Auroral kilometric radiation at substorm onset

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Abstract. The temporal relationship of substorm signatures that occur in different regions of space is an important part of substorm research. In the present study we investigate the relative timing between sharp enhancement of auroral kilometric radiation (AKR) and auroral breakups. It is found, on the basis of 136 isolated substorm events identified with global auroral images from the Polar ultraviolet imager (UVI), that (1) 70% (83%) of the time AKR enhancements were detected within ±1 (±2) min of the auroral breakups; (2) AKR onset tends to occur, on an average, slightly later (0.36 min) than the corresponding auroral breakup; and (3) similar to previous study results, substorm-associated AKR has a forbidden area at Polar altitude in the noon sector. These results suggest that when the satellite is suitably located, the enhancement of AKR is a good substorm onset indicator and it can be used to time substorm onsets adequately within the ~1 min of uncertainties from the UVI observations, especially if confirmed by other substorm onset identifiers. The average frequency for the enhancement of AKR at substorm onset is found to be ~300 kHz, corresponding to an upper limit of the AKR source altitude of ~4700 km. The entire AKR frequency band expands to ~64–650 kHz within a few minutes after onset, corresponding to a wider source altitude of ~2100–12,000 km, a typical zone for auroral electron acceleration. We suggest that the fast expansion of the AKR source region along the local magnetic field lines, equivalent to the expansion of the auroral acceleration region, should be considered as one of the fundamental signatures in the substorm expansion phase.

1. Introduction

Auroral kilometric radiation (AKR) is bursty radio waves of the highest frequency (~30–800 kHz) generated by auroral zone plasma. This radio emission has a source altitude of ~1–3 RE [Gurnett, 1974; Kurth et al., 1975; Alexander and Kaiser, 1976; Gallagher and Gurnett, 1979], near the acceleration altitudes in the premidnight sector from 2000 to 2400 magnetic local time (MLT) [Gurnett, 1974; Kurth et al., 1975; Green et al., 1977; Gallagher and Gurnett, 1979; Green and Gallagher, 1985], and is related to discrete auroral arcs [Gurnett and Frank, 1973; Green et al., 1979; Benson and Calvert, 1979; Benson and Akasofu, 1984; Huff et al., 1988].

Intense AKR is found to be correlated well both in occurrence and in intensity with magnetospheric activities [Benediktov et al., 1968; Dunckel et al., 1970; Gurnett, 1974; Kaiser and Alexander, 1977] and can be a very reliable indicator of auroral disturbances [Voos et al., 1977; Kaiser and Alexander, 1977]. Recently, Murata et al. [1997] developed an AKR index based on the integrated plasma wave intensity over a band-
width of 50-800 kHz from the Geotail plasma wave observations. More recently, Kurth and Garnett [1998] have also developed a similar index using the integrated power flux in the same frequency range as observed by the Polar plasma wave instrument. These studies have shown a new potentially promising index for probing the state of the magnetosphere and ionosphere. There are other advantages of using AKR as a tool for substorm onset and intensification diagnostics. First, the angular distribution of AKR is usually large, depending on the wave frequencies [Green et al., 1977; Green and Gallagher, 1985], enough to be easily observed by a high-altitude spacecraft. Second, within the emission cone the intensity of AKR is uniform [Green and Gallagher, 1985]. Third, the temporal resolution of electric field instruments is usually much better than 1 min.

