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DE-1 OBSERVATIONS OF ORDINARY MODE AND EXTRAORDINARY MODE AURORAL KILOMETRIC RADIATION

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Abstract. Observations of auroral kilometric radiation (AKR) made with DE-1 indicate the presence of both ordinary and extraordinary wave modes. Although the two modes usually occur separately, they are sometimes observed together. When both modes are present, the ordinary-mode component tends to occur at lower frequencies and with lower amplitudes than those of the accompanying extraordinary-mode component. On the other hand, the local electron gyrofrequency is an absolute lower frequency cutoff for both modes. Ordinary mode intensities are proportional to extraordinary mode intensities but less by roughly a factor of 50. Extraordinary mode ray paths are generally confined to a cone within 50° of the source magnetic field direction and ordinary mode emissions are typically observed outside of this cone. This behavior suggests that both components are produced within the same source region but are then refracted differently as they escape.

Introduction

Auroral kilometric radiation (AKR) is a strong impulsive radio emission, with frequencies between 50 kHz and 600 kHz, which originates on nightside auroral field lines in association with discrete auroral arcs [Gurnett, 1974]. The high frequency emission in Figure 1 is a typical example. (The lower-frequency funnel-shaped emission is auroral hiss.) The AKR is presumably generated at or just above the local electron cyclotron frequency in the low-density auroral plasma cavity [Benson and Calvert, 1979; Calvert, 1981a,b]. A variety of mechanisms have been proposed as sources for the radiation (see review by Grabbe [1981]), but the observations have not yet allowed a definitive choice among them. One important distinction between the various theories is the mode of propagation which they predict for the emissions: Some theories favor the left-hand polarized ordinary mode (designated 'O'), while others favor the right-hand polarized extraordinary mode (X). Features consistent with the presence of each mode have been reported, but unambiguous measurements of the polarization were not available until the launch of the DE-1 satellite.

Most previous observations have suggested that AKR was X-mode radiation. Extraordinary-mode propagation gave, for instance, the best fit to observed angular distributions in the ray tracing studies of Green et al. [1977], and it was also consistent with the cutoff of AKR at the local electron gyrofrequency (f_g) noted by Gurnett and Green [1978]. Direct measurements of wave polarizations made by Voyagers 1 and 2 also supported the identification of AKR as X-mode radiation [Kaiser et al., 1978; see also Oya and Morioka, 1983], and the case for X-mode propagation of AKR was subsequently strengthened through study of AKR signatures on ISIS ionograms [Benson and Calvert, 1979; Calvert, 1981a]. More recently, Shawhan and Gurnett [1982] made direct determinations of AKR polarization using data from the DE-1 plasma wave receiver and found that the AKR in two test intervals was X-mode. Oya and Morioka [1983] have criticized Shawhan and Gurnett's results and have presented other data in which, by contrast, the AKR appears to be O-mode. Benson [1984] has also recently used propagation cutoffs to infer the occurrence of O-mode AKR. These conflicting results have generated considerable controversy, partly because of ambiguities in the interpretation of the measurements, but also because the observation of both modes is difficult to reconcile with theory.

We present here AKR polarization measurements made during 53 passes of the DE-1 satellite over the auroral region. The study uses the same technique as Shawhan and Gurnett [1982], but on a much larger data set. Our results confirm that the dominant component of auroral kilometric radation is in the extraordinary mode, but they show that a significant ordinary mode component is also often present.

Instrumentation and Method of Analysis

DE-1 is in a polar orbit with a 90° inclination, an apogee of 4.65 R_e geocentric and a perigee of 675 km altitude (details of the spacecraft and orbital characteristics are given by Hoffman et al. [1981]). The orbit precesses at a rate of 108° a year, and thus during the time span surveyed in this study (September 1981 to October 1983) the entire range of auroral altitudes which are accessible to DE-1 were sampled.

DE-1 includes a plasma wave instrument (PWI) which makes spectral and polarization measurements over a frequency range from 2 Hz to 400 kHz [Shawhan et al., 1981]. The instrument uses two dipole antennas for electric field measurements, one oriented along the spin axis (EZ) and the other rotating in the spin plane (EX). Magnetic wave components are measured using a rotating loop antenna. The spacecraft spins in a "cartwheel" mode with its spin axis perpendicular to the orbital plane. Since the magnetic field at high latitudes is nearly vertical, the spacecraft rotation sweeps the EX antenna approximately through the magnetic field direction twice each spin.

