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SATELLITE INTERFEROMETRIC MEASUREMENTS OF AURORAL KILOMETRIC RADIATION

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Abstract. The first satellite interferometric measurements of auroral kilometric radiation (AKR) were performed by cross-correlating the waveforms detected by the ISEE 1 and ISEE 2 spacecraft. Such correlations were measured at 125 and 250 kHz for projected baselines perpendicular to the source direction ranging from 20 to 3868 km. High correlations were found for all projected baselines, with little or no tendency to decrease even for the longest baselines. These results must be interpreted differently for incoherent and coherent radiation. For incoherent radiation, the correlation as a function of the baseline is the Fourier transform of the source brightness distribution, and this implies an average source region diameter for all of the bursts analyzed of less than about 10 km. For such small source diameters, the required growth rates are too large to be explained by existing incoherent theories, strongly indicating that the radiation must be coherent. For coherent radiation, an upper limit to the source region diameter can be inferred instead from the angular width of the radiation pattern. The close similarity of the spectra at the longest baselines indicates that the angular width of the radiation pattern must be at least 2.5°, implying that the diameter of the source must be less than about 20 km. At present, the proposed closed-loop radio lasing model is the only known mechanism for providing sources this small.

Introduction

The purpose of this paper is to present the first satellite interferometric measurements of auroral kilometric radiation (AKR). AKR is the most intense electromagnetic radiation generated in the earth's magnetosphere, occurring in the frequency range from 50 to 700 kHz with an average radiated power of approximately 10^7 watts [Gallagher and Gurnett, 1979]. Gurnett [1974] showed that AKR is associated with discrete auroral arcs. Polarization and direction-finding measurements [Kaiser et al., 1978; Shawhan and Gurnett, 1982; Mellott et al., 1984; Kurth et al., 1975; Calvert, 1985] have shown that the radiation is generated along auroral field lines at frequencies near the local electron cyclotron frequency mainly in the right-hand polarized extraordinary mode. The spectrum has clearly defined upper and lower cutoff frequencies which fluctuate over a wide range on a time scale of tens of minutes. High resolution measurements [Gurnett et al., 1979] show that the spectrum consists of numerous narrowband bursts with bandwidths sometimes less than 100 Hz.

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Although a variety of mechanisms have been proposed for the generation of AKR, only the Doppler-shifted cyclotron resonance instability [Melrose, 1976; Wu and Lee, 1979] has gained general acceptance. Omidi and Gurnett [1984] computed the path integrated growth rates for this mechanism and concluded that even with electron velocity distributions much steeper than those which are observed, a 70 km amplification length is required to explain the observed AKR intensity. Recently, Calvert [1982] has proposed an AKR generation model involving wave feedback very similar to an optical laser, with local density irregularities serving as mirrors. The laser model predicts discrete bursts of nearly monochromatic radiation, very similar to those which are observed. The laser model also requires less wave growth than amplification alone, since the only requirement is that the net gain around the feedback path be greater than one.

The interferometric measurements presented in this study are from the ISEE 1 and 2 spacecraft which are in nearly identical eccentric earth orbits with apogees at geocentric radial distances of about 23.7 R_E. With these orbits the spacecraft can detect AKR emissions from the auroral region as illustrated in Figure 1. ISEE 1 and 2 have identical wideband receivers that can be tuned to a variety of frequencies from 31 kHz to 2 MHz. The bandwidth of the receivers is 10 kHz. The electric field waveforms detected by the two spacecraft are converted to a frequency range of 0.65 to 10.0 kHz for transmission to the ground where they are recorded on analog tapes at the NASA telemetry stations. The waveforms can then be cross-correlated to perform interferometric measurements. See Shawhan [1979] for a description of the wideband receivers and interferometry system.

Long Baseline Interferometry

For simplicity and ease of data processing, the cross-correlations were performed with a one-bit correlator. For such a correlator, the actual correlation must be computed using the equation [Weinreb, 1963],

$$\rho_m = \sin(\frac{\pi}{2}C_o) \tag{1}$$

where C_o is the correlator output. In the presence of receiver and telemetry noise, the correlation must also be corrected for the signal-to-noise ratio according to the relation

$$\rho = [\langle S_1^2/V_1^2\rangle\langle S_2^2/V_2^2\rangle]^{-1/2}\rho_m \tag{2}$$

where S_1 and S_2 are the signal voltages, V_1 and V_2 are the signal-plus-noise voltages, ρ_m is the correlation computed from Equation 1, and the

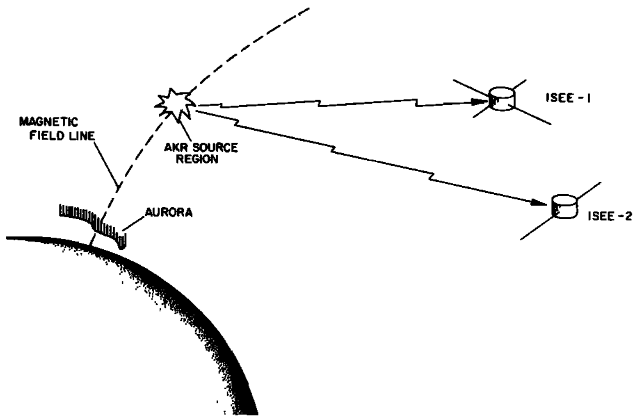

Fig. 1. From nearly identical orbits, both ISEE 1 and ISEE 2 can detect AKR emissions from the auroral region. From the cross-correlation of the detected signals and the observed radiation pattern, an upper limit to the apparent source region diameter can be determined.

angle brackets represent time averages over the periods of measurement.

Correlation measurements must be interpreted differently for incoherent and coherent sources. For an incoherent source, the radiation emitted from different elements in the source region is uncorrelated, whereas for a coherent source the radiation emitted from different elements in the source region is correlated. For an incoherent source, it is customary to interpret the interferometer output as the Fourier component of the two-dimensional source region brightness. The correlation for a source region with brightness distribution S(x,y) is

$$\rho(u,v) = \iint S(x,y)e^{-i(2\pi/\lambda)(ux+vy)}dxdy \qquad (3)$$

where u and v are the x and y projections of the baseline between the two spacecraft, and x and y are the angular source-region coordinates. Since ISEE 1 and 2 can only measure the correlation at one baseline for each individual event, the source region brightness distribution must be modeled, and for this we have used a Gaussian brightness model. For a circular two-dimensional Gaussian brightness distribution the correlation can be shown to be

$$\rho = e^{-(\pi b\alpha/2\lambda)^2} \qquad (4)$$

where α is the angular width of the source region, b is the projected baseline of the interferometer, and λ is the wavelength. Equation 4 shows that for an incoherent source the correlation rapidly drops to zero if the angular width of the source exceeds λ/b.

For coherent radiation, the radiation emitted from different elements in the source region is correlated, and the traditional method of interferometry analysis (Equation 4) cannot be used. However, the apparent width of the radiation pattern may be used to estimate an upper limit to the source diameter. The angular width of the radiation pattern is limited by diffraction and is approximately λ/d, where d is the diameter of the source. For the specific case of a Gaussian brightness distribution, the source diameter is given by

$$d = \frac{\lambda}{\pi \sin(\theta/2)} \qquad (5)$$

where θ is the angular width between the 1/e power points of the radiation pattern.

Results

Correlations have been measured at projected baselines ranging from 20 to 3868 km at frequencies of 125 and 250 kHz. Most of the measurements were made on the nightside of the earth at radial distances greater than 10 R_E. A typical example of the correlations observed is shown in Figure 2. The top two panels show the spectra of a series of AKR bursts received by ISEE 1 and 2 and the bottom panel shows the measured cross-correlation. The sinusoidal modulation of the correlation is caused by the difference in frequency of the local oscillators in the two receivers as well as other slow variations in the spacecraft-source geometry. The amplitude of the sine wave gives the measured correlation ρ_m. The correlation for this event, after correcting for the signal-to-noise ratio is $\rho = 0.81$. If the source is assumed to be incoherent with a Gaussian brightness distribution, the source size can be computed from Equation 4. With a baseline length of b = 3260 km, the angular size of the source turns out to be $\alpha = 1.08 \times 10^{-4}$ rad. Using the source-to-spacecraft distance for this event, which was about 13.4 R_E, the source diameter is estimated to be about 9 km.

Correlation measurements similar to that shown in Figure 2 have been performed for 52 events extending over a large range of baselines. Figure 3 shows a plot of the correlation as a function of the projected baseline for all of the bursts analyzed. Each point in Figure 3 represents the average correlation measured for about

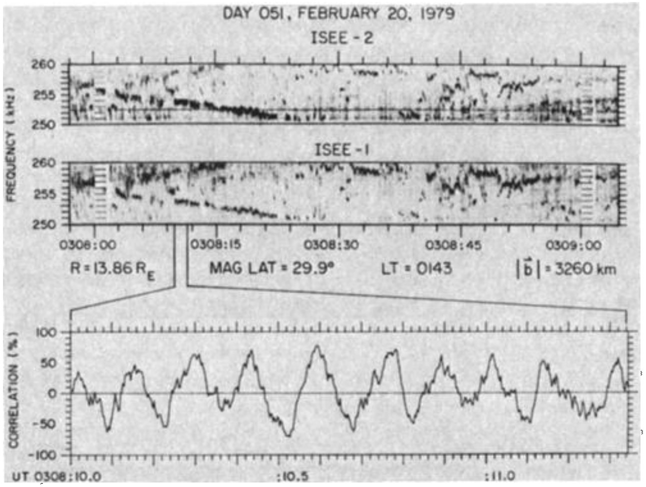

Fig. 2. The top two panels show the spectra of a series of AKR bursts observed by ISEE 1 and ISEE 2. The bottom panel shows the correlation for one of these bursts. The sinusoidal modulation is caused primarily by the difference in the two local oscillator frequencies.

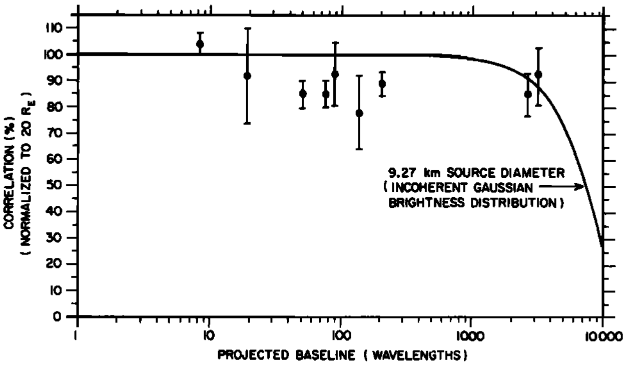

Fig. 3. The best fit of the correlation amplitude as a function of baseline to a Gaussian brightness distribution implies a source diameter of less than 9.27 km for incoherent sources. The source region diameter is determined primarily by the correlation at the longest baseline.

five separate events at each baseline. Since the angular size of the source depends upon the source-spacecraft distance, these correlations have been normalized to a fixed source distance of 20 R_E. This plot shows that the correlation is essentially constant and slightly less than 100% out to the longest baselines which were available. The best fit of Equation 4 through the available points gives a source diameter of 9.27 km. However, since the observed correlations remained high even for the longest baselines, this constitutes only an upper limit for the apparent source size, and it could actually be much smaller. These measurements show that if the source is incoherent then the source region must be very small, less than about 10 km.

If the source is assumed to have a coherent Gaussian-shaped radiation pattern, the source diameter can be computed from Equation (5). Because nearly identical spectra are observed by both spacecraft at the largest available baseline separations, again only an upper limit to the source diameter can be determined. For the longest baseline (~ 3868 km) the angular width of the radiation pattern at apogee must have been at least 2.5°. The corresponding source diameter then must therefore be no larger than about 20 km at 250 kHz.

