Seasonal and solar cycle dynamics of the auroral kilometric radiation source region

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[1] Several year’s worth of observations from the plasma wave instruments on both Magnetopause-to-Aurora Global Exploration (IMAGE) and Polar spacecraft are used to study the seasonal and solar cycle variations in the spectrum of auroral kilometric radiation (AKR). Only AKR observations when the spacecraft were in the Northern Hemisphere emission cones were used. The results from the seasonal analysis show significant changes in the AKR spectrum as a function of dipole tilt. The average AKR spectral peak for positive dipole tilt is \(~150\) kHz but is \(~300\) kHz during times of negative dipole tilt. In addition, the average emission spectrum for positive tilt is up to two orders of magnitude weaker over the 200–500 kHz frequency range when compared with the average emission spectrum for negative tilt. Assuming the cyclotron maser mechanism for AKR, these results imply that the AKR source region (the auroral density cavity) moves to higher altitudes during the summer and to lower altitudes during the winter. Using data from the DE-1 plasma wave instrument, the magnetic local time of average AKR source region is also investigated with dipole tilt. From these observations it is found that for negative dipole tilt a broad AKR source region exists, ranging from \(~18\) to \(~24\) MLT, with peak emission coming from \(~20\) MLT. In comparison, under positive dipole tilt the source region narrows (\(~20\) to \(~24\) MLT) with peak emission at \(~22\) MLT. Taking into account the above seasonal effect, a comparison of the average spectra from IMAGE and Polar plasma wave data also demonstrates a solar cycle effect. The average AKR spectrum at solar maximum has the same structure with dipole tilt as at solar minimum but is typically lower (by as much as \(1–2\) orders of magnitude). The observations presented support the concept that the expected increases in ionospheric densities (with positive dipole tilt for the Northern Hemisphere and solar EUV flux increases during solar maximum) play a significant role in magnetospheric-ionospheric coupling by: (1) shortening the altitude range of the auroral plasma cavity, (2) confining the cavity to a smaller range of MLT and closer to midnight, and (3) decreasing the overall intensity of AKR by lessening the density depth of the auroral density cavity. The results of this study should be taken into account in future studies of using AKR as a substorm index and other statistical emission cone studies at both low and high frequencies.

INDEX TERMS: 2736 Magnetospheric Physics: Magnetosphere/ionosphere interactions; 2772 Magnetospheric Physics: Plasma waves and instabilities; 2704 Magnetospheric Physics: Auroral phenomena (2407); 2788 Magnetospheric Physics: Storms and substorms; KEYWORDS: auroral kilometric radiation, seasonal variation, solar cycle variation, auroral density cavity, auroral acceleration region


1. Introduction

[2] The auroral kilometric radiation (AKR) emission spectrum has been measured extensively [see, e.g., Gurnett, 1974; Kaiser and Alexander, 1977]. In general terms, AKR is observed over a frequency range from \(~80\) to \(~600\) kHz with the peak intensity around 250 kHz. In addition to its large-scale structure, the AKR emission spectrum also contains narrow band drifting emissions structures [see, e.g., Gurnett et al., 1979] and harmonics [see, e.g., Benson, 1982; Mellott et al., 1986].

[3] Recent results by Kumamoto et al. [2003] have shown seasonal and solar cycle variations in the vertical distribu-
tion of the occurrence probability of AKR emissions from low altitude Akebono measurements. In that study, ionospheric density variations were believed to be mainly responsible for the changes in the AKR source altitude. All the AKR observations reported by Kumamoto et al. [2003] were remote from the AKR source region. It is important to note that the Kumamoto et al. [2003] study was not able to determine what portion of the drop in the frequency of occurrence of AKR emissions, at low altitudes, during the solar maximum and during the summer season was due to vertical motion of the AKR source up the auroral field line or to a propagation effect (more refraction) with the expected increase in the height of the ionosphere. In addition, Kumamoto and Oya [1998] also noted a seasonal difference in the AKR intensity from Akebono plasma wave data with increases in intensity in the winter polar region over the summer polar region.

