

THE AKR OF THE EARTH: FROM STUDIES INSIDE THE SOURCES TO DISTANT OBSERVATIONS AND REMOTE SENSING

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Abstract

One follows the path of the Auroral Kilometric Radiation (AKR) from the inside of the sources up to remote observation points. Wave and plasma processes related to the AKR that are encountered along this travel are described and discussed. This paper is organized as a review of the observations of the AKR with emphasis on the ones recently obtained with the experiments of the Viking satellite that crossed about fifty sources.

Inside the sources, the AKR appears to be generated at a frequency very close to the electron gyrofrequency, sometimes below. Direct observations of the wave electric field show that it lies in a plane quasi perpendicular to the geomagnetic field. Ion and electron observations show that the AKR is generated inside field-aligned acceleration structures. The observation of up-flowing ion beams inside the sources is indicative of a keV field-aligned potential drop from the bottom of the acceleration region to the altitude of the satellite. This can account for the removal of the thermal electrons from these regions. In the velocity space, electron measurements give evidence of an enhancement of particles trapped between the magnetic mirror point and the point where they are reflected by the parallel 'electrostatic' field. This 'bump' in the velocity space is an efficient free energy source for the Cyclotron Maser Instability (CMI). In the AKR source regions, the plasma density is extremely low, and the plasma is strongly magnetized. Furthermore, the analysis of the plasma density inside a large number of sources compared to the plasma density in non-emitting regions shows the existence of a threshold for the plasma density above which the AKR is not generated.

At the edges of the sources, down-going electron beams testify the presence of acceleration regions above the satellite. Related to these beams, intense short duration electrostatic bursts are observed. The edges of the source regions present sharp density gradients perpendicular to the geomagnetic field. The role that these gradients play for the escape or the trapping of the energy is discussed in the light of analytical and simulation studies. The possibility of a mode conversion due to these gradients is discussed.

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1 Introduction

As it is the case for all of the explored magnetized planets, the Earth is an intense radio source. The most intense component of the terrestrial radio emissions originates above the auroral region and is called Auroral Kilometric Radiation (AKR hereafter). Because of its frequency range (50–700 kHz) well below the cutoff frequency of the ionosphere, it is reflected upward by the ionospheric layers; hence spacecraft observations are needed.

From the astrophysical point of view, the interest of AKR studies is to provide observations in order to constrain the planetary radio emission mechanisms.

Discovered in 1965 by the USSR Elektron 2 satellite [Benediktov et al., 1965], most of the observations were made far from the sources. These observations have shown that the sources are located in the night sector, at about 70° invariant latitude, between 1.5 and 3 R_E (Earth radii) geocentric distance. The waves propagate mainly in the R–X mode [Green et al., 1977; Kaiser et al., 1978; Shawhan and Gurnett, 1982] but weaker L–O and Z modes have been observed [Oya and Morioka, 1983; Mellot et al., 1984, 1985, 1986; Benson, 1985; Benson and Wong, 1987; de Feraudy et al., 1987; Calvert and Hashimoto, 1990]. The emissions occur during periods of strong magnetic disturbances [Benediktov et al., 1968] and are associated to the electron precipitations which give rise to the discrete aurora [Gurnett, 1974; Benson and Akasofu, 1984].

Observations in the source region have given evidence of low plasma densities [Benson and Calvert, 1979; Benson and Akasofu, 1984] which have been interpreted as a large-scale single plasma cavity [Calvert, 1981a; Persoon et al., 1988]. Such low densities have been measured by the S3–3 satellite but only during the crossing of acceleration structures [Temerin et al., 1981; Mozer and Temerin, 1983].

In this paper, we discuss the observations and the theories of AKR in the light of the new Viking results which show that the sources are indeed small-scale structures ($< 1^\circ$ invariant latitude wide), where specific wave and plasma properties were observed by the means of several experiments (wave antenna, particle detectors). These new observations of the AKR sources lead to reconsider several previous results (direct generation of O and Z mode, cold plasma dominant in the generation region, free energy source, significance of the angle of emission, ...) but also make the possibility of relating wave observations to parameters of large scale magnetospheric structures, as needed in radioastronomy, very difficult.

2 Study of the structure of the AKR sources

2.1 Evidence of small scale structures

2.1.1 Localization

The attempts for the identification of AKR sources has progressively shown that small-scale structures are concerned. We briefly review these investigations.

The basic method used to localize the source from remote observation of the emission is to proceed towards the source by ray tracing. In the light of the earliest observations very far from the Earth, there was clear evidence that AKR is generated at high latitudes in both hemispheres [Benediktov et al., 1965, 1968; Dunckel et al., 1970]. A step forward was made with direction finding techniques: The signal is spin modulated, the phase of the spin modulation is used to derive the direction of the wave electric field plane from which the arrival direction of the rays is inferred. Such studies have led to delimit the extension of the source region in altitude [Gurnett, 1974], latitude and local time [Kurth et al., 1975; Kaiser and Stone, 1975]. Nevertheless, the concept of one single source region in each hemisphere was retained. The localization of the sources by lunar occultation of the emission received by the RAE-2 satellite was consistent with a generation inside a narrow range of auroral field lines [Kaiser and Alexander, 1976].

Further observations showed that the instantaneous spectrum of the AKR is constituted by a multitude of narrow-banded peaks [Gurnett et al., 1979; Gurnett and Anderson, 1981; Morioka et al., 1981]. The lowest bandwidth measured by auto correlation methods is of the order of 10 Hz [Baumback and Calvert, 1987]. These observations suggested that AKR is generated in several small scale structures. In parallel, the size of an AKR source was estimated to be of the order of 10 km by interferometry of the signals simultaneously received by the ISEE 1 and ISEE 2 spacecraft [Baumback et al., 1986]. Improvements of the direction finding method were obtained with DE 1 spacecraft using the relative phase of the signal received on two orthogonal antennae. This method, that gives the average wave normal direction over one spin period, has been used to demonstrate that the frequency of the peak of the emission increases with a decreasing altitude of generation [Calvert, 1985]. Furthermore, it was used for the initialization of ray-tracing [Huff et al., 1988]. However, even these precise direction finding methods only gave a broad localization of the sources. They were of little help by the determination of the local generation-frequency compared to the local electron gyrofrequency with the resolution required by the narrow bandwidth of the emission. Indeed, the best way to study the sources and the conditions for AKR emission is to intercept source locations by satellites.

2.1.2 AKR source crossing

Whenever a satellite cruises through a region where AKR sources are likely to be found, the criterion of interception of one source is a priori the intensity. It is natural to consider that the source is closest when the intensity is a maximum. Occasionally, the closest approach to the source is indeed the interception. Benson and Calvert [1979] showed from ISIS 1 observations, that the envelope of the spectrogram gives an indication of the beaming angle of the emission which completes efficiently the criterion for the intensity for AKR source crossing. As a matter of fact, the low frequency envelope of an AKR burst recorded during auroral zone crossing has a characteristic 'V' shape. Assuming that the frequency of the peak emission is a monotonous function of the altitude, as suggested later on by remote observations [Calvert, 1985], one can easily verify that this shape is characteristic of an emission beamed upwards, or eventually perpendicularly to the planetary magnetic field direction, with an angle of the emission cone that is constant or decreasing monotonously with altitude. Then the waves observed at the lowest frequency

are generated closest to the satellite. Moreover, this frequency gives an upper bound of the local frequency of generation. This observation of Benson and Calvert [1979] used by Benson et al. [1980], Calvert [1981*a,b*], Benson [1985], Benson and Akasofu [1984] has led to important conclusions:

- The emission is radiated at a large angle to the geomagnetic field.
- The waves are generated close to the local electron gyrofrequency (within the 50 kHz resolution of the ISIS 1 receiver).
- Multiple source interceptions have been identified along single auroral region passes.

These points allowed the first identification of ‘in situ’ observations of the sources. In turn, this led to evidence the correlation of AKR sources with the presence of inverted ‘V’ electron precipitations and the observation of very low values of the plasma frequency, much below the electron gyrofrequency (see following sections). However, ISIS 1’s orbit only crossed the low altitude region of AKR generation (below 3500 km) and the spectral resolution of the receivers ($\delta f \simeq 50$ kHz) did not fit to the narrow bandwidth of the emission, leading to an uncertainty of about 350 km at 3500 km of source altitude which is not matched to the small size of the AKR sources as it appeared from later observations. After ISIS 1, the Swedish satellite Viking has been the next satellite experiment from which AKR source crossings have been identified. The interest in the Viking observations stems from the fact that Viking crossed the nightside auroral region in the broad altitude range where AKR was believed to be generated. Its wave experiment had a frequency resolution of about 1% of the AKR frequency range. A detailed description of Viking and of all the experiments can be found in a special issue of Geophysical Research Letters [April 1987, vol. 14, number 4]. In the next subsections, we describe the wave and particle characteristics inside the sources. Most of them have been determined from the fifty AKR sources crossed by Viking.

Because the source regions can be extremely narrow structures, as suggested by the narrow bandwidth of the emission, the criterion used for the ISIS 1 source crossing identifications has been completed by a criterion on the wave intensity at the vicinity of the electron gyrofrequency f_{ce} . For this purpose, the source approach can be quantified by computing the electrostatic energy density E_{AKR} in the vicinity of the electron gyrofrequency integrated from $f_{ce} - 5$ kHz to $f_{ce} + 10$ kHz [Hilgers et al., 1991*a*] during an event such that the lower frequency of the AKR spectrum merges with f_{ce} . It is then considered that a maximum of E_{AKR} corresponds most probably to a position of the satellite inside the source. For such positions, it has been possible to determine the wave and particle properties from a statistical study over about 50 AKR source crossings.

2.2 Wave characteristics inside the sources

Figure 1 shows the dynamic spectrum of one electric component (upper panel) and one magnetic component (lower panel) obtained with the Viking V4 H experiment. A line is drawn at the electron gyrofrequency f_{ce} . Far below f_{ce} , one observes the auroral hiss.

Above f_{ce} , the AKR exhibits the characteristic ‘V’-shaped lower cutoff. Around 2238.00 and 2239.10 U.T., the lower cutoff merges with the electron gyrofrequency. As described above, these two periods correspond to the AKR source flyby. The electrostatic energy E_{AKR} integrated in the vicinity of f_{ce} (Figure 2, panel *e*) for these periods, provides a quantitative criterion for the source approach.

2.2.1 Generation frequency

Inside the AKR sources observed by Viking, the gyrofrequency ranges from 105 kHz to 350 kHz. Thanks to the frequency resolution of the Viking wave experiment ($\sim 1\%$), it has been shown that the local frequency of generation f is closer to the electron gyrofrequency than was previously believed: $(f - f_{ce})/f_{ce} < 0.08$ [Hilgers et al., 1991*a*]. In a few cases, the peak frequency was even below f_{ce} . This shows that at least part of the waves are not accounted for by supraluminous cold plasma extraordinary mode. These waves can be either cold plasma mode (mode O), or extraordinary supraluminous mode with the dispersion properties of a non thermal plasma [Wu et al., 1981, 1982; Wong et al., 1982; Pritchett, 1984*a, b*; Winglee, 1983, 1985; Le Quéau et al., 1984*a, b*; Strangeway, 1985, 1986; Le Quéau and Louarn, 1989].

2.2.2 Refractive index

The electromagnetic nature of the AKR at its generation site has been studied by Bahnsen et al. [1989]. They have shown that inside the sources the ratio of the magnetic signal (one component perpendicular to the spin plane) to the electric one (one component in the spin plane), is close to the velocity of light c . This is verified in particular at the local frequency of generation f which was identified as the lowest frequency peak. These authors notice, however, that very close to the cutoff frequency, this parameter is often less than c . This is consistent with the fact that a part of the radiation (the lower frequency edge of the peak) is at its cutoff frequency. It is not clear, however, if this part of the radiation is locally generated or if it comes from elsewhere.

2.2.3 Polarization

There is actually no direct measurement of the polarization of the AKR inside the sources. The EXOS-D satellite, that has the most complete wave instrumentation (the wave forms of 5 components of the electromagnetic field are recorded) [Oya et al., 1990] had problems with saturation of the receiver in the crucial frequency domain of local generation in the sources [Morioka et al., 1990]. The observed electromagnetic nature of the waves as reported above, and particularly the observed cutoff frequency in the vicinity of f_{ce} , strongly suggests a supraluminous extraordinary mode. Although there is no direct measurement of the rotation sense of the polarization, the geometry of the wave electric field has been measured by the Viking wave experiment [Hilgers et al., 1991*b*]. It has been found that the wave electric field lies in a plane within an angle of 10° to the normal of the geomagnetic field

Given the small size of the source structure, the geometry of the wave electric field is certainly strongly influenced by the gradients at its edge. Thus the geometry shows that the waves inside the limited plasma of the source region propagate predominantly on T–E mode (Transverse Electric mode). It is also shown that this geometry is clearly different from that of the wave electric field outside the source region.

2.2.4 Wave electric field intensity

The spectral intensity at the frequency peak of the emission inside the sources covers a large range of values. With Viking, spectral intensities between a few $\mu\text{Vm}^{-1}\text{Hz}^{-\frac{1}{2}}$ to a few $\text{mVm}^{-1}\text{Hz}^{-\frac{1}{2}}$ have been observed, with a maximum of occurrence at $0.1\text{mVm}^{-1}\text{Hz}^{-\frac{1}{2}}$. This typical value leads to a radiation power ($c\epsilon_0 E^2$) of about $3 \times 10^{-11}\text{Wm}^{-1}\text{Hz}^{-1}$. The fact that the filter bandwidth is larger than the emission bandwidth leads to an underestimation of this spectral intensity. A lower bound of the particle/wave energy conversion efficiency can be found. Since the emission bandwidth is smaller than that of the receiver, one must multiply the above spectral intensity by the filter bandwidth ($\simeq 2\text{kHz}$) to calculate the instantaneous power of a single emission. One obtains a typical value of about $3 \times 10^{11}\text{eVm}^{-2}$ for the flux of wave energy. If the typical values $n = 1\text{cm}^{-3}$ and $\mathcal{E} = 1\text{keV}$ are taken for the electron density and the mean energy in the expression of the electron power flux ($n\sqrt{(2m\mathcal{E})\mathcal{E}}$), one finds a value equal to $2 \times 10^{16}\text{eVm}^{-1}$. Then the particle/wave energy conversion efficiency is of about 2×10^{-5} with some maximum two orders of magnitude higher.

2.3 Plasma characteristics inside the sources

There exist two sources for the electrons of the flux tubes: The ionosphere which is populated with low energy electrons and the plasmashet, populated with electrons of higher energy (a few eV to a few keV). The velocity distribution of these two electron populations acquire, however, specific features when at the same time a field-aligned potential drop – as observed within the AKR source region – is present.

Figure 2 is a composite showing particle measurements in the vicinity of the two AKR sources crossed during orbit 237. The maxima of the wave electric energy density inte-

Figure 1: (color plot, next page) Dynamic spectrum of one electric field component (upper panel) and one magnetic component (lower panel) during orbit 237 between 2236:00 UT and 2244:00 UT. At the left is the color scale of the amplitude in telemetry units (logarithmic); 255 corresponds to the threshold $\simeq 10^{-8}\text{mVm}^{-1}\text{Hz}^{-\frac{1}{2}}$ and 0 to amplitudes $\geq 100\text{dB}$ above the threshold.

Figure 2: (color plot, following page) Probe current (panel a), electron spectra and ion spectra (panels b and c) with the corresponding pitch angle (panel d), and the wave electric energy density integrated in a 15 kHz bandwidth around the electron gyrofrequency (panel e), recorded during orbit 237 (from Hilgers [1991]).

grated in a 15 kHz bandwidth around the electron gyrofrequency (panel e), localizes the source closest approach.

2.3.1 *Suprathermal electrons*

The association of AKR generation with the precipitating electron giving rise to the discrete aurora has been abundantly demonstrated [Gurnett, 1974; Kurth et al., 1975; Kaiser and Alexander, 1976; Alexander and Kaiser, 1976; Voots et al., 1977; Benson and Akasofu, 1984; Huff et al., 1988]. The direct correlation with the inverted ‘V’ electron precipitation has been demonstrated by in situ observations [Benson and Calvert, 1979; Benson et al., 1980]. The Viking particle experiment showed many inverted ‘V’ events (Figure 2, panel b). These events are believed to be the signatures of field-aligned electrostatic potential structures that are located above the satellite. In the velocity space, enhanced fluxes along the geometrical loss-cone are commonly observed throughout the inverted ‘V’ electron events. Louarn et al. [1990] have studied in detail the particle signatures of an AKR source crossed by Viking. They have shown that it is located in a narrower region than the inverted ‘V’ structure. In this region, the electrons with energies less than several hundreds of eV have disappeared and the geometrical loss-cone is replaced by a feature that has been identified as resulting from trapped electrons. Then, the remaining nonthermal features at high energy are a downward beam parallel to the magnetic field and enhanced fluxes of the trapped electrons with an average velocity perpendicular to the magnetