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Accelerated Electrons as the Source of Auroral Kilometric Radiation

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Abstract. Data from the Fast Auroral Snapshot Explorer (FAST) have confirmed that Auroral Kilometric Radiation (AKR) is generated by the accelerated electrons in the auroral density cavity. FAST observations of the electron distribution within the AKR source region show a characteristic horse-shoe distribution expected from the parallel electric field acceleration and magnetic mirroring of the electrons, the precipitating portion of which constitute the auroral electrons. Within the density cavity it is likely that the hot electrons carry most, if not all, of the plasma density. The AKR wave characteristics within the source region show that the lower frequency cut-off is below the cold electron gyro-frequency, and near the cut-off, the wave electric and magnetic field polarization is consistent with perpendicularly propagating X-mode waves. Taken together these observations are consistent with the cyclotron maser instability, but with the inclusion of relativistic effects in the wave dispersion, as well as the resonance condition. This allows the accelerated electrons to generate AKR, and further the replenishment of the distribution by the parallel electric field ensures that AKR can be generated over a large altitude range on auroral zone field lines

1. Introduction

Auroral Kilometric Radiation (AKR) is an intense radio emission generated by the earth's auroral zone. First observed as ~ 1 MHz extra-terrestrial noise by Beneditkov et al. (1965), the emission properties were characterized in the mid 1970s and early 1980s, mainly by D. A. Gurnett and colleagues. Gurnett (1974) showed that the peak power emitted in AKR was ≈ 10^9 W, about 1% of the total power deposited into the ionosphere as auroral particle precipitation. Through direction finding techniques Kurth et al. (1975) found that AKR was generated on auroral zone field lines. This was confirmed by lunar occultation experiments (Alexander and Kaiser, 1976). Mellott et al. (1984) showed that AKR was mainly R-X mode radiation, with a weak L-O mode component.

The preferred generation mechanism for R-X mode radiation is the cyclotron maser instability Wu and Lee (1979). This instability depends on the relativistic electron gyro-resonance condition:

$$\omega - k_\parallel v_\parallel = \Omega_e \sqrt{1 - v^2/c^2} \tag{1}$$

where ω is the wave frequency, $k_\parallel$ is the wave vector parallel to the ambient magnetic field, $v_\parallel$ is the parallel velocity of the resonant particles, Ω_e is the cold (non-relativistic) electron gyro-frequency, v is the resonant particle speed, and c is the speed of light. This equation corresponds to an ellipse in velocity space, which ensures that high energy electrons in the tail of the distribution cannot damp the wave.

Figure 1 shows an electron distribution function acquired by the Fast Auroral Snapshot Explorer (FAST) within the auroral density cavity (Calvert, 1981), where AKR is generated. The black curves also mark the loss-cone hyperbola and acceleration ellipse (Chui and Schulz, 1978) associated with a large scale parallel electric field on an auroral-zone field line. In a cold-plasma the R-X mode cut-off lies above the cold-electron gyro-frequency, and the resonance condition given by Eq. (1) therefore requires $k_\parallel \neq 0$. This moves the resonance ellipse away from the origin of Fig. 1. Indeed it can be shown that only for $\omega < \Omega_e$ will the ellipse enclose the origin. Hence the loss-cone, which is the feature in the electron distribution to the left of Fig. 1, is the primary free energy source for R-X mode waves in a cold plasma.

The plasma within the auroral density cavity is not cold, and several workers (Wu et al. 1982; Le Quéau et al., 1984;

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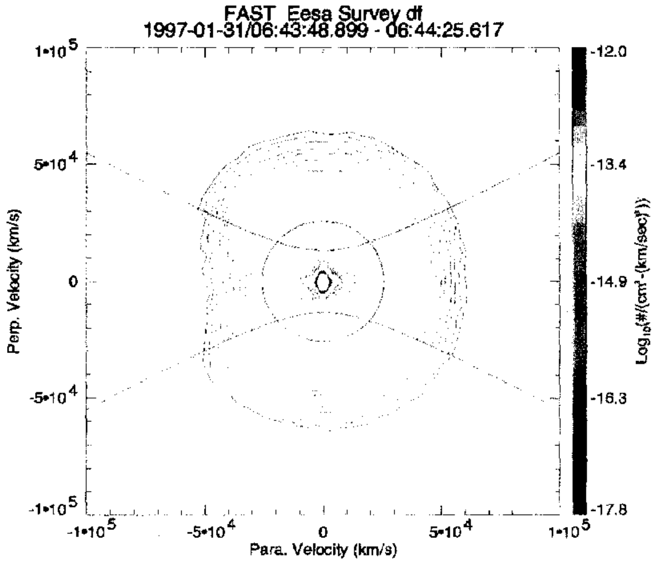

Fig. 1. Electron phase distribution observed within the auroral acceleration region by the FAST spacecraft. Contours of phase density, using a logarithmic scale, are plotted as a function of parallel and perpendicular velocity, with downward electrons corresponding to positive parallel velocities.

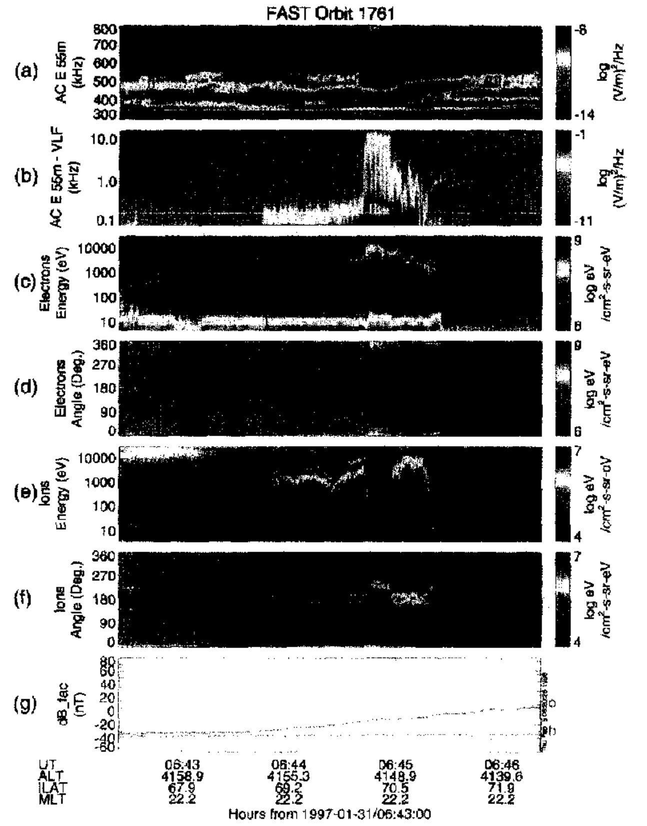

Fig. 2. Particle and field measurements acquired by FAST, including data from the auroral acceleration region (from Strangeway et al., 1998).

Pritchett, 1984; Pritchett and Strangeway, 1985; Strangeway, 1985; Strangeway, 1986) have shown that the R-X mode cut-off can drop below Ω_e if relativistic effects are also included in the dispersion relation. In particular Pritchett and Strangeway (1985) demonstrated through dispersion analysis and simulations that distributions similar to that shown in Fig. 1, which we refer to as a horse-shoe distribution, can generate AKR, and furthermore these waves are generated at large angles to the field. In this case the primary free energy for the waves is the perpendicular velocity gradient associated with the electrons lying outside of the acceleration ellipse, rather than the loss cone.

Strangeway (1985, 1986) analyzed in detail the appropriateness of the relativistic dispersion relation for auroral electron distributions. He showed that the relativistic modifications caused by a distributions such as that shown in Fig. 1 were appropriate, but he also found that any appreciable cold (or cool) plasma had the effect of introducing a stop-band between the unstable branch and the freely propagating R-X mode. At that time it was not known how much cold plasma, if any, was present within the auroral density cavity. Recent results from FAST indicate that this concern was unfounded, and we will review here the evidence for direct generation of R-X mode AKR by horse-shoe distributions.

The outline of the paper is as follows. In the next section we will briefly review the plasma characteristics of the AKR source region, with particular emphasis on the electron distribution, and plasma density. We discuss the wave characteristics, i.e., lower frequency cut-off, polarization, and bandwidth in the third section. Our conclusions are that the accelerated and mirroring electrons are the primary free energy source for AKR, and that this free energy source can be continually replenished by the parallel electric field in the auroral acceleration region.

2. AKR Source Region: Plasma Characteristics

Figure 2, from Strangeway et al. (1998), shows FAST particle and field observations for one passage of the spacecraft through the auroral acceleration region. Panel a shows AKR spectra, with the white line giving the local cold electron gyro-frequency. Panel b gives VLF data. Panels c and d show electron energy and pitch angle spectra, while panels e and f give ion spectra. The bottom panel, g, shows the deviations of the magnetic field from the model field (IGRF). The primary region of electron precipitation, from 06:43:15 to 06:45:20, is associated with an upward field-aligned current.

The interval at the center plot is characterized by an intense narrow upward ion beam of a few keV energy. At the same time there is a clear minimum in the electron energy flux below 1 keV. The presence of the ion beam, together with the deep minimum in the electron flux, indicates that the spacecraft is within the auroral

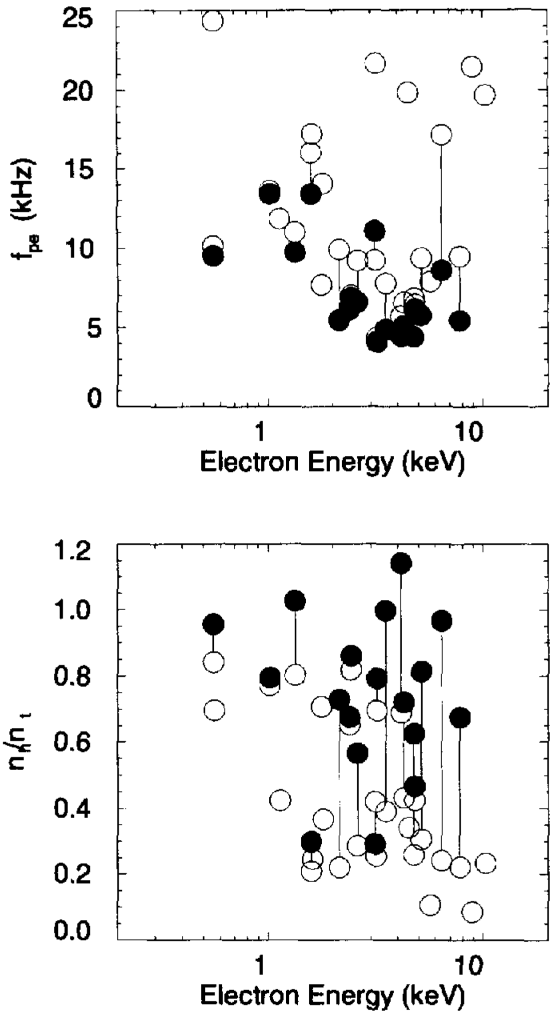

Fig. 3. Comparison of inferred plasma densities and hot electron densities. The top panel shows the plasma frequencies deduced from VLF data, while the bottom panel shows the density comparison (after Strangeway et al., 1998).

acceleration region. Just before 06:45 UT the ion beam disappears, to be replaced by an ion conic, and there is an increased flux of lower energy electrons within the loss-cone. These electrons are back-scattered secondary electrons, which are excluded from the acceleration region by the parallel electric field. At this time the accelerating potential is entirely above the spacecraft. For reference, the phase density plot in Fig. 1 was calculated from the average of the electron fluxes observed from 06:43:48 to 06:44:26 in Fig. 2, when the spacecraft was within the acceleration region and the fluxes were relatively constant.

Inside the acceleration region the VLF data show clear evidence of whistler-mode waves propagating on the resonance cone. This is most apparent for the interval just prior to the ion conic, where the spin modulation of the VLF signal shows a clear dependence on frequency. Because the VLF data have not been despun, any linearly polarized signal will have a minimum in intensity twice per

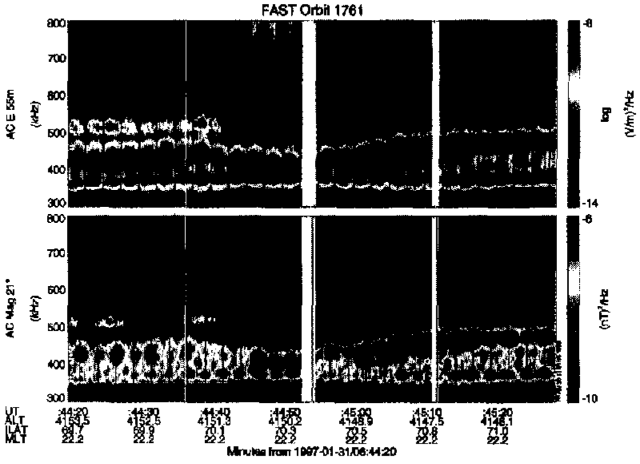

Fig. 4. Example of wave electric and magnetic field polarization in the AKR source region.

spin. That the phase at which the minimum occurs changes as a function of frequency has been shown by Strangeway et al. (1998) to be consistent with waves on the whistler-mode resonance cone, and these authors used this dependence to determine the electron plasma frequency. For this orbit, the plasma frequency was found to be 4 kHz within the acceleration region, corresponding to a plasma density of ≈ 0.25 cm^{-3}.

Strangeway et al. (1998) analyzed VLF data from some 28 density cavities, as shown in Fig. 3. The top panel shows the inferred plasma frequency, with the open and closed signals indicating plasma frequencies determined by two different approaches, as discussed by Strangeway et al. (1998). Because the closed symbols require a signal which does not vary significantly over multiples of the spin-period (apart from the spin modulation itself), these data are probably more robust. The bottom panel compares the electron number density calculated by integrating the fluxes above 100 eV (n_h) with that obtained from the VLF data (n_t). It is apparent that the hot electrons account for most, if not all, of the plasma density within the acceleration region.

3. AKR Source Region: Wave Characteristics

If the hot electrons are the dominant species, then it is possible for the R-X mode cut-off to move below the cold electron gyro-frequency. Ergun et al. (1998), using high temporal resolution burst mode data as well as data from the Plasma Wave Tracker (PWT) on board FAST, have shown that the AKR cut-off is at the relativistic gyro-frequency within the acceleration region, rather than the cold electron gyro-frequency. The relativistic electron mass is calculated using the average electron energy. This gives a typical downward shift of the order 1% (~ 3 kHz), which is much larger than any uncertainty in the total field (~ 0.1%).

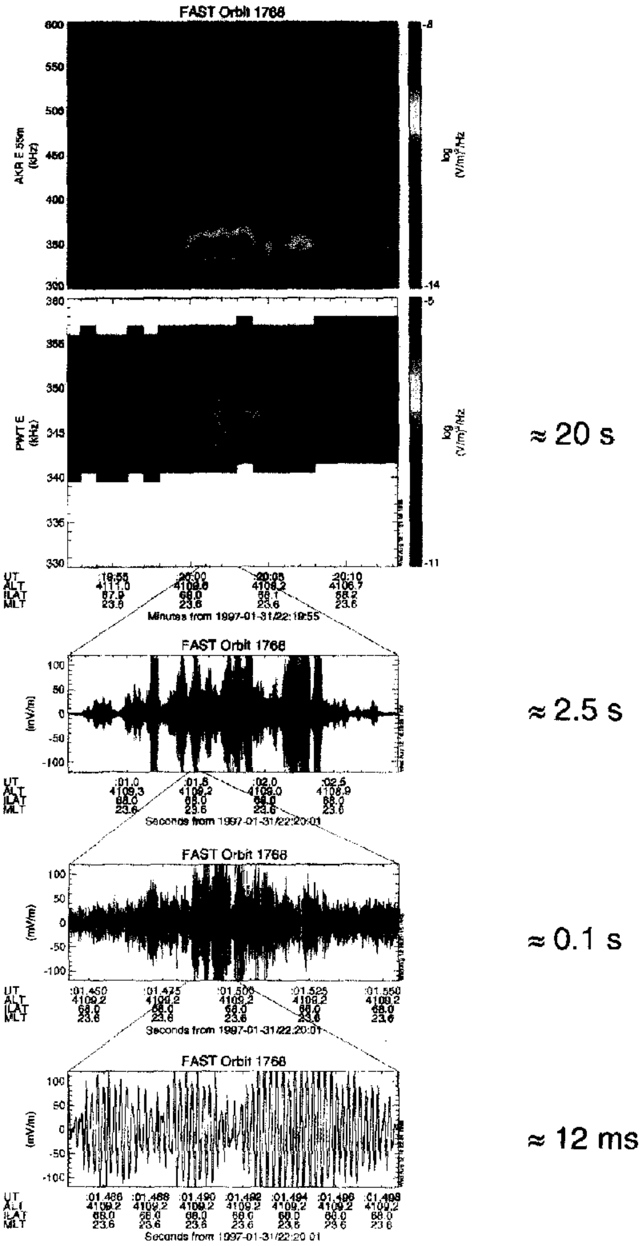

Fig. 5. Wave form acquired by the FAST Plasma Wave Tracker (PWT) inside the AKR source region. The top panel shows data from the onboard frequency analyzers, with the next panel showing FFTs of the PWT wave form, with 16 kHz Nyquist frequency. The bottom three panels show successively smaller intervals of wave form data. Note that only a few wave oscillations are seen in the wave form because of the mixing down to baseband by the PWT. High resolution burst-mode data display similar packet-like structure.

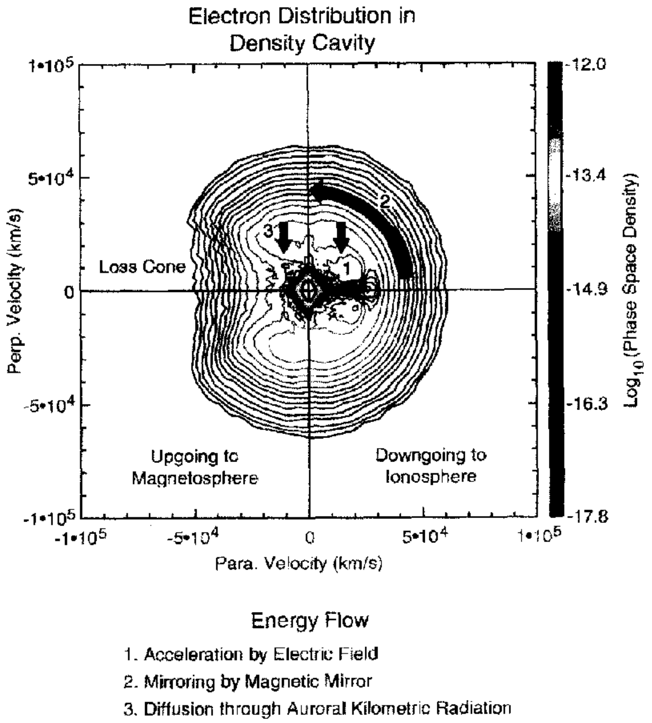

Fig. 6. Cartoon showing the energy flow within the AKR source region.

In addition to the frequency range of AKR, Ergun et al. (1998) also determined the wave polarization, and found that the wave electric field was within ~ 3 degrees of perpendicular to the ambient field. This is consistent with a perpendicularly propagating X-mode wave, but a parallel propagating R-mode wave would also have a perpendicular wave electric field. The two modes can be distinguished by the wave magnetic field, and Fig. 4 shows wave spectra from the 55-m wire boom (top panel) and search coil (bottom panel). The data have not been despun, and the vertical lines indicate when each antenna is closest to the ambient magnetic field. At the low frequency cut-off the wave electric field is clearly polarized perpendicularly to the ambient magnetic field, whereas the wave magnetic field is polarized parallel to the ambient field. This is consistent with a perpendicularly propagating X-mode wave.

Ergun et al. (1998) also investigated the bandwidth of AKR, and reported bandwidths as low as 100 Hz. Baumback and Calvert (1987), on the other hand, have reported bandwidths as low as 5 Hz. Because bandwidth can be interpreted differently, depending on the analysis method used, we will instead present an example of the wave form observed within the AKR source region, as shown in Fig. 5. The bottom three panels show shorter and shorter intervals of data. The envelope in the middle panel is caused by spin modulation, but the packet-like structure is inherent to the data at each resolution. The shortest packets are a few ms long. This would imply a "bandwidth" of a few 100 Hz. We suggest that any comparisons between theory and data would best be performed in the time domain so as to avoid any ambiguity in the definition of bandwidth.

Pritchett et al. (1999) have used numerical simulations and analytical theory to investigate the bandwidth of AKR, and have found that the intrinsic bandwidth given by the linear growth rate is insufficient to explain a bandwidth of the order 100 Hz. They suggest that temporal or spatial nonuniformities may be required.

4. Conclusions

The FAST data have demonstrated clearly that the AKR source region has very low plasma densities, and further that the hot electrons are the dominant contributor to the density. Moreover, the observed electron distribution function is similar to that used by Pritchett and Strangeway (1985) in their simulations, a point also made by Delory et al (1998). The low frequency cut-off is often below the cold electron gyro-frequency, and the wave polarization near the cut-off is consistent with perpendicularly propagating X-mode waves. These results are all consistent with the hypothesis put forward by Pritchett and Strangeway (1985) that the accelerated and mirroring electrons are the free energy source for AKR, rather than the loss-cone. For convenience we refer to this type of distribution as a horse-shoe distribution.

Because the horse-shoe distribution is caused by the combination of downward acceleration in a large-scale parallel electric field and the magnetic mirroring of the accelerated particles, free energy is constantly being resupplied to the electron distribution function. Thus we can envisage the flow of energy as shown in Fig. 6. Parallel energy gained from the electric field (step 1) is converted to perpendicular energy by the mirror force (step 2). This energy is then available for the generation of AKR, resulting in diffusion to lower perpendicular velocities (step 3). As also pointed out by Louarn et al. (1990), on the basis of Viking observations, this process can operate throughout the acceleration region, explaining why AKR covers such a broad range in frequencies. Indeed, provided that phase space accessibility is maintained along the field lines (Chiu and Schulz, 1978), the process acts in a continuous manner along the auroral field lines. Furthermore this replenishment of free energy does not apply to a loss-cone driven instability. Once the free energy has been removed from the loss-cone, there is no process to put free-energy back into the distribution. This may be one of the more compelling reasons for considering the horse-shoe distribution to be the source of AKR.

In conclusion the FAST spacecraft data provide conclusive evidence that it is the accelerated and mirroring electrons which generate AKR, rather than the loss-cone. A further consequence of this observation is that parallel electric fields may be an important source of free energy for generating radio waves, not just at the earth, but also at other planets, such as Jupiter, or even astrophysical radio sources, (Ergun et al., 2000).

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