It is noteworthy that the amplitude of this noise component increased dramatically immediately after the AKR breakup (beige area in panels d and e). This may be a manifestation of a current flowing rapidly into the ionosphere. This two-step increment of the FAC derived from the *dH/dt* data was confirmed from the variation in the geomagnetic H-component. The H-component at Tjornes showed an exponential decrease before the AKR breakup and a rapid fall after the AKR breakup, as shown in the bottom panel of Fig. 2.

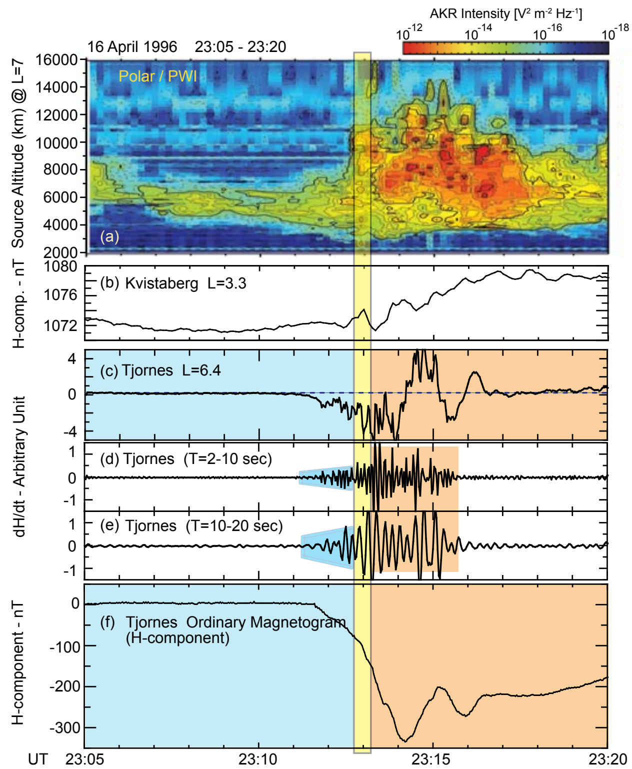

Fig. 2. Vertical evolution of AKR during substorm on 16 April 1996 and related geomagnetic variations. **(a)** $a-t$ diagram of AKR from Polar/PWI; AKR breakup (from 7000 to 12 000 km) occurred about 23:13 UT (vertical rectangle) above pre-existing low-altitude AKR (from 4000 to 6000 km). **(b)** H-component of geomagnetic field at mid-latitude station, Kvistaberg (L=3.3); Pi2 pulsation started almost simultaneously with AKR breakup. **(c)** *dH/dt* record at auroral station, Tjornes (L=6.4); high-latitude Pi2 pulsation started around 23:10 UT. **(d)** and **(e)** band-passed components of Tjornes pulsation; pass-bands were 2–10 and 10–20 s, respectively. **(f)** Ordinary magnetogram at Tjornes.

On the basis of these and many other observations, like those by Morioka et al. (2007, 2008), we present a schematic illustration of AKR source dynamics during a substorm in Fig. 3, together with the auroral oval activity and high-latitude Pi2 pulsations.

2.2 Vertical evolution of auroral acceleration and auroral substorm

The precursor phase 1–5 min prior to AKR breakup is characterized by the gradual appearance/intensification of low-altitude AKR, indicating the evolution of an inverted-V type acceleration region. AKR breakup is the manifestation of a sudden build-up of the field-aligned acceleration region above a pre-existing low-altitude acceleration region. Here, we investigate the relationship between the vertical evolution of the field-aligned acceleration and auroral substorm.

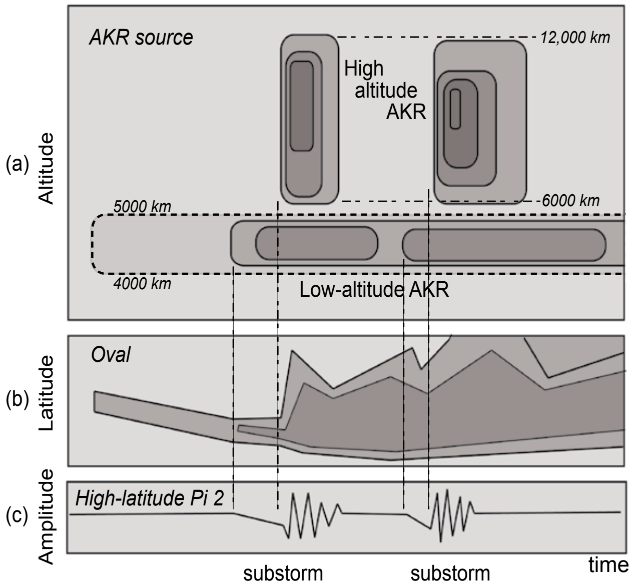

Fig. 3. Schematic illustration of substorm-time evolution of **(a)** AKR source, **(b)** auroral oval, and **(c)** high-latitude Pi2 pulsation.