Discussion

A successful theory for the generation of AKR must account for the high correlations obtained from these interferometric measurements. Two models for the generation of AKR will be examined to determine if high correlations can be explained. The first model assumes that AKR is simply amplified galactic background radiation, as assumed by Omidi and Gurnett [1982] and tacitly assumed by most others [Melrose, 1976; Wu and Lee, 1979; etc.]. For large source diameters, the solid angle of the amplified galactic radiation received by each spacecraft is the same as the angular size of the source region as viewed from the spacecraft. For small source diameters, comparable to the wavelength of the radiation, diffraction effects spread the waves over a wider angle and permit a larger solid angle of the amplified galactic background noise to be received by the two spacecraft. The cross-correlation between the signals detected by the spacecraft is given by the ratio $\Delta\Omega/\Omega$, where $\Delta\Omega$ is the overlap in the solid angle of the amplified galactic background noise viewed by the two spacecraft and Ω is the total solid angle. For angular spacecraft separations greater than the angular size of the source, as was usually the case for ISEE 1 and 2, the geometric solid angles never overlap, as illustrated in the top panel of Figure 4, and the correlation should always have been zero. However, to account for the high observed correlations, the actual solid angles of the amplified galactic background radiation must overlap almost completely. This requires that the source region diameters must be only a few kilometers so that diffraction effects can produce the required overlap, as illustrated in the bottom panel of Figure 4. For such small source diameters very high growth rates (perhaps exceeding 10 dB per kilometer) are required to produce the observed intensities. Such high growth rates are much greater than those estimated for the cyclotron instability [Wu and Lee, 1979; Melrose, 1976; Omidi and Gurnett, 1982]. This result strongly implies that the radiation must be coherent.

Calvert [1982] has proposed wave amplification

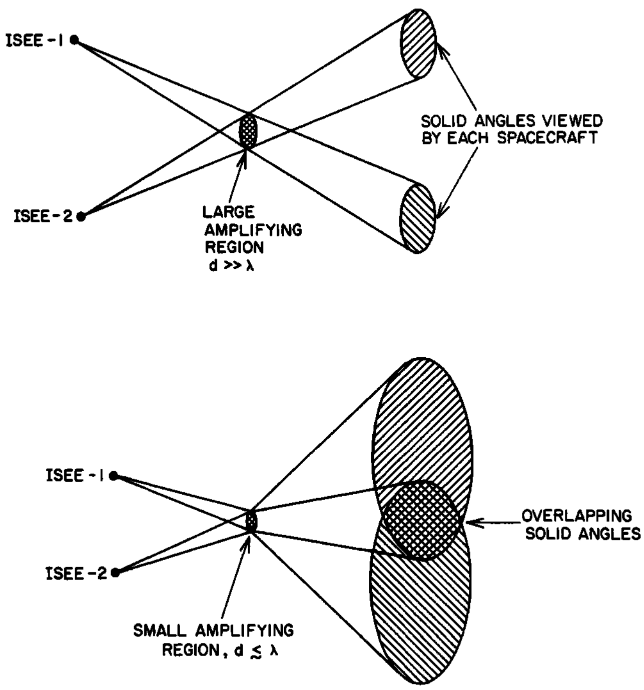

Fig. 4. The top panel illustrates that for angular spacecraft separations greater than the angular source size, the solid angles of amplified galactic background radiation illuminating each spacecraft would not overlap and the detected signals should be uncorrelated. The bottom panel illustrates that for source region diameters comparable to the wavelength of the radiation, diffraction effects could produce solid angles which overlap and produce a correlation (although such small sources would seem to require unrealistically high growth rates).

with feedback to explain the observed intensity and discrete structure of the AKR. This mechanism also has the merit of producing a coherent source with an angular size in agreement with these observations. According to this theory, the apparent laser length can be determined from the observed spacings of the discrete AKR components and was found to be about 25 km. By straightforward laser theory [see Verdeyen, 1981], this implies an exit spot width of about 5 km and a beamwidth of about 10°, entirely consistent with the new interferometric observations.

Conclusions

For a source emitting incoherent radiation, the correlation measurements imply a source region diameter of less than about 10 km. For coherent radiation, the radiation pattern must have an angular width of at least 2.5°, and hence a source region diameter of less than about 20 km. The high correlations observed are totally inconsistent with simple amplification of galactic background radiation (unless the amplifying regions are smaller than expected and the growth rates are substantially larger than predicted), but they are consistent with the proposed coherent laser mechanism of Calvert [1982].

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