While the use of AKR onset or intensification to time substorm onset seems to be natural [e.g., Slavin et al., 1993; Murata et al., 1995], there is no statistical evidence indicating the accuracy of AKR onset as an indicator of substorm onset. In a recent paper we presented a clear example of simultaneous observation of AKR onset and auroral breakup as well as an example of inconsistency between the two types of onset signatures when the satellite was located at local noon [Liou et al., 1999]. For that particular event on May 3, 1997, the Polar satellite was located at 7.1 R_E, geocentric coordinates, and at 1143 MLT and 69.3° magnetic latitude (MLAT), and should be located well within the AKR emission cone [Green et al., 1977; Green and Gallagher, 1985]. Indeed, a continuous band (~100-400 kHz) of AKR was observed, but there is no clear evidence of wave intensification near the onset time [see Liou et al., 1999, Plate 4]. This puts the reliability of AKR intensification as a substorm onset indicator in question. As we all know, substorm-related studies that use different indicators for substorm onset can often lead to confusion because most of the major substorm onset indicators do not occur simultaneously [Liou et al., 1999]. Therefore a good knowledge of the relative timing of different substorm signatures is the key for constructing a coherent global picture of the substorm process that leads to substorm onset. In this study we will investigate in detail the timing of AKR onset in relation to substorm onset as determined by auroral breakups.

We will also investigate typical AKR frequencies at and after auroral breakup. This information is important because the frequency range of AKR can be used to infer the source altitude of the parallel potential drops, and the AKR onset frequency can be used to determine where the auroral particle acceleration is first initiated.

There have been only a few attempts to correlate AKR fluctuations with auroral intensities. On the basis of a case study with observations made from the Polar spacecraft, Imhof et al. [1999] reported a median correlation (r = 0.51) between integrated (30-800 kHz) AKR electric field intensity and integrated X-ray (2-12 keV) flux over a 6-hour local time range in the premidnight sector. Later, with 13 more events from the same observations they concluded that correlations of AKR wave fluctuations with X-ray flux emitted from 1800 to 0200 MLT varied from poor (r = 0.29) to good (r = 0.82) but the temporal correlation of sharp increases between the two signals was uncertain because of the low X-ray counting rate [Imhof et al., 2000]. These results should not be surprising as the source of the X-rays comes mainly from the high-energy (above a few keV) part of the precipitating electron energy spectrum and from central plasma sheet electrons that produce diffusive aurora particularly in the postmidnight sector where X-ray auroras maximize. In the present study, we will focus on the relative timing between auroral breakups and the enhancements of AKR. This is achievable because both breakup arcs and AKR are associated with inverted-V auroral acceleration events [e.g., Garnett, 1974].

For the purpose of this study a reliable timing of substorm onset is required. To achieve this goal, satellite global auroral images will be used. Although other substorm onset indicators such as high-latitude geomagnetic bays, low-latitude Pi2 pulsations, and dispersion-less energetic particle injections at geosynchronous altitude may be used for this type of study, they are typically delayed with respect to the auroral breakup [Liou et al., 1998, 1999, 2000]. These pilot study results have strongly suggested that the auroral breakup can be reliably used as a common time frame for magnetospheric substorms.