Figure 4 shows an isolated substorm on 29 December 1996, which was initially reported by Liou et al. (2000). The top panel is a sequence of nightside (18:00–06:00 MLT) UV auroral images from Polar/UVI. The images were obtained by a combination of Lyman-Birge-Hopfield long (LBHL) and short (LBHS) filters in the wavelength range 140–180 nm. The narrow blue horizontal bar under each panel indicates the exposure time. The faint arc around 65–67° magnetic latitude in the premidnight sector (image (i)) developed into a "sudden brightening" (Liou et al., 2000) between images (ii) and (iii). The second panel shows the ULF data at Kakioka. Long period oscillation began at ∼16:38 UT and became strong after 16:41 UT. From these auroral and ULF sequences, Liou et al. (2000) defined the "commencement of auroral substorm" at 16:38:51 UT±41 s (horizontal green rectangle in panel b) and Pi2 onset at ∼16:41:34 UT (green arrow in panel b).

The evolution of the field-aligned acceleration for this substorm is shown by the $a-t$ diagram of AKR source in the bottom panel of Fig. 4. Low-altitude AKR (centered at about 3000 km) appeared at ∼16:41 UT (vertical blue rectangle in panel) and gradually enhanced the power. The start time of this low-altitude AKR is between that of the "sudden brightening" and "Pi2 onset" defined by Liou et al. (2000). In the course of the enhancement, the AKR breakup occurred at 16:44 UT ranging in altitude from 5000 to 9000 km, completing the explosive growth in power within 30 s (vertical beige rectangle).

Figure 4c and d shows the band-pass filtered components (T=30–40 and 50–60 s, respectively) of pulsation at Kakioka. The longer period (50–60 s) component showed two significant rises around 16:40 UT (roughly concurrent with the appearance of low-altitude AKR) and around 16:44 UT (almost simultaneous with AKR breakup). The shorter period (30–40 s) component, on the other hand, showed a distinct enhancement around 16:44 UT. These indicate that the original wave form of the irregular pulsation (panel b) was a superposition of a new Pi2 pulsation at 16:44 UT on the pre-existing one that started around 16:40 UT, and that the first and second Pi2 pulsations are closely related with the appearance of low-altitude AKR and AKR breakup, respectively.

It should be noted, looking again at the top panel of Fig. 4, that the AKR breakup was almost simultaneous with the distinct auroral intensification that accompanied the poleward expansion (image (vi) in the panel). This suggests that the strong intensification and poleward expansion of the onset arc is not a simple activation of the previous auroral activity but is associated with a catastrophic change (sudden build-up of the high-altitude acceleration region) in the M-I coupling region. The time sequence for the 29 December substorm is summarized later (Fig. 7a).

Another example of substorm onset on 3 April 1996 is shown in Fig. 5. This substorm event has also already been described by Liou et al. (1999). They used a method to objectively evaluate the development of auroral luminosity and determined a "sudden auroral brightening" at 15:31:20 UT±18 s (indicated by the green rectangle in panel b) by using the start of the increase in the area-integrated auroral luminosity. This brightening can also be recognized from raw UV image (image (ii)) in panel (a). Following the gradual and continuous evolution of this bright region in intensity and in longitude (images (iii), (iv), and (v)), a violent intensification of auroral brightness with poleward expansion occurred in the pre-midnight sector around 15:35:48 UT (image (vi)). Subsequently, this auroral activity developed into a global substorm expanding to both the poleward and post-midnight regions (image (viii) and thereafter).

Figure 5b shows low-latitude Pi2 pulsation at Kakioka. The onset time, determined by Liou et al. (1999), was 15:32:07 UT (indicated by the green arrow). Figure 5c and d shows the band-passed components; the pass-bands were T=20–30 and 40–50 s, respectively. The band-passed components showed that they rose twice before 15:37 UT, that is, the Pi2 event at Kakioka was a superposition of two onsets of irregular pulsations that began around 15:32 UT (first Pi2) and 15:35 UT (second Pi2).

Figure 5e is the $a-t$ diagram of AKR source for the period of interest. Low-altitude AKR appeared from 3000 to 4000 km at around 15:32 UT (vertical blue rectangle) and gradually intensified. The start time of the low-altitude AKR was roughly concurrent with both the "sudden auroral brightening" and the "onset of the first Pi2" defined by Liou et al. (1999). Around 15:35:30 UT, the AKR broke up with explosive growth in the altitude range from 4000 to 8000 km (vertical beige rectangle). Note that this AKR breakup,

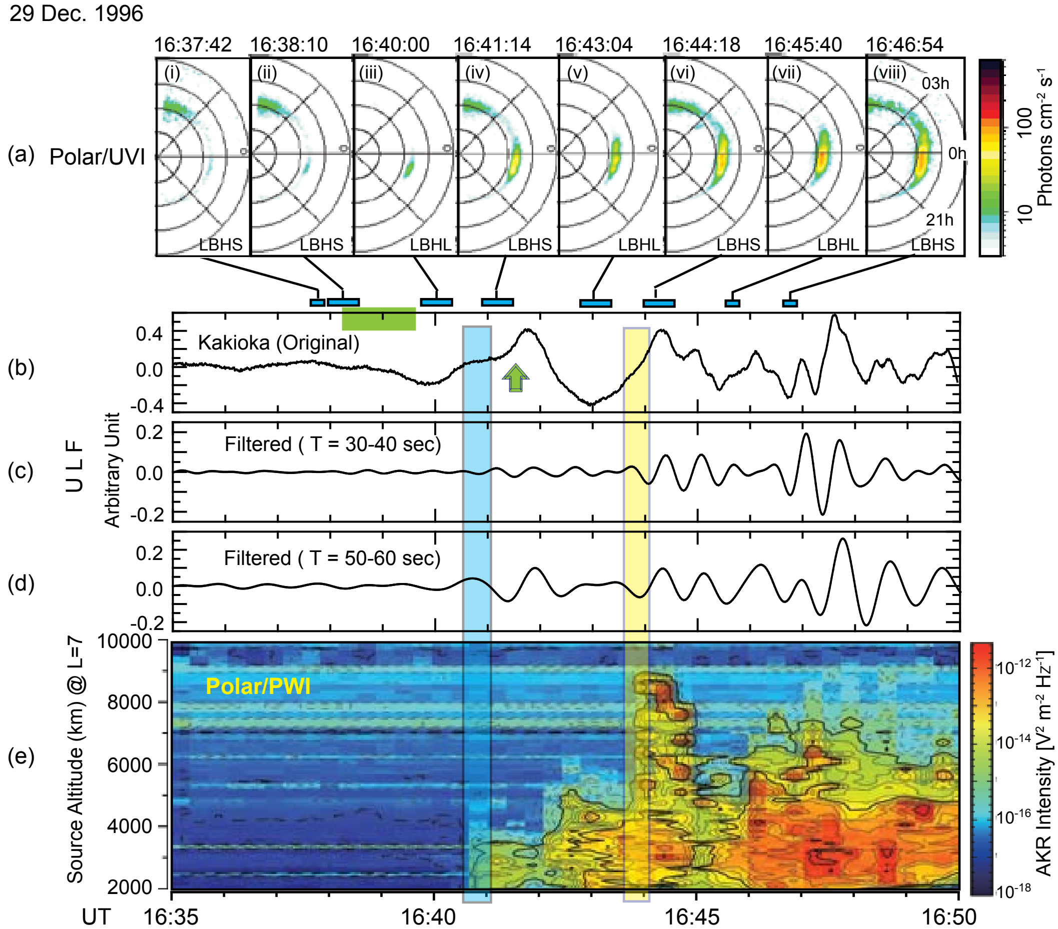

Fig. 4. Relationship between global auroral activity, AKR development, and low-latitude Pi2 pulsation on 29 December 1996. **(a)** Polar/UVI images in dark hemisphere showing initial brightening around 16:38 (image (ii)) and breakup/poleward-expansion around 16:44 UT (image (vi)).Small horizontal rectangles under images indicate exposure times. Green rectangle indicates "sudden brightening" defined by Liou et al. (2000). **(b)** *dH/dt* record from Kakioka; green arrow shows onset of Pi2 pulsation defined by Liou et al. (2000). **(c)** and **(d)** Filtered components (T=30–40 and 50–60 s) of *dH/dt* data at Kakioka. **(e)** $a-t$ diagram of AKR from Polar/PWI. Low-altitude AKR appeared around 16:41 UT (blue vertical rectangle), and high-altitude AKR appeared around 16:44 UT (beige vertical rectangle).

which means the sudden connection of a certain region in the plasma sheet to the local onset site in the ionosphere through the field-aligned acceleration region, was almost simultaneous with the auroral intensification/poleward expansion (image (vi) in panel a) and the second Pi2 onset at Kakioka. After 15:37 UT, there happened two AKR breakup accompanying two Pi2 pulsations, reflecting the multiple onset substorm. The sequence of the phenomena before 15:38 is summarized in Fig. 7b.