The cyclotron maser instability [Wu and Lee, 1979] is believed to be the mechanism for the generation of AKR. For generation of AKR near the local electron gyrofrequency the cyclotron maser instability requires a source of free energy in the electron distribution and

\[ f_p/f_g < 0.3, \]

(where \( f_p \) is the electron plasma frequency and \( f_g \) is the electron gyrofrequency). In the auroral zone, the above condition is met in a density cavity formed from the evacuation of low energy background plasma by a parallel electric field [Benson and Calvert, 1979; Calvert, 1981; Benson, 1985; Ungstrup et al., 1990; Hilgers, 1992] or near the edges of such cavities [Fung and Vines, 1994]. The observation that the AKR emission frequency is very near the local \( f_g \) in the auroral zone density cavity [see, e.g., Hilgers et al., 1991] where the electron distribution function has a number of sources of free energy [Ergun et al., 2000] is the strongest observational evidence supporting the cyclotron maser instability. The observed AKR spectrum can be used to estimate the altitude range of the source region [Lee et al., 1980]. The peak intensity in the AKR spectrum is where the density in the auroral zone cavity is the lowest, maximizing the growth rate for the instability. A study of the AKR spectrum is, therefore, a study of the location of the auroral density cavity and the auroral acceleration region.

The purpose of this paper is to analyze the average spectral features of the AKR spectrum on both seasonal and solar cycle timescales over its entire frequency range and deduce the spatial extent and location of the auroral density cavity and the auroral acceleration region in both altitude and local time. These observations are important for determining the effect of the ionosphere on substorm processes that are initiated in the magnetosphere.

2. Observations

The observations used in this study are from the plasma wave instruments on the polar orbiting Imager for Magnetopause-to-Aurora Global Exploration (IMAGE), Polar, and Dynamics Explorer-1 (DE) spacecraft. The IMAGE spacecraft was launched on 25 March 2000 into a highly elliptical polar orbit with initial geocentric apogee of 8.22 Earth radii (\( R_E \)) and perigee altitude of 1000 km. The Radio Plasma Imager (RPI) instrument on IMAGE is a highly flexible radio sounder that transmits and receives coded radio frequency pulses in the frequency range from 3 kHz to 3 MHz. RPI also makes passive radio measurements that will be used in this study. RPI utilizes three orthogonal dipole antennas of 325 m (\( X \) axis), 500 m (\( Y \) axis), and 20 m (\( Z \) axis), all tip-to-tip lengths. The \( X \) axis antenna was 500 m at the beginning of the mission but was shortened to 325 m when it apparently collided with a micrometeor or orbital debris on 3 October 2000. For more details on the operations of RPI, see Reinisch et al. [2000]. The Polar spacecraft was launched on 24 February 1996 into a highly elliptical polar orbit with initial perigee and apogee of 2.2 and 9 \( R_E \) geocentric radial distance respectfully. The plasma wave instrument (PWI) on Polar is designed to measure the electric field from 0.1 Hz to 800 kHz on three antennas. The instrument operated successfully until August 1997. PWI AKR spectral observations used in this study were taken from the long (~130 meters tip-to-tip) EU antenna (unless otherwise stated) when the instrument was in the logarithmic sampling mode. For more details on the operations of the Polar/PWI instrument, see Gurnett et al. [1995]. DE-1 was launched on 3 August 1981 into a polar orbit (90° inclination) with initial apogee of 4.65 \( R_E \) geocentric radial distance and a perigee of 675 km altitude with an orbital period of about 7 hours. The PWI on DE measured spectral and polarization measurements over a frequency range from 2 Hz to 400 kHz. The DE/PWI electric field measurements used in this study are all from the 200 m tip-to-tip wire antenna. For a more complete description of the DE/PWI, see Shawhan et al. [1981].

3. Seasonal Variations

The AKR spectrum can be investigated for seasonal variations by analyzing the data as a function of dipole tilt angle. Figure 1 is the distribution of AKR as a function of dipole tilt angle. The AKR spectrum extends over a larger frequency range for negative dipole tilt angles than for positive dipole tilt angles. The spectrum: (1) the AKR emission spectrum shifts down in frequency with increasing dipole tilt and (2) the emission spectrum presents two main seasonal effects on the average AKR spectrum: (1) the AKR emission spectrum shifts down in frequency as the AKR were explicitly excluded from this study. In addition, as shown in Figure 1 no clear harmonic structure is observed in the average spectrum of the emission. Mellott et al. [1986] from DE-1 observations did not show any precise harmonic correspondence and the examples were quite rare and relatively weak. In this study obvious harmonic relationship will be averaged out.
The average AKR spectrum peaks around ~260 kHz and is very broad extending from ~80 to nearly 500 kHz. In contrast, for positive dipole tilt angles the spectrum is narrower (from 60 to 250 kHz) and peaks near 150 kHz.

Such a dramatic shift in the AKR spectrum with dipole tilt angle has also been observed with IMAGE/RPI within a single orbit. Figure 3 is an RPI spectrogram near solstice, when the Northern and Southern Hemispheres of Earth are near the extremes in dipole tilt, and the IMAGE orbit plane is close to the dawn-dusk meridian. The intense AKR is observed in the Northern Hemisphere at the beginning of summer while the Southern Hemisphere observations occur near winter. Assuming an AKR source region at 22 MLT and invariant latitude of 70° the solar zenith angle of the source’s ionospheric foot point is computed for each hemisphere respectively and listed at the bottom of Figure 3. For a solar zenith angle of less (greater) than 90° the ionosphere is in darkness (20:10-23 UT). The summer observations (large positive dipole tilt in the Northern Hemisphere) appear to have a much broader spectrum than expected when compared with the averaged spectral results of Figure 2 (red curve). Comparisons of this nature clearly appear to have a much broader spectrum than expected when compared with the averaged spectral results of Figure 2 (red curve). Comparisons of this nature clearly illustrate the rapid change in frequency range and intensity of any individual AKR event emphasizing that the main results of the observations presented in this paper concern only the average spectrum.

Adopting the cyclotron maser theory as the probable generation mechanism for AKR, the observed shifts of the AKR spectrum can be interpreted as changes in the location of the auroral zone density cavity with dipole tilt, assuming that the AKR spectral peak is generated at some fixed $f_p/f_g < 0.3$. Since the AKR emission peak occurs when the $f_p/f_g$ ratio is smallest, then in this analysis, a matching of the same AKR intensity at frequencies on opposite sides of the peak may be used to derive the contours of $f_p/f_g$. Figure 4 is a qualitative illustration of the AKR spectrum mapped into contours of $f_p/f_g$ for a 70° invariant auroral field line using the T96 magnetic field model [Tsyganenko, 1995]. Consistent with the observations presented in Figures 1 and 2, the source region during extreme negative dipole tilt angles (winter) shows the auroral zone density cavity stretching from a region where $f_g = 500$ kHz to nearly $f_g = 80$ kHz. In contrast, for extreme positive dipole tilt angles the source region extent is much smaller, has moved further up the field line, and has a lower frequency boundary of 60 kHz and an upper frequency boundary near 250 kHz.

The time averaged AKR source location has been determined by Gallagher and Gurnett [1979] to be between 22 and 24 MLT and below 2.5 RE but at the time of that study no effort was made to investigate any seasonal variation in the source location. On the basis of the dramatic effect dipole tilt angle has on the emission spectrum, and therefore source region altitude, it is essential that variations in the source location in MLT also be investigated. To perform this analysis, the DE/PWI archived data set was chosen because of the extensive coverage in the AKR source region altitudes, MLT, and over all dipole tilt angles.

Figure 5 is a plasma wave map at 186 kHz (near the AKR spectral peak) of all DE/PWI observations from 16 September 1981 through 23 June 1984 when the spacecraft measured a local $f_g$ between 186 to 280 kHz in MLT and invariant latitude. This range in gyrofrequency was chosen to provide adequate statistics where each pixel has more than 50 and as many as 320 observations while balancing smearing of the source region location due to the expected broad emission pattern. Plasma wave maps will allow us to look for “hot spots” in the wave intensities, thereby identifying either the source region or sites of plasma wave amplification. The MLT versus invariant latitude distribution of the 186 kHz electric field wave measurements in Figure 5 have been sorted with respect to negative...
Figure 3. IMAGE/RPI spectrogram showing the AKR spectrum for northern summer and southern winter. The $f_g$ (red) and $f_p$ (white) lines are form model values.

(Figure 5a) and positive (Figure 5b) dipole tilt angles. It is important to note that IMAGE/RPI observations (not shown here) show the same trend as the DE/PWI data shown in Figure 5 but with much less statistical confidence.