2. Observations

In this study we will use AKR data acquired from the International Solar Terrestrial Physics (ISTP) Polar plasma wave investigation (PWI) [Gurnett et al., 1995] and auroral images taken by the Polar ultraviolet imager (UVI) [Torr et al., 1995]. While other AKR data can also be used for this kind of study, it is more likely to have matching data periods from a single satellite than from two different satellite observations. In general, UVI starts taking images at an altitude of ~5 R_E. At this altitude the Polar satellite is most likely located in the AKR emission cone.
Plate 1. (a) A sequence of nightside auroral images in the long (LBHL) and short Lyman-Birge-Hopfield (LBHS) bands acquired from the Polar ultraviolet imager on December 29, 1996. The times shown are the center times of each snapshot accumulated in 36 s. The latitude (10° increments) and magnetic local time (2-hour increments; dusk at the bottom and midnight to the right of each frame) are in AAGCM coordinates. (b) The time spectrogram of the plasma wave electric field acquired from the Polar Plasma Wave Instrument (PWI) Sweep Frequency Receiver (SFR) for 1600 UT to 1700 UT on the same day.
Plate 1 shows a sequence of UVI auroral images for a moderate, isolated substorm interval from 1637:42 UT to 1646:07 UT on December 29, 1996. Contours of magnetic latitudes (MLAT) of 60°, 70°, and 80° and magnetic local time (MLT) with a 2-hour increment in Altitude Adjusted Corrected Geomagnetic Coordinates (AACGM) [Baker and Wing, 1989] are overlaid. Note that only the nighttime part of the northern oval is shown with dusk at the bottom and midnight to the right of each frame. The time tags indicate the centers of the integration periods of ~37 s. For this event an auroral substorm commenced at 2300 MLT and 68° MLAT at 1638:51 UT ± 41 s as indicated by a sudden brightening of aurora in the midnight sector in the third frame of Plate 1a, which is followed by a continuous expansion of an auroral bulge that reached over 72° MLAT and spanned ~3 hours MLT at ~1657 UT (not shown). Ground-based magnetic field measurements at Kakioka (located near midnight) also showed a positive bay commencing at ~1643 UT (the minimum in the H component of the magnetic field). A Pi2 onset was identified at ~1641:34 UT (not shown). In accord with the UVI observations the Polar PWI plasma wave data as shown in Plate 1b do not see any wave activity in the AKR band before the substorm onset, indicating a quiet magnetosphere/ionsphere. A weak AKR signal of ~1 x 10^{-14} V^2 m^{-2} Hz^{-1} in the 400-800 kHz range was observed at ~1640:25 UT followed by an increase of both wave intensity (up to ~1 x 10^{-12} V^2 m^{-2} Hz^{-1}) and bandwidth (a decrease of the lower limit from 400 to 100 kHz).

Although the Polar satellite was located at the local evening sector ~2000 MLT, a favored local time for observing AKR [Green and Gallagher, 1985], the onset of AKR occurred ~1.5 min later than the auroral breakup. Since the latitude of the Polar satellite is a bit lower (~43° MLAT), it is not whether this delay is typical or not because we have shown an example of a simultaneous onset event in a previous paper [Liou et al., 1999].

To answer this question, we have conducted an intensive search for AKR onset events based on a list of 136 isolated substorms, which is a shorter version of the entire list of ~650 auroral breakup [Liou et al., in press, 2000], for the period of April 1996 to May 1997. The timing of AKR enhancements corresponding to the 136 auroral breakups is determined and compared to obtain a statistical mean of the relative onset time between the AKR and the auroral breakup.

Figure 1 shows the histogram of the time difference (positive for a lag AKR and negative for a lead AKR relative to auroral breakup) between the AKR enhancements and the auroral breakups. A near-symmetric distribution is obtained with a peak near the zero time difference. It is also shown that 36% (49 events) of the AKR enhancements occurred simultaneously (within the ~1-min uncertainty of the UVI auroral images) with the auroral breakup and 70% (95 events) of the AKR enhancements took place ±1 min from the auroral breakup. There are slightly more lag events than lead events; the average time difference is 0.36 min with a standard deviation of 1.07 min. Interestingly, ~7% (10
events) of the surveyed events do not show corresponding AKR enhancement.

Figure 1b shows results from 61 isolated AKR onset events similar to those shown in Plate 1. Interestingly, the shape of the distribution is almost identical. It is found that 39% (24 events) of the events were simultaneous and 79% (48 events) occurred within 1 min of the auroral breakup. Similarly, there are more lag events than lead events; the average lag time is 0.36 min with a standard deviation of 0.9 min. There are 3 events (5%), 2 on the dayside and 1 in the premidnight sector but at very low latitude, corresponding to a void of emission in the AKR band.

We have also studied the AKR wavelength band at and after substorm onsets, and results are given in Figure 2. The center frequency of the substorm-associated AKR, \( f_c \), at onset ranges from \( \sim 100 \) to \( \sim 600 \) kHz (see Figure 2a). The majority of the events (\( \sim 86\% \)) occurred between \( f_c \sim 200 \) kHz and \( f_c \sim 400 \) kHz. We did not find AKR onset frequencies below 100 kHz. After substorm onsets, the frequency band of the AKR waves always expands in both directions on a timescale of a few minutes. The occurrence of the lower end of the AKR wave band is plotted in Figure 2b, and the higher end of the AKR wave band is plotted in Figure 2c. The average AKR frequency is \( \sim 60 \) kHz for the lower end and \( \sim 650 \) kHz for the higher end. Note that the highest AKR frequency can, in several events, exceed the PWI instrument threshold of \( \sim 800 \) kHz.