3 Discussion

On the basis of the dynamic behavior of AKR, the vertical evolution of the auroral acceleration region was investigated in connection with the global development of auroral substorms. Four typical substorm events were analyzed in detail. The sudden build-up of the high-altitude acceleration at substorm onset was derived from the AKR breakup. The AKR source region at the breakup expanded in the altitude range from 6000 to 12 000 km on average and showed explosive growth of power up to 1000 times within 30 s. The breakout of the high-altitude acceleration was always accompanied by low-latitude Pi2 pulsation. The low-altitude acceleration region, which appeared/intensified 1–5 min prior to the breakout of the high-altitude acceleration, was identified from the high-frequency AKR band (250–350 kHz), for which the altitude ranged from 4000 to 5000 km on average. This acceleration region would correspond to the inverted-V acceleration region located along the auroral oval (e.g. Lin and Hoffman, 1979) and is formed through the interaction between the magnetospheric and ionospheric plasmas (Knight, 1973; Chiu and Schultz, 1978).

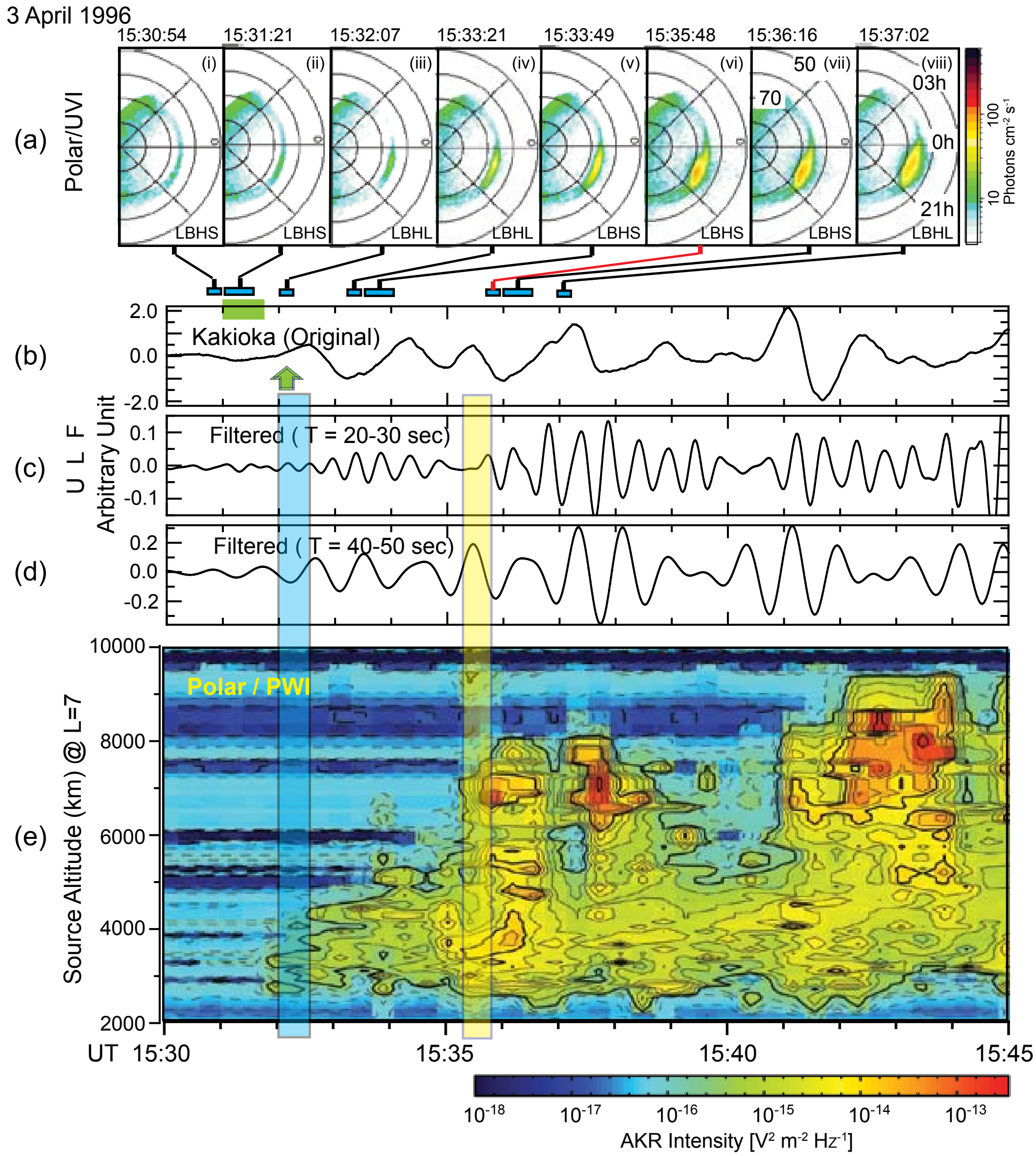

Fig. 5. Relationship between global auroral activity, AKR development, and low-latitude Pi2 pulsation on 3 April 1996. **(a)** Polar/UVI images in dark hemisphere showing initial brightening around 15:31 (image (ii)) and breakup/poleward-expansion around 15:35 UT (image (vi)). Small horizontal rectangles under images indicate exposure times. Green rectangle indicates "sudden brightening" defined by Liou et al. (1999). **(b)** *dH/dt* record from Kakioka; green arrow shows onset time of Pi2 pulsation defined by Liou et al. (1999). **(c)** and **(d)** Filtered components (T=20–30 and 40–50 s) of *dH/dt* data at Kakioka. **(e)** $a-t$ diagram of AKR from Polar/PWI. Low-altitude AKR appeared around 15:32 UT (blue vertical rectangle), and high-altitude AKR appeared around 15:35 UT (beige vertical rectangle).

The low-altitude AKR described in this paper may be explained by either of two possible categories of electron acceleration. The first is the large-scale quasi-static field-aligned electric field that has been discussed as a self-consistently formed electrostatic potential structure due to the anisotropic magnetospheric plasma distribution, such as quasi-static double layers (e.g. Block, 1972; Ergun et al., 2004), electrostatic shocks (e.g. Swift, 1975), and the magnetic mirror process (e.g. Chiu and Schulz, 1978). The other category is the Alfvénic acceleration in which electrons are accelerated by Alfvénic perturbations though the ionospheric resonator (e.g. Lysak and Song, 2003; Ergun et al., 2006; Su et al., 2008). Short-burst AKR and Jovian S burst are explained though this process (Ergun et al., 2006; Su et al., 2008). Which acceleration is essential or more effective at substorm onset is still unclear at this time.