We used data from the Sweep Frequency Correlator of the DE-1 PWI, and we focused on measure-

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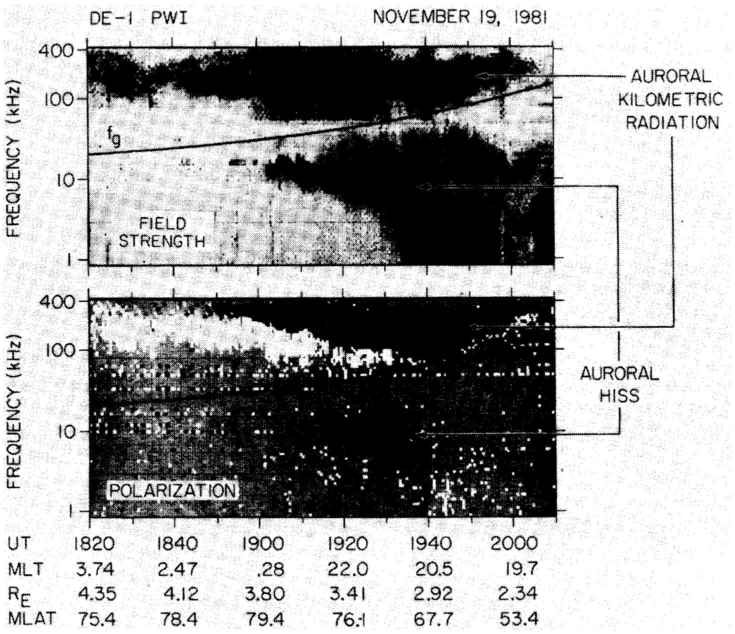

Fig. 1. DE-1 electric field (a) and polarization (b) spectrograms. Electric field intensities measured using the EX antenna are shown in the upper half of the figure where the darkest regions correspond to the most intense emissions. The associated wave polarizations are presented in the lower half of the figure where black represents waves which were right-hand polarized with respect to the nadir (magnetic field) direction and white, waves which were left-hand polarized. The thin, nearly horizontal line represents the local electron gyrofrequency.

ments taken when the correlator was connected to the two orthogonal electric antennas. The phase between signals from those two antennas varies as a function of the spin phase of the EX antenna in a manner which depends upon the ellipticity and direction of arrival of the waves, as well as upon the sense of polarization of the radiation. An unambiguous determination of the sense of the wave polarization can nonetheless be made when the instrument is operated in this mode.

On the other hand, when the correlator is connected to the EX antenna and the magnetic loop, an ambiguity exists and the same phase pattern can indicate either upward-going right-handed waves or downward-going left-handed waves. DE-1 is usually at high enough altitudes over the auroral region that one can safely assume, as we have, that the AKR reaching the satellite is travelling upwards. This assumption is supported by observations made in a third configuration of the instrument in which the correlator is connected to the EZ antenna and the magnetic loop, in which case the direction of the Poynting flux can be determined. Whenever AKR was observed while the instrument was in this third configuration, the Poynting flux was, as expected, directed upwards.

Phase information obtained for the emissions shown in the top half of Figure 1 is shown in the bottom half of the figure. Right-hand polarized emissions are coded black and left-handed radiation is coded white. As expected for whistler mode radiation, the auroral hiss is right-hand polarized. The AKR, on the other hand, appears in two modes, a lower-frequency left-handed component and a higher-frequency right-handed component. Similar simultaneous appearances of both modes occur in about 15% of DE AKR observations. Most observations show isolated X-mode radiation (70% of the cases), and in the remaining 15% of the cases isolated O-mode emissions are observed.

Amplitude Measurements

One characteristic of the emissions which was obvious even in initial scans of the data was that the extraordinary-mode AKR was generally stronger than the accompanying ordinary-mode component. We have quantified this result using measured electric field amplitudes. AKR is very impulsive, and several averaging steps were necessary in order to achieve reliable amplitude estimates. We began with spectra which had been averaged over three consecutive frequency sweeps (96 seconds). Amplitudes were then averaged over adjacent frequency steps, and measurements were averaged over each event. This procedure produced the data which are plotted in Figure 2, where the amplitude of the O-mode AKR is plotted as a function of the amplitude of the simultaneously occurring X-mode AKR. As can be seen, the ratio of the power in the two modes is consistently near 50. The two anomalous points (both from September 22, 1981), represent the only intervals we observed during which O-mode AKR was stronger than the simultaneously occurring X-mode AKR. The data from this pass were unremarkable in other aspects, except for an unusually high local plasma density (f_p/f_g 0.8).

Occurrence Patterns

The distributions of lower cutoff frequencies for the two modes were similar, even though, when both modes are present simultaneously, the O-mode almost generally occurs at lower frequencies. On

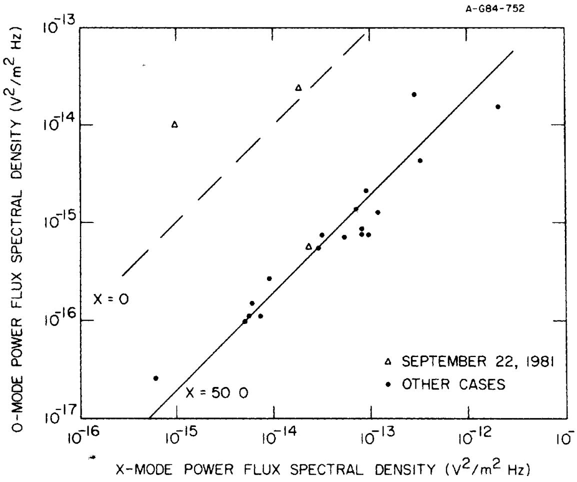

Fig. 2. Relative Amplitudes. The squares of the electric field spectral densities for simultaneously occurring ordinary and extraordinary-mode AKR are plotted against one another.