It has been reported that AKR is uniformly emitted into a large frequency-dependent emission cone, with a larger cone angle corresponding to a higher-frequency AKR wave [Green et al., 1977; Green and Gallagher, 1985]. Therefore the lower frequency end of the AKR spectrum can be biased toward higher frequencies if Polar was, on the average, located at lower latitude. To address this question, we have plotted the magnetic MLAT-MLT locations of the Polar satellite for all events as diamonds in Figure 3. There are three stars, two on the dayside and one on the nightside, representing the three events of no AKR emission. It can be seen from Figure 3 that indeed several events were taken at latitudes below 60°. We recalculate the lower frequency end for those high-latitude (\( > 60^\circ \) MLAT) events, and results are plotted as dashed lines in Figure 2b. It is clearly shown that the two occurrence histograms are almost identical in shape and in population mean and standard deviation (numbers in parentheses are derived from high-latitude events).

**Figure 2.** Histogram of the average AKR frequency at substorm onset (Figure 2a); the lower bound and the higher bound of the AKR frequency band after the substorm onset are shown in Figures 2b and 2c, respectively.
3. Discussion

A detailed case study of the onset times of AKR at auroral substorms on a timescale of ~1 min conducted previously by Liou et al. [1999] has shown simultaneous occurrence of the two onsets as one would expect because AKR is associated with discrete auroras [e.g., Garnett and Frank, 1973] and onset arcs are discrete. In the present paper we showed explicitly an AKR event clearly lagged relative to the auroral breakdown by ~1.5 min. More surprisingly, this delay is common as indicated by our statistical results. The lag time between the AKR onset or enhancement and the auroral breakdown is 0.36 min. A simple statistics t test indicates that the upper limit of the 95% confidence interval on the distribution mean is 0.54 min and the lower limit of the interval is 0.18 min (0.07 and 0.53 min for isolated AKR events). Therefore the average of 0.36-min delay of AKR onset times relative to auroral breakdown found on the basis of the present study is statistically significant.

There are a few events corresponding to a void of emission in the AKR band. We found that for these events the Polar spacecraft was located either in the noon sector or at too low latitudes (see Figure 3). Interestingly, these events should have been at least inside the AKR emission cone at 178 kHz [Green and Gallagher, 1985]. Nonetheless, our result is generally consistent with previous findings that AKR is rarely seen in the noon sector [Kaiser and Alexander, 1977]; this is because AKR is more closely associated with intense electron acceleration [e.g., Green et al., 1979] which occurs mainly in the midnight sector. This important fact should be incorporated into the new AKR index proposed by Kurth and Garnett [1998].

The small delay of the AKR onset or enhancement with respect to the auroral breakdown may be because AKR plasma waves produced at onset are too weak to be detected by the Polar PWI. In many events that we surveyed, AKR wave power started weaker but intensified after the expansion of the substorm. On the other hand, it may be that precipitating electrons that produce onset arcs result from a direct dumping of the high-energy plasma sheet electrons and therefore are not subjected to acceleration in regions of parallel potential drop, the source of AKR. One more possibility is that the delay is due to a finite AKR wave propagation time. AKR waves are primarily generated in the R–X mode; its group velocity increases with the wave frequency from zero to the speed of light. A zero group velocity corresponds to the local electron gyrofrequency, or the lowest end of the AKR wave band. If this is the case, wave frequency dispersion in the AKR power should be present. Indeed, the AKR wave spectrum often shows changing vertical structure with time after the onset. However, a detailed analysis of the wave spectrum is beyond the scope of the present study.