The evolution of the high-altitude acceleration is independent of the low-altitude acceleration because the high-altitude AKR spectra show a separate development from that of the pre-existing low-altitude AKR. It should be, however, noted that the high-altitude AKR is ignited in the course of the gradual intensification of the low-altitude AKR as shown in Fig. 6. The figure shows power evolutions of low- and high-altitude AKR for the four substorms represented in this study. The upper and lower traces of each panel show the time-profile of the height-integrated AKR power for the high-altitude and low-altitude AKR, respectively. The vertical arrows indicate AKR breakup. Note that AKR breakups were ignited when the low-altitude AKRs were increasing and almost reaching something like their saturation level. From these features, it is suggested that the growth of the low-altitude acceleration is a necessary condition for the breakout of the high-altitude acceleration. This also leads to an inference that the increasing FAC along the inverted-V potential (low-altitude acceleration region) induced the current driven instability (Kindel and Kennel, 1971) in the local M-I coupling region which would develop into the high-altitude acceleration region. Another possible high-altitude acceleration process may be the Alfvénic one, which accelerates superthermal electrons at substorm, as observed by FAST and IMAGE satellites (Mende et al., 2003a, b).

The FAC evolution around onset was derived from the *dH/dt* and H-components of the geomagnetic field in the auroral region. It showed a two-step increment corresponding to the evolution of the field-aligned acceleration. The first step, which was characterized by an exponential increase in westward electrojet current, was almost concurrent with the appearance/intensification of the low-altitude acceleration and continued until the breakout of the high-altitude acceleration. The increasing FAC carried short period *dH/dt* signals, which are attributed to the fluctuation component of the increasing FAC. The second step, the start of which was characterized by a steep fall in the magnetic H-component starting with large amplitude *dH/dt* fluctuations, was accompanied by the sudden build-up of the high-altitude acceleration. This sudden change in FAC suggests a rapid current flow into the ionosphere that diverged from the tail-current disruption region in the near earth plasma sheet (e.g. Lui, 1996).