The observations presented in Figure 5 show a clear distinction in the location of the maximum wave intensity with dipole tilt angle (referenced to the Northern Hemisphere). For negative dipole tilt angles (Figure 5a) the AKR source region extends to near dusk with the source centroid near $\sim$20 MLT. For positive dipole tilt angles (Figure 5b) the source region is more confined to 20–24 MLT with the centroid near $\sim$22 MLT. It is these latter observations that are more consistent with the Gallagher and Gurnett [1979] results.

4. Discussion of Seasonal Effect

Seasonal variations in the production of AKR were found by Kasaba et al. [1997] from GEOTAIL/PWI observations. These authors showed that AKR is more active in the winter hemisphere for higher frequencies (500 kHz). These observations are consistent with the average AKR spectrum for negative dipole tilt shown in Figure 1 illustrating that the effect reported by Kasaba et al. [1997] is due to a spectral enhancement of AKR emission at those frequencies rather than other effects such as propagation.

Morooka and Mukai [2003] used Akebono in situ measurements to find a seasonal dependence on the altitude profile of the parallel acceleration region. These authors believed that the seasonal dependence in the altitude of the parallel acceleration region was due to the seasonal depen-

Figure 4. Qualitative contours of $f_p/f_g$ of the auroral density cavity under dipole tilt extremes showing the shift in AKR source region up the field line during the summer and a lower altitude and longer source region during the winter.

Figure 5. The magnetic local time distribution of the average AKR source region from 186 kHz electric field measurements from the DE/PWI for (a) negative and (b) positive dipole tilt angles. Over three years of in situ observations were used where $f_g$/186 kHz ranged from 1 to 1.5.
dence of the ambient plasma density with a lower density during the winter causing the acceleration region to move to lower altitudes. Johnson et al. [2001] further show that the depth in density of the auroral zone density cavity is strongly controlled by solar illumination. Liou et al. [2000] also found that precipitating electron events at higher energy typically occurred during the winter than in the summer.

To more fully investigate the density dependence on the AKR spectrum an auroral zone density model was created based on the observational results from Janhunen et al. [2002] for an AKR source at 67° invariant latitude field line at selected magnetic local times. Janhunen et al. [2002] found that the density depletion tended to move to higher altitude when the ionospheric footprint was in the sunlight compared to the darkness. For the field line used the ionospheric solar zenith angle ranged from 75° to 145° (where 90° is the terminator). The range in AKR cavity location used was 2.4 to 1.7 RE where the latter altitude used is when the cavity is in total darkness. The peak in the AKR spectrum was predicted based on the minimum density within the center of the auroral density cavity mapped to the local gyrofrequency. Figure 6 shows the resulting peak frequency in the AKR spectrum as a function of dipole tilt angle based on cavity altitude. Curves A–F are for AKR source region field lines whose foot points range from 18 to 23 MLT respectively. The break point in the spectral peak occurs when solar zenith angle is 90° to the field line at the foot point. Consistent with the results of Janhunen et al. [2002] the auroral density cavities tend to occur at higher altitudes if their magnetic footprint was in the sunlit ionosphere. The model results only qualitatively match the observed average AKR spectral trend as shown in Figure 1, but does demonstrate the ionospheric density control of the auroral cavity location and the resulting AKR emission spectrum given a source of free energy in the precipitating electron distribution function. The model in Figure 6 clearly does not take into account all the changes in density structures that must be occurring with dipole tilt as reflected in the AKR spectral changes of Figure 1 (and later in Figures 7 and 8). It is because the model is so elementary that we hesitate to conclude more than showing the expected trends rather than use the model to explain details in the observations.

To more fully investigate the density cavity altitude variation of the source region versus tilt angle, the maximum frequency at which AKR is observed in POLAR/PWI frequency spectra was measured using the Ez antenna (14 m tip-to-tip). The observations were then binned by frequency and tilt angle and normalized by the total number of observations for each tilt angle bin. The results of the analysis are shown in Figure 7a, which plots the percentage of time the upper frequency of AKR was observed to occur for a particular frequency versus dipole tilt angle bin. Figure 7b translates these observations into the density cavity altitude versus solar zenith angle by mapping the AKR frequency with the local $f_g$ along an auroral zone field line at 22 MLT and 70° invariant latitude.