Nonetheless, when the satellite is suitably located (within the AKR emission cone), AKR onsets or enhancements can be a good substorm onset indicator. They can be used to time substorm onset adequately within the ~1-min uncertainty of the UVI observations, especially if confirmed by other substorm onset identifiers. This is because during magnetically active periods, onset arc-associated AKR is often difficult to separate from those associated with other discrete aurora.

The typical wave frequencies for AKR during substorm periods range from just above 20 kHz to more than 800 kHz, though AKR wave power is usually much smaller at the two ends of the frequency range. At onset, AKR waves are usually produced at a narrow frequency range (~200–400 kHz). After onset the AKR frequency band expands rapidly, that is, within a few minutes. The rapid bandwidth increase of AKR during the substorm expansion phase has been reported previously, Kaiser and Alexander [1977] reported that AKR events begin at high frequencies (~400–500 kHz) and spread to lower frequencies as the substorm expands. Recently, Anderson et al. [1998] studied plasma wave
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emissions during two magnetically active periods and reported that the frequencies of the AKR wave emissions expand in both directions. Since AKR is generated near the local electron cyclotron frequency with a typical source spectral bandwidth of ~2.5% [Roux et al., 1993], the measured AKR frequency can be used to infer the upper limit of the source region. On the basis of the International Geomagnetic Reference Field (IGRF) magnetic field line model we found that AKR is most likely created at an altitude of ~3600–6300 km with a peak around 4700 km at substorm onset. This occurrence peak altitude is consistent with the averaged AKR source altitude of ~4200 km determined from FAST observations [Ergun et al., 1998].

After substorm onsets, the average AKR frequency expands to ~60–650 kHz within a few minutes, a period much shorter than the expansion phase of a typical substorm. A series of intensifications of AKR emissions were often observed after the first expansion onset and seemed to be responding to a series of intensifications of aurora, resulting, but not always, in a wider AKR wave frequency spectrum. There are previous studies indicating that the intensity of AKR is associated with parallel potential drops [Green et al., 1979; Benson and Calvert, 1979], but what controls the frequency band of AKR is not clear at this time and will be the subject for future investigation. This expansion of AKR frequency band corresponds to a source altitude from ~2100 to 12,000 km, which is in good agreement with the statistical source altitudes of the quasi-static, parallel electric fields [e.g., Mazer et al., 1977; Mazer, 1981] and coincides with the altitude range of the plasma cavity as determined from the contour of plasma density at 0.1 cm^-3 [Calvert, 1981], as required for a cyclotron maser instability to occur [Wu and Lee, 1979]. It is important to note that these electric field and plasma density measurements were not made specifically shortly after the substorm onset as we did in the present study. An implication of this good agreement is that in an average sense, auroral acceleration processes, whether associated with a substorm or not, operate in a constant magnetospheric region.

4. Conclusions

Plasma emissions in the AKR band observed by the Polar satellite during 136 isolated substorm periods are investigated with particular interest in the timing of AKR enhancement relative to its corresponding auroral breakup and the change of AKR wave spectrum before and after onsets. Several important results were found and can be summarized as follows: (1) 70% (83%) of the time, AKR enhancements were detected ±1 (±2) min from the auroral breakup; (2) AKR onsets occur slightly later (~0.36 min) than auroral breakups; (3) substorm-associated AKR has a forbidden area at Polar altitude in the noon sector; (4) the average frequency for the enhancement of AKR at substorm onset is ~300 kHz, corresponding to an upper limit of the AKR source altitude of ~4700 km; and (5) the entire AKR frequency band expands to ~64–650 kHz shortly after onset, corresponding to a wider source altitude of ~2100–12000 km. These results suggest that (1) the enhancement of AKR is a good substorm onset indicator and (2) the expansion of the auroral acceleration region along the local magnetic field lines should be considered as one of the basic signatures in the substorm expansion phase.

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