Comparison of UV aurora images with AKR development revealed an important connection between the space-time development of the auroral substorm and the vertical evolution of the auroral acceleration during the substorm. Figure 7 summarizes the time sequence of the onset processes for the substorm events depicted in Figs. 4 and 5. The horizontal length of each arrow indicates the ambiguous time span to determine the start time of each phenomenon. The "sudden auroral brightening", defined from the UV images, is roughly concurrent with the appearance/intensification of the low-altitude accelerations (within 1–2 min). This means that so-called "sudden auroral brightening" is not the result of abruptly formed auroral acceleration but is enhancement of the pre-existing inverted-V type acceleration. This is consistent with a previous study that showed that low-altitude AKR radiates from the activated auroral oval before AKR breakup (Morioka et al., 2007). The classic auroral morphology of Akasofu (1964) stated that the first indication of a substorm expansive phase is "a sudden brightening (within a few minutes) of one of the quiet arcs a few thousand kilometers in length approximately centered at the midnight meridian". The activation of a quiet arc with a longitudinal length of a few thousand kilometers is consistent

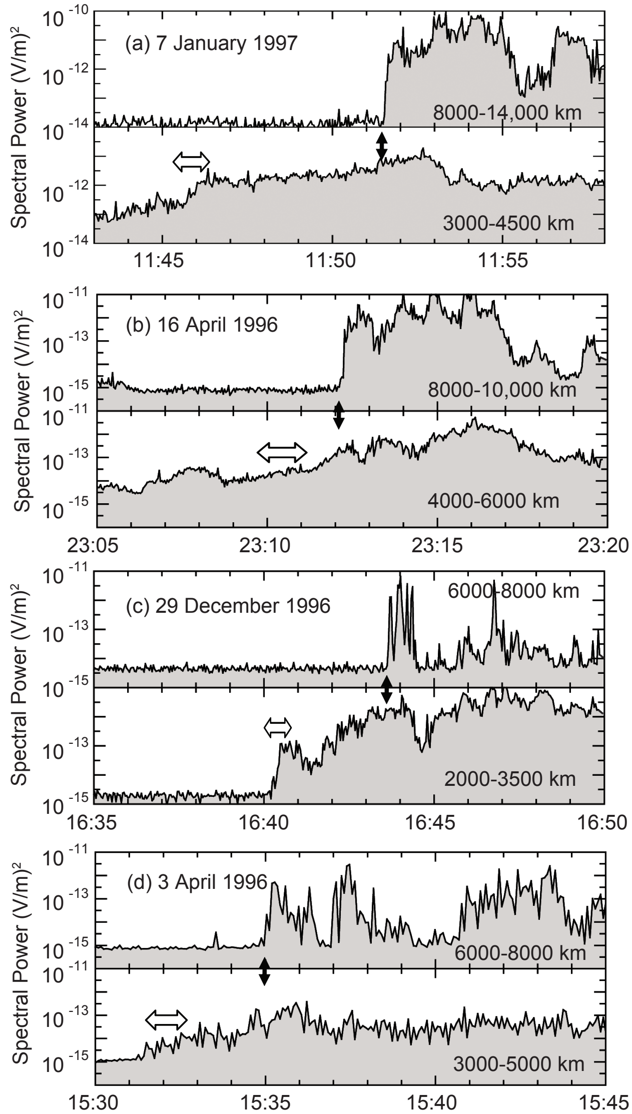

Fig. 6. Height-integrated power profile of AKR for the four substorms represented in Figs. 1, 2, 4, and 5. The upper and lower traces of each panel indicate power profile of high-altitude and low-altitude AKR, respectively. Altitude range for height-integration is shown in each panel. Horizontal and vertical arrows in each panel indicate rise of low-altitude AKR and onset of high-altitude AKR, respectively.