Figure 6. Model of the peak in the AKR spectrum as a function of dipole tilt angle. Curves A-F all show the rapid drop in the peak AKR spectrum with MLT. The break point in the spectral peak occurs when the solar zenith angle is 90° to the field line at the foot point.

Figure 7. (a) Occurrence probability of the maximum frequency of AKR from Polar/PWI (Ez antenna) plotted versus dipole tilt angle. (b) Map of the AKR observations (where the wave frequency equals the local $f_g$) along an auroral zone field line at 22 MLT and 70° invariant latitude and plotted versus the solar zenith angle. Solar zenith angles less than 90° have the foot of the field line in sunlight and shows the AKR density cavity at altitudes over 2500 km higher than at solar zenith angles where the foot of the source field line is in the darkness.
than AKR is observed. Although our approach is very different spectrum and not on the location of the spacecraft when study is based on the structure of the observed AKR winter (Kumamoto et al. [2003]). These authors presented the vertical profiles of occurrence probability of AKR sources as observed by the Akebono plasma wave instrument and showed that the highest occurrence probably drop in altitude by nearly 2000 km between summer (~5500 km) and winter (~3500 km). It is important to note that the average AKR spectrum of Figure 1 is based on observing AKR independently of spacecraft location. Changes in the size of the emission cone, due to refraction, are not a factor in our analysis. Unlike the Kumamoto et al. [2003] paper this study is based on the structure of the observed AKR spectrum and not on the location of the spacecraft when AKR is observed. Although our approach is very different than Kumamoto et al. [2003] we are finding similar results.

As shown in Figure 7b, the lowest altitude of the density cavity ranges from ~4300 km where the solar zenith angle at the foot of the field line is below 90° (in sunlight) and quickly moves to ~2500 km, where it levels off (in darkness). The above analysis is consistent with Kumamoto et al. [2003, Figure 2]. These authors presented the vertical profiles of occurrence probability of AKR sources as observed by the Akebono plasma wave instrument and showed that the highest occurrence probably drop in altitude by nearly 2000 km between summer (~5500 km) and winter (~3500 km). It is important to note that the average AKR spectrum of Figure 1 is based on observing AKR independently of spacecraft location. Changes in the size of the emission cone, due to refraction, are not a factor in our analysis. Unlike the Kumamoto et al. [2003] paper this study is based on the structure of the observed AKR spectrum and not on the location of the spacecraft when AKR is observed. Although our approach is very different than Kumamoto et al. [2003] we are finding similar results.

Early in the study of AKR, Gurnett [1974] found a positive correlation between AKR and discrete auroral arcs. Since that time, a number of authors have also confirmed that relationship [see, e.g., Huff et al., 1988; Liou et al., 2000]. The shift in the source centroid of AKR from 20 (negative dipole tilt, Northern Hemisphere) to 22 MLT (positive dipole tilt, Northern Hemisphere) is consistent with the more recent work of Newell et al. [1996] who showed that the frequency of aurora was independent of solar cycle in darkness but there was a significant suppression of discrete aurora by sunlight and that ionospheric conductivity is a key factor in controlling the occurrence of discrete aurora.

It is well known that EUV and shorter wavelength emissions from the sun greatly intensifies during solar maximum causing a general enhancement in ionospheric densities. On the basis of the results presented here, it is intriguing to compare the average spectral characteristics of AKR between solar minimum and solar maximum. If ionospheric densities play a major role in the location and depth of the auroral density cavity (the AKR source region), as this study strongly suggests, then we would also expect the average AKR spectrum to have exhibit a solar cycle variation with the unexpected result that AKR would be less intense during solar maximum.

5. Solar Cycle Variations

Since the Polar plasma wave observations were taken during the last solar minimum and IMAGE plasma wave measurements were taken during the most recent solar maximum a comparison of the average spectra will be used to investigate solar cycle effects. It is not possible to compare simultaneous observations by Polar/PWI and IMAGE/RPI since the former was not operating after the launch of IMAGE. However, observations from Polar/PWI and IMAGE/RPI can be compared with Wind/Wave measurements. An in-flight calibration check of the IMAGE/RPI instrument was done by comparing the simultaneous observed power flux measurements of several type III radio bursts with those from the Wind/Waves instrument. A similar analysis was performed between simultaneous Polar/PWI and Wind/Waves instruments of several Solar Type III radio bursts. Both comparisons showed that these instrument were making measurements that were, at times nearly identical, or within less than 10 db and therefore in reasonable agreement. For details on the Wind/Waves instrument, see Bougeret et al. [1995].

