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Daily variations of auroral kilometric radiation observed by STEREO

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[1] Daily variations of terrestrial auroral kilometric radiation (AKR) are considered; an effect that is detected in STEREO/WAVES data. It has been found that the intensities of the AKR emitted from Northern and Southern sources are modulated with a period of ∼24 hours. The occurrence frequency of the AKR has been shown to be strongly dependent on the orientation of the rotating oblique magnetic dipole of the Earth relative to the Sun. AKR is found to occur more often and emit in a broader frequency range when the axis of the terrestrial magnetic dipole in the given hemisphere is oriented toward the nightside. We suggest that the observed ∼24 h variations of AKR are connected with diurnal changes of the ambient plasma density in the auroral region. **Citation:** Panchenko, M., et al. (2009), Daily variations of auroral kilometric radiation observed by STEREO, *Geophys. Res. Lett.*, *36*, L06102, doi:10.1029/2008GL037042.

1. Introduction

[2] Auroral kilometric radiation (AKR) is a powerful and strongly variable electromagnetic emission radiated from the auroral regions of the Earth's magnetosphere at frequencies between 20 and 1000 kHz (detailed properties are reviewed by *Kaiser et al.* [1984]). In addition to the rapid intensity fluctuations, which are manifestations of the fast dynamic processes in the magnetosphere, long quasi-periodic variations have also been detected in the AKR spectra. There are several studies which report on the seasonal and solar cycle related variations of AKR intensity, its occurrence and frequency range [*Kumamoto and Oya*, 1998; *Green et al.*, 2004; *Kumamoto et al.*, 2003]. In particular, it has been found that AKR has a higher intensity, a broader frequency range, and occurs more often in the winter polar regions as well as during the maximum of the solar cycle. A statistical analysis of AKR measured by Interball-2/Polrad has also revealed the dependence of the altitudinal size and location of the AKR sources on the varying indices of geomagnetic activity [*Mogilevsky et al.*, 2005].

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[3] Early spacecraft observations of AKR have shown that its sources are fixed in local magnetic time and magnetic latitude [*Kaiser et al.*, 1978; *Green et al.*, 1977]. Therefore the rotation of Earth causes the AKR radiation pattern to nod up and down relative to a fixed remote observer. In particular, this effect was observed by *Kaiser et al.* [1978] as daily variation of AKR occurrence frequency. The recent studies by L. Lamy et al. (Diurnal modulation of the AKR observed by Cassini/RPWS, submitted to *Journal of Geophysical Research*, 2008) also indicate the presence of 24 h and 12 h modulation in AKR spectra measured by Cassini/RPWS.

[4] In this paper we present a new result regarding the analysis of the periodic modulations of AKR, observed by STEREO Behind spacecraft (S/WAVES experiment). The specifics of observational conditions in this very case make it possible to relate the detected daily (∼24 hour) modulations of AKR intensity, and frequency range of the emission, as well as the AKR occurrence frequency, with variation of the ambient plasma density due to the periodic change of the auroral region exposure to the Sun.

2. Observations and Data Analysis

[5] Solar TErrestrial RElations Observatory (STEREO) consists of two identical spacecraft (STEREO-A and STEREO-B), launched on October 25, 2006. After the last swing-by maneuver (January 21, 2007) STEREO-B passed by the vicinity of the Earth, through the dusk side of the magnetosphere, in the direction from the dayside to the nightside (Figure 1). Such a favorable trajectory enabled long duration observations of AKR, whose sources are known to be located mostly in the dusk-night part of the magnetosphere. In our study we use the observations from the STEREO/WAVES (S/WAVES) experiment [*Bougeret et al.*, 2008]. The data were measured by the HFR1 receiver (0.125–2 MHz), which provides spectral and cross-spectral power densities and makes possible the determinations of the radio wave polarization and direction-of-arrival.

[6] With the distant location of the spacecraft relative to the Earth, the AKR sources from both hemispheres could be observed simultaneously and their position might be assumed to coincide with the Earth's center. Taking into account that AKR is circularly polarized [*Panchenko et al.*, 2008, and references therein], the polarization measurements capability of the S/WAVES instrument has been used for the AKR identification and its subsequent separation between the emission radiated by Northern (righthand polarization) and Southern sources (lefthand polarization). The Poynting flux and Stokes parameters of the analyzed AKR were derived from the same direction-finding algorithm as developed for the Cassini/RPWS [*Cecconi and Zarka*, 2005].

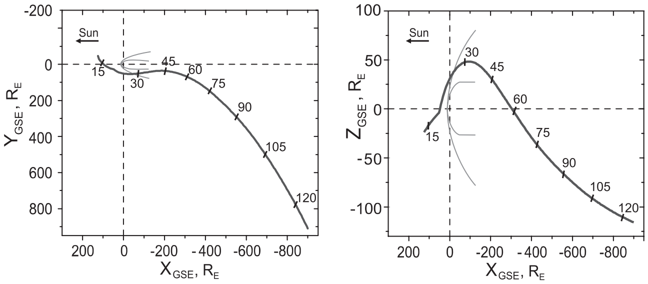

Figure 1. STEREO-B orbit in GSE coordinates. Ticks indicate the day of year, 2007.

[7] The analyzed data record covers a period between January 23, 2007 and May 1, 2007 when STEREO-B provided the best quality quasi-continuous observations of AKR. The corresponding AKR time profiles (for Northern and Southern sources) have been produced by integration of the radio emission over the frequency range from 125 to 700 kHz, where AKR occurs most frequently.

[8] The final data profiles were normalized to the intensity at a distance of 100 R_e, and then treated to detect possible quasi-periodic variations. For this purpose, we used a combination of a "sliding window" Fourier (SWF) and nonlinear Wigner-Ville (WV) transform techniques [*Shkelev et al.*, 2004; *Khodachenko et al.*, 2006].

3. The 24 Hour Modulation of AKR Spectra

[9] Figures 2b and 2d show the intensity profiles of the AKR, emitted by Northern and Southern sources, respectively. Figures 2a and 2c represent the corresponding SWF dynamical spectra of AKR modulations, whereas Figures 2e and 2f show their time averaged profiles. The intense ~24 hour lines are easily seen in the SWF dynamical spectra of AKR modulation from both Northern and Southern hemispheres. The strength of the modulation lines correlates with AKR intensity. The spectral peak of the AKR variations is determined at 0.0116 ± 0.0008 mHz (corresponding period 23.9 ± 1.7 h) and 0.0113 ± 0.0008 mHz (corresponding period 24.6 ± 1.9 h) for the radiation emitted from Northern and Southern AKR sources, respectively (Figures 2e and 2f).

[10] There are at least two possible explanations of the observed 24 h variations of the AKR. These may be related with specific geometrical configuration between AKR sources and the observer, or with the internal plasma processes in the AKR sources controlled by the Earth's rotation.

[11] In particular, the 'geometrical' modulation mechanism consists in periodic occlusion of the AKR source observed by the remote spacecraft located close to the ecliptic plane. Since the axis of the terrestrial magnetic dipole does not coincide with the Earth's spin axis (tilt angle is ≈10.3°, according to IGRF model for 2007) the plasmasphere, dense and opaque for the kilometric radio emission, can occlude the AKR sources once a day (Figure 3a). This effect should be more prominent for the high frequency part of the AKR spectrum, i.e., for the sources located at lower altitudes. However, using a simple geometrical model of the AKR source visibility with a straight-line propagation of the radio emission, it can be shown that the plasmasphere affects visibility of the AKR only at particular parts of the STEREO-B trajectory. In the model the sources of the AKR, observed at 700 kHz (the upper frequency of the analyzed radiation), are assumed to be on magnetic field line 21 h MLT at 70° inv.Lat [*Green et al.*, 1977], and the outer edge of the plasmasphere is taken at L-shell 4. Figure 3b shows the 3D trajectory of STEREO-B in the solar magnetic coordinates, in which one cycle of a spiral corresponds to one day. The green line indicates the part of the STEREO-B trajectory where the plasmasphere cannot occlude the AKR sources below 700 kHz.

[12] To exclude the shading effect of plasmasphere, in the analysis below we used the data recorded only between January 23, 2007 and February 18, 2007 when STEREO-B was located at sufficiently high latitudes in the Northern hemisphere. We studied the AKR occurrence frequency as a

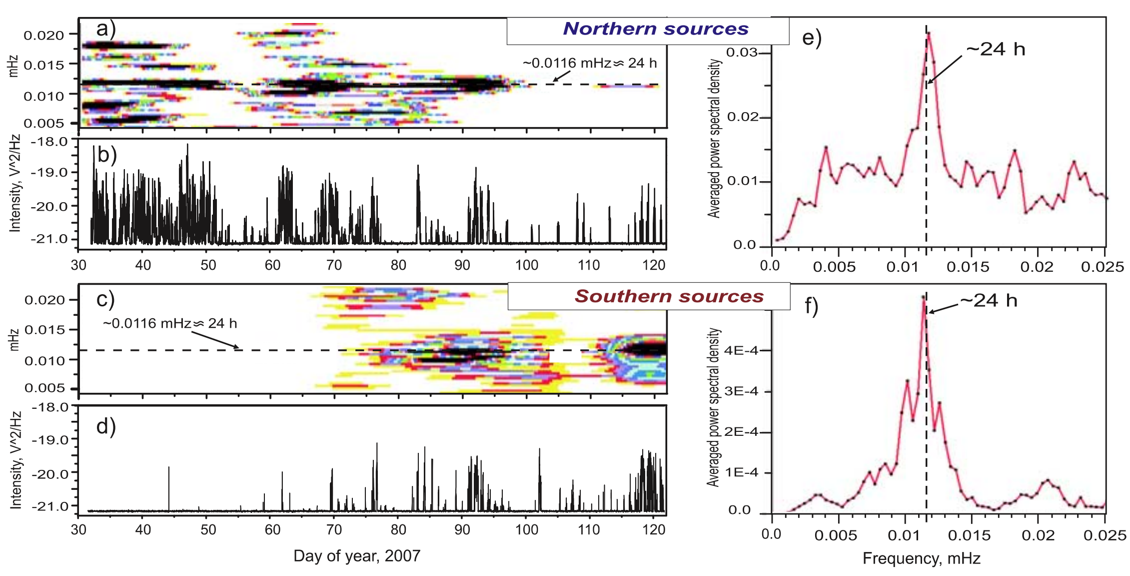

Figure 2. (a, c) SWF dynamical spectra of modulations. (b, d) Intensity profiles of AKR emitted by Northern and Southern sources. Black color in the modulation spectra means the highest values of the spectral density. (e, f) The time averaged profiles of the SWF dynamical spectra.

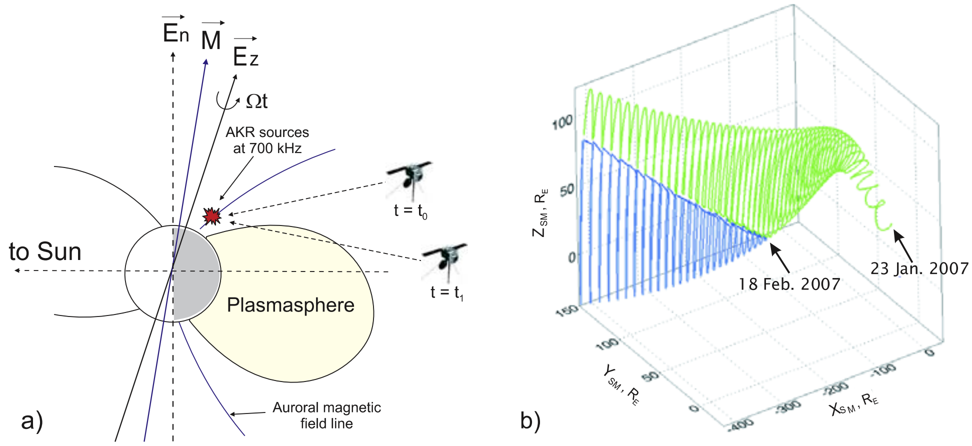

Figure 3. (a) Schematic view of AKR source visibility. $\vec{E}_n$ is a normal to the ecliptic plane and $\vec{M}$ is the axis of the terrestrial magnetic dipole, tilted by $\approx$10.3° from the Earth's rotation axis $\vec{E}_z$. (b) 3D trajectory of the STEREO-B in the solar magnetic (SM) coordinates (terrestrial dipole axis is along Z). The green line is the part of the STEREO orbit where the plasmasphere cannot shade the AKR sources at frequencies 700 kHz. The blue line indicates the part of the trajectory when the AKR sources at 700 kHz are not visible due to plasmasphere occlusion.

function of the frequency of the emission and the local time (LT) of the terrestrial magnetic dipole axis. The results in Figure 4 demonstrate the strong dependence of the AKR occurrence frequency on the orientation of the magnetic dipole with respect to the Sun. In particular, the Northern sources are more frequent when the magnetic dipole is tilted to the nightside (from 18 h LT to 8 h LT through 0 h LT). Another important feature seen in Figure 4 concerns daily variation of the AKR frequency range, which becomes narrower (upper frequency changes from >550 kHz down to <400 kHz) when the magnetic dipole is oriented toward the dayside. In view of these results we draw the general conclusion that, when in a course of a day the magnetic dipole is oriented in a given hemisphere toward the nightside (away from the Sun), the AKR generation is more efficient and covers a broader frequency range. The nature of this effect may be connected with the daily modulation of the ambient plasma density, caused by the varying solar illumination of the auroral ionosphere. The higher ionospheric densities in the more illuminated side may reduce the occurrence frequency of the AKR and the emission frequency range.

[13] The discussed daily variations of the AKR and its frequency range are very similar to seasonal [*Green et al.*, 2004] and solar cycle [*Kumamoto et al.*, 2003] variations of the AKR. According to *Green et al.* [2004], seasonal variations of the AKR are also related with the tilt of the terrestrial dipole relative to the Sun. The authors suggest that during the summer the lower edge of the AKR source cavity shifts to higher altitudes due to increased ionization of the auroral ionosphere illuminated by the Sun. This increases the local plasma frequency in the lower part of the auroral flux tubes and therefore affects the operation of the AKR electron-cyclotron maser (ECM). The solar cycle variations of AKR, reported by *Kumamoto et al.* [2003] and the measured increase of the ambient auroral plasma density (below 8000 km) during the solar maximum, may also be connected with the increased plasma up-welling from the ionosphere, caused by a higher solar EUV flux. *Kumamoto et al.* [2003] suggested that more dense ambient plasma results in reduction of the field-aligned potential drops, important for the ECM operation, and may therefore be responsible for the observed decrease of occurrence probability of AKR during solar maximum.

[14] Besides of that, solar illumination influence on the ambient plasma density and size/position of the plasma depletions in the auroral regions has been investigated. *Laakso et al.* [2002] have found that polar plasma density is clearly higher in the dayside than in the nightside, and supposed that this is due to higher ionospheric refilling rates on the dayside. *Janhunen et al.* [2002] report that during the year the position of the auroral plasma depletion cavities, which are believed to be AKR sources, tends to move to higher altitude when the corresponding ionospheric footpoint is in sunlight.

[15] There are several studies which show that ionospheric conditions controlled by the sunlight may also affect acceleration of auroral particles responsible for the phenomenon of the discrete auroral arcs [*Newell et al.*, 1996; *Morooka and Mukai*, 2003]. The latter are known to be strongly correlated with AKR [e.g., *Kaiser et al.*, 1984]. In particular, *Newell et al.* [1996] have reported that electron acceleration events in the auroral region occur more frequently in darkness (lower plasma density) than sunlight. *Morooka and Mukai* [2003] have also shown that the auroral electron acceleration region moves to lower altitudes during winter, when the density of auroral ambient plasma is lower.

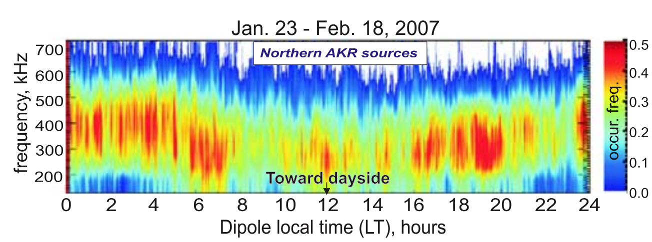

Figure 4. Normalized occurrence frequency and frequency range of the AKR emitted from the Northern hemispheres as functions of the local time of the axis of the magnetic dipole. Color indicates fraction of AKR occurrence frequency relative to all observations.

[16] Having in mind the ECM nature of the AKR, all these effects, i.e., dependences of the occurrence probability and position of auroral cavities, as well as the electron acceleration on solar illumination, one can expect periodic variations of the AKR occurrence frequency and the frequency range of the emission. These are clearly seen in the seasonal [*Green et al.*, 2004], solar cycle [*Kumamoto et al.*, 2003] and daily (Figure 4) variations of AKR spectra.

4. Conclusions

[17] The variations of 24 h of the AKR occurrence frequency, intensity, and the frequency range of the emission, as reported in this paper have been shown to be connected with the changing orientation of the rotating terrestrial magnetic dipole relative to the Sun. The effect is caused by the varying solar illumination of the auroral ionosphere, which in turn produces daily variations of the auroral ambient plasma density. The detected daily variations of the AKR occurrence frequency and the emission frequency range look very similar to those observed on the annual (seasonal variations) and solar activity cycle time scales. It is reasonable to expect a similar physical mechanism for all these types of the AKR variations.

[18] Variations of the local plasma density, caused by the varying solar illumination of the auroral ionosphere may result in the periodic variation of the position and altitudinal size of the AKR source cavity as well as in the periodic variations of the field aligned potential drop, which is important for the generation of the AKR via the ECM process. The details of these processes require further clarification and are subject for further study.

[19] Connected with the terrestrial rotation, daily variations of the AKR can, in principle, originate also from the periodic nodding of the emission cone [*Kaiser et al.*, 1978] or of the narrow beaming pattern of the AKR [*Mutel et al.*, 2008] relative to a fixed remote observer. In this case variations of the emission spectra should be registered when the spacecraft is located near the edge of the emission cone (i.e., only at certain parts of the spacecraft trajectory). However, our analysis shows that the same kind of 24 h variations of the AKR takes place during the whole time interval of observation, and these variations do not depend on the mutual position of the spacecraft and AKR sources.

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