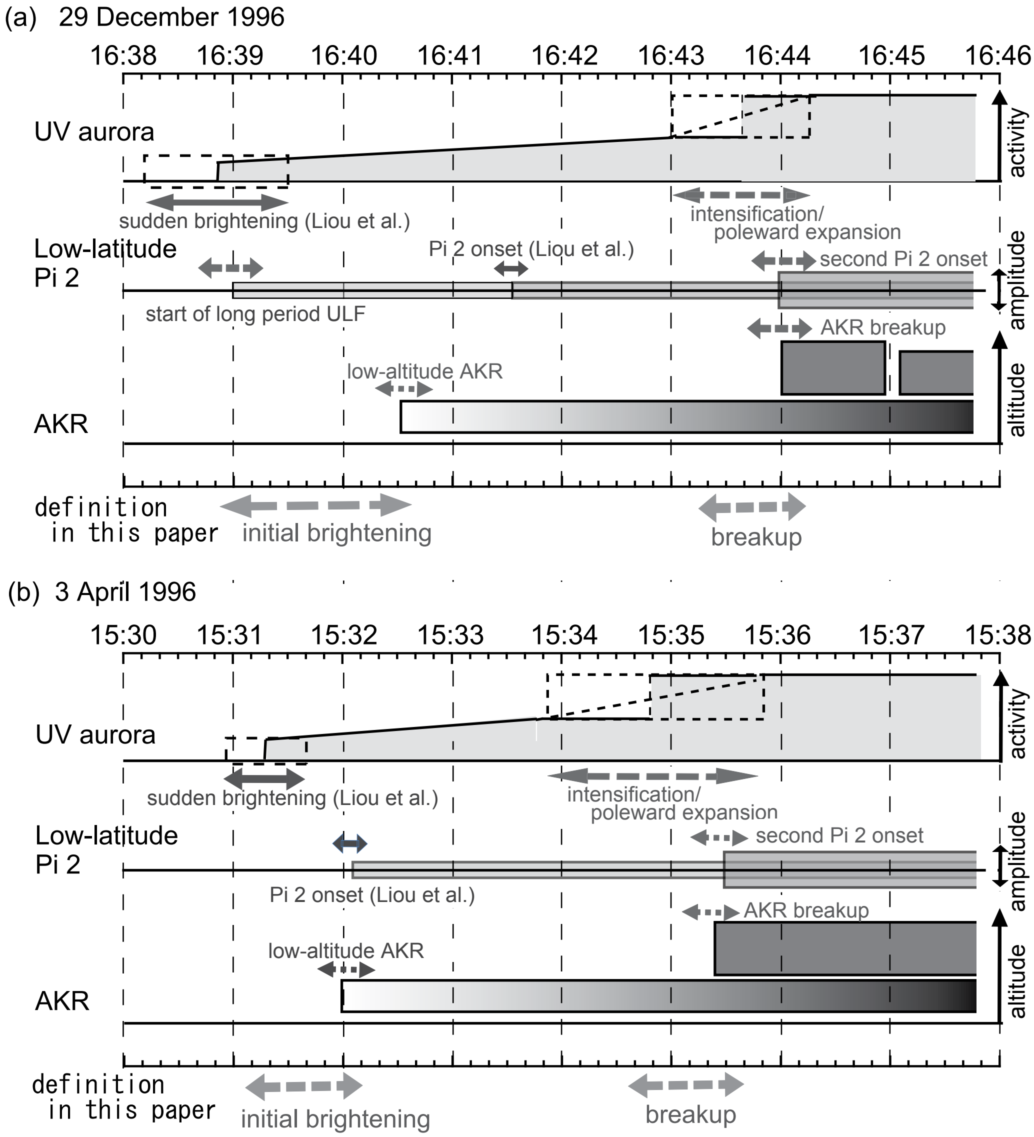

Fig. 7. Schematic illustrations of time sequence for **(a)** substorm on 29 December 1996 (see Fig. 4) and **(b)** substorm on 3 April 1996 (see Fig. 5). Vertical axes for UV aurora, Pi2, and AKR in each panel correspond to activity, amplitude, and altitude, respectively. Horizontal arrows indicate time tolerance for determining start time of each substorm step.

with the appearance/intensification of the pre-existing low-altitude acceleration surrounding the nightside oval (Morioka et al., 2007).

By "sudden", we mean a time scale of "within 30 s", considering the growth time of AKR breakup (less than 30 s, see vertical arrows in Fig. 6) in this paper. In this sense, the start of the so-called "sudden auroral brightening" and "appearance/intensification of low-altitude acceleration" is not always "sudden". The "sudden auroral brightening" is sometimes rather gradual, as seen in Fig. 4a and Fig. 5a. The "appearance/intensification of low-altitude acceleration" shows gradual rise as shown in Fig. 6 in which horizontal arrows indicate the start of low-altitude AKR intensification. We thus propose using the term "initial brightening" rather than "sudden brightening" to describe the start of an isolated auroral substorm (as illustrated by the bottom left arrow in each panel of Fig. 7). The start time of these phenomena is the time when they exceed the instrument threshold. Given these considerations, a time lag of 1–2 min between the initial brightening of the aurora and the start of the low-altitude AKR, as shown in Fig. 7, is not essential for understanding substorm evolution but may be an apparent time delay (Kepko and McPherron, 2001).

The strong auroral intensification accompanying the poleward expansion after the initial brightening is directly related to the breakout of the high-altitude acceleration (AKR breakup), as illustrated in Fig. 7. Although there remains an ambiguity of 1–2 min related to the time difference between the intensification and poleward expansion due to the observational sequence of UVI, it can be strongly suggested that the suddenly built high-altitude acceleration region expands immediately poleward. This is consistent with that the poleward edge of the auroral bulge is associated with intense electron precipitation and upward FAC, accompanied with field-aligned acceleration region (Fujii et al., 1994). The epoch of strong auroral intensification and poleward expansion is consistent with the "breakup characterized by poleward expansion and Pi2 pulsation" defined by Voronkov et al. (2003). The term "breakup" is appropriate for describing this phase of an auroral substorm (as illustrated by the bottom right arrow in each panel of Fig. 7).