In order to investigate solar cycle variations in the AKR spectrum it is now clear that these comparisons can only be valid under the same conditions of dipole tilt angle since significant variations exist with dipole tilt as shown in the previous section. Figure 8 is in the same format as Figure 1 but is the AKR data from the Polar/PWI from March to May 1996 and February to September 1997 when the instrument was connected to the Eu antenna. Although this data set is somewhat limited (no Polar/PWI data is available for the extreme negative dipole tilt angles when PWI was connected to the Eu antenna) it is the longest antenna on Polar (130 m tip-to-tip) and therefore produces measurements most comparable to those from IMAGE/RPI. It is clear from Figure 8 that the average Polar/PWI AKR spectra shows the same trend to lower frequencies with higher dipole tilt as the IMAGE/RPI observations presented in Figure 1. It is important to note that Figures 7 and 8 are showing two different portions of the AKR density cavity. Figure 7 is an occurrence plot of the upper AKR frequency (observed just above the noise level) or the lowest altitude portion of the density cavity. Figure 8 is the AKR average spectrum in which the most intense emissions (yellow and red colors) are coming from near the center of the density cavity. As illustrated in Figure 4, although the entire density cavity moves up the field line with increasing dipole tilt the center of the density cavity does not maintain its relative location. A more detailed comparison between Polar/PWI and IMAGE/RPI AKR average spectra is shown in Figure 9 also shows this relationship.

Figure 9 shows the average AKR intensity for positive dipole tilt angles (top panel) and negative dipole...
tilt angles (bottom curve). The red curves are the IMAGE/RPI data taken during solar maximum and the blue curves are the Polar/PWI data taken during solar minimum. This comparison shows a characteristic decrease in the intensity of AKR over the solar cycle with the AKR intensity typically less by about an order of magnitude during winter seasons during solar maximum. In addition, for positive dipole tilt conditions the AKR spectrum for higher frequencies, observed during solar maximum, is significantly below (by nearly two orders of magnitude) the solar minimum observations for the higher frequency portion of the spectrum (>200 kHz).

6. Discussion

[24] Higher ionospheric densities during the summer season somewhat reduces the AKR intensity and changes the spectral peak emission. These observations imply that the AKR source region, from winter to summer, moves up the auroral field lines and also lessens the depth of the density cavity. Adding the solar cycle effect further reduces AKR intensity on top of the seasonal variation over almost the entire frequency range. Higher ionospheric densities would also increase the refraction of AKR waves upward (or away from the ionosphere) resulting in a smaller averaged AKR emission cone compared with times with lower ionospheric densities.

[25] These effects on the AKR spectrum were not known before the previous emission cone studies by Green et al. [1977] or Gallagher and Gurnett [1979] which used multiyear AKR observations spanning several seasons and significant portions of a solar cycle. The results presented in this paper call into question the interpretation that the AKR emission cone at low frequencies is hollow based on previous statistical studies. Green and Gallagher [1985] combined 3.5 years of IMP-6 (March 1971 to September 1974) and over 4 years of Hawkeye plasma wave data (June 1974 to April 1978) to obtain the detailed intensity distribution of the AKR emission cone at 178, 100, and 56.2 kHz. These authors showed that the AKR emission cone at 178 and 100 kHz had less then 10 dB variation in the average intensity across nearly the entire emission pattern. Larger variations were found at the lower frequency (56.2 kHz) that was reinterpreted by Calvert [1987] as the signature of a hollow cone. The observations used in those studies covered 7 years worth of data from just after solar maximum through solar minimum. The average AKR spectrum at solar maximum (Figure 1) and solar minimum (Figure 8) show considerable variation at frequencies below 100 kHz with respect to the dipole tilt. The Green and Gallagher [1985] and the Calvert [1987] studies were unaware of this effect at that time. Without the benefit of resorting the data with respect to dipole tilt the interpretation by Calvert [1987] of a hollow emission cone at 56.2 kHz may not be substantiated.

[26] For over 25 years AKR has been known to be a reasonably reliable indicator of auroral substorm activity. Voots et al. [1977] related the AKR intensity at 178 kHz with the auroral electrojet index AE. These authors used observations from the plasma wave instrument on IMP-6 taken in 1971 (August–December) and in 1973 (December–March) just after solar maximum. Considerable variations can be noted in their Figure 5 scatterplot of AKR intensity versus AE index. In their comparisons of AKR spectra with the AE index, Kaiser and Alexander [1977] found the frequency of the peak in the emission spectrum tended to decrease with AE. These authors used IMP-6 observations from 1971 (April) to 1972 (September) and from RAE 2 from 1973 (July) to 1975 (July) spanning several complete dipole tilt cycles and extending from solar maximum to solar minimum. More recently, Kurth and Gurnett [1998] developed an AKR index by integrating the observed power spectrum and proposed using that as a proxy for AE. Kurth et al. [1998] compared the AKR index derived from AKR observations from the Polar and Geotail wave instruments with the AE index for the January 1997 magnetic cloud event and found reasonable agreement provided that the observations were taken when the spacecraft were in the AKR emission cone and attributed other discrepancies to potentially hollow AKR emission cones at high and low frequencies. Although it is impossible to determine the exact origin of the discrepancies in each of these studies due to their statistical nature it is anticipated that if both seasonal and solar cycle effects on the AKR spectrum, as presented in this study, were to be taken into account a significant improvement in the correlation of AKR intensity with AE might be obtained.

7. Conclusions

[27] The results presented in this paper are compelling, showing that there are significant variations in the average AKR spectrum as a function of dipole tilt and with the solar cycle. Table 1 presents a summary of these spectral changes.

[28] Since the number of geomagnetic storms and their intensities greatly increases with solar activity it is generally believed that AKR would be more intense during solar maximum. From Table 1 the average AKR spectrum is the...
least intense and narrowest in overall frequency range during summer/solar maximum and most intense and broadest during winter/solar minimum, a somewhat surprising result based on previous perceptions.

[30] A consistent picture has emerged in which ionospheric density enhancements from sunlight during both positive dipole tilt configurations and solar maximum produce significant effects in the AKR spectral structure, source location, and emission intensity. The observations imply that the main auroral density cavity moves upward in altitude and becomes less pronounced as Earth’s dipole changes from extreme negative values to extreme positive values.

[31] The expected increases in ionospheric densities (with positive dipole tilt and solar EUV increases during solar maximum) play a significant role in magnetospheric-ionospheric coupling by: (1) shortening the altitude range of the auroral plasma cavity, (2) confining the cavity to a smaller range of MLT and closer to midnight, and (3) decreasing the overall intensity of AKR by lessening the depth of the auroral density cavity.

[32] The results presented in this paper call into question the interpretation that the AKR emission cone at low frequencies is hollow based on previous statistical studies that do not take into account the dipole and solar cycle variations in the AKR average spectrum and source location. In addition, previous studies that have found reasonable correlations between AKR with the AE substorm index or use AKR as a substorm index may find an even better result by taking into account the average spectral variations as a function of dipole tilt and solar cycle.

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References


Table 1. Summary of Average AKR Spectral Characteristics

<table>
<thead>
<tr>
<th>Solar maximum</th>
<th>Summer</th>
<th>Winter</th>
</tr>
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<tbody>
<tr>
<td>least intense</td>
<td>narrowest frequency range (~60–250 kHz)</td>
<td>broad frequency range (~60–500 kHz)</td>
</tr>
<tr>
<td>lowest spectral peak frequency (~150 kHz)</td>
<td>high spectral peak frequency (~250 kHz)</td>
<td></td>
</tr>
<tr>
<td>Solar minimum</td>
<td>moderately intense</td>
<td>most intense</td>
</tr>
<tr>
<td>intermediate frequency range (~60–435 kHz)</td>
<td>broadest frequency range (~50–675 kHz)</td>
<td></td>
</tr>
<tr>
<td>intermediate spectral peak frequency (~220 kHz)</td>
<td>highest spectral peak frequency (~300 kHz)</td>
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