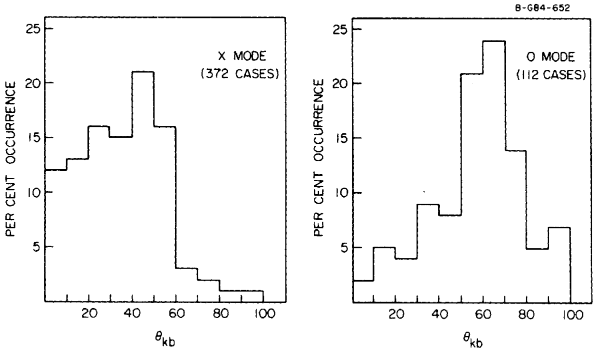

Fig. 4. Directions of propagation with respect to the source magnetic field line for X-mode and O-mode AKR. Measurements were made at five minute intervals along high latitude evening sector passes.

the other hand, the local electron gyrofrequency constitutes an absolute lower limit for both components: Although the low-frequency cutoffs often occur above that frequency, they never extend below it. Note that frequencies down to f_p should theoretically be accessible to O-mode waves.

This pattern suggests that the two modes are produced within the same source region but are refracted differently after they leave the source, as proposed by Hashimoto, [1984]. This difference in refraction, can easily account for the appearance of the O-mode at lower frequencies, as illustrated in Figure 3. Consider the pictured satellite: It would be outside the 100 kHz X-mode emission cone, inside the 200 kHz X-mode cone, and within the O-mode emission cone for both frequencies. However, since the X-mode emissions are generally stronger than the associated O-mode emissions, they should dominate whenever the two modes overlap, and thus the O-mode should be detectable only below the lowest frequency at which the X-mode can reach the satellite.

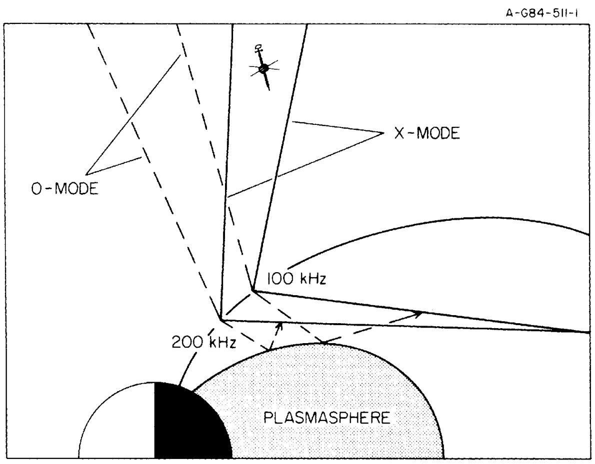

Fig. 3, Propagation characteristics of ordinary-mode (dashed lines) and extraordinary-mode (solid straight lines) auroral kilometric radiation. Emission cones for 100 and 200 kHz AKR are drawn assuming that the radiation is generated at the local electron gyrofrequency on the 70° invariant magnetic field line (solid curved line).

This hypothesis was tested by studying the directions of propagation for the two components. We first determined the lower frequency cutoffs of both X-mode and O-mode AKR at five minute intervals along high latitude evening sector orbits. We then assumed a source on the field line at 70° invariant magnetic latitude, and projected ray paths back along a straight line to the point on that field line where the local electron gyrofrequency equalled that of the observed AKR. (Although the actual ray paths are curved, ray tracing such as that by Hashimoto [1984] indicates that a straight-line approximation should be adequate here.) The angle between the ray path and the magnetic field direction was then measured. As shown in Figure 4, the expected pattern is observed: X-mode AKR is generally restricted to angles less than about 50°, whereas O-mode radiation is typically observed at larger angles.

Conclusions

Our most important observation, which is based on the DE polarization measurements, is that the auroral kilometric radiation propagates in both the X-mode and the O-mode. When the two components occur simultaneously their amplitudes are well correlated, and the X-mode is generally stronger by a factor of about 50. Furthermore the patterns in the occurrence of the two components can easily be explained if the two modes are produced within the same source region, but refracted differently as they exit.

The dominance of the X-mode supports the picture of AKR as being driven by cyclotron resonance with an electron loss-cone [Wu and Lee, 1979], and at the same time, it effectively rules out Z-mode to O-mode coupling [Benson, 1975; Jones, 1977] as a major AKR source. On the other hand, since the ratio of the O-mode to X-mode amplitudes is higher than can easily be accounted for by an O-mode maser [Melrose et al., 1984; see also Lee et al., 1980], the origin of the O-mode probably requires an alternative explanation. The correlation between the two components suggests to us that the O-mode might be generated as a by-product of an initially-pure X-mode oscillation, possibly by polarization mismatch at the source boundary [Calvert, 1982], or by mode splitting at the walls of the auroral plasma cavity.

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