It is interesting to note that the precursor-like phase before auroral breakup (between initial brightening and breakup) may correspond to pseudo breakup. That is, pseudo breakup may be the case when enhanced low-altitude AKR (initial brightening) is not followed by AKR breakup (auroral breakup and poleward expansion). If that is the case, the buildup of high-altitude acceleration divides substorms between substorm onset and pseudo breakup. The confirmation of this implication is future work.

The association of AKR breakup with auroral breakup and poleward expansion indicates that the sudden evolution of the high-altitude field-aligned acceleration abruptly connects the local onset site in the ionosphere with a certain area in the plasma sheet, and consequently suggests that the local M-I coupling region plays an essential role in igniting the auroral breakup. This suggestion is very interesting in connection with the indication by Lyons et al. (2002) based on their detailed study of the substorm breakup arc that "the process that initiates the onset of substorm does not require the occurrence of plasma sheet changes, significant enough to affect magnetosphere-ionosphere electrodynamics".

The low-latitude pulsation sometimes responds twice to a substorm. The first time is around the initial brightening and/or the start of the low-altitude acceleration intensification (Fig. 7a and b). This pulsation is not always observed or is very weak at low latitudes as seen in Fig. 1, where a typical Pi2 pulsation is accompanied by only the breakup of the high-altitude AKR (Morioka et al., 2008). The reason may relate to the nature of the initial brightening, which sometimes shows a gradual evolution, as described above. The second response is almost concurrent with the breakup accompanied by poleward expansion and is common in a substorm. Thus, the low-latitude Pi2 pulsation is generally excited at two important phases of an auroral substorm: "initial brightening" and "breakup". The differences in the origin and driving force between these Pi2 pulsations are still unclear.

There has been a long discussion about what process is essential for triggering a substorm in connection with the plasma dynamics around the plasma sheet inner boundary. The in-situ observations around the inner plasma sheet have proposed substorm-related plasma dynamics, such as high speed earthward plasma flow and its braking (e.g. Shiokawa et al., 1998), resultant inertia current (e.g. Haerendel, 1992), explosive growth phase (Ohtani et al., 2000), tail current disruption and dipolarization (e.g. Lui, 1992), buildup of substorm current system and substorm current wedge (e.g. Akasofu, 2003; McPherron et al., 1973), and Pi2 pulsation excitation (e.g. Kepko et al., 2004). Our investigation of the vertical evolution of the field-aligned acceleration and related FAC at substorm onset would provide new insights into the substorm onset process and contribute to the study of the causality between the plasma dynamics in the plasma sheet and auroral substorms through the M-I coupling process.

4 Conclusion

The vertical evolution of the auroral acceleration region was investigated in connection with the global development of auroral substorms. The investigation showed that the auroral acceleration process at substorm onset basically consists of two steps. The first step is the appearance/intensification of the low-altitude acceleration region at an altitude of 4000–5000 km, which induces the initial brightening accompanying the exponential increase in the upward FAC 1–5 min before the formation of a high-altitude acceleration region. The second step is the breakout of the high-altitude field-aligned acceleration (at an altitude of 6000–12 000 km) above the pre-existing low-altitude acceleration, which results in violent auroral breakup and poleward expansion. The strong FAC reinforcement with large amplitude fluctuation in the second stage suggests a rapid current flow into the ionosphere that diverted from the tail current disruption region in the near earth plasma sheet.

Acknowledgements. We are grateful to K. Shiokawa, A. Ieda, Y. Miyashita, and A. Kadokura for their useful comments and discussions. We also thank the Polar/PWI team (Principal Investigator is D. Gurnett). The 1-s resolution geomagnetic data were gathered by the Kakioka Magnetic Observatory, Japan Meteorological Agency, and provided through the WDC-2 for Geomagnetism at Kyoto University, Japan. The geomagnetic data from the Syowa-Tjornes conjugate-pair stations were kindly provided by the Auroral Data Center at the National Institute of Polar Research, Japan. We thank the SAMNET team for the magnetometer data. SAMNET is operated by Lancaster University and is funded by STFC.

Topical Editor R. Nakamura thanks L. Anfersson, R. J. Strangeway, and another anonymous referee for their help in evaluating this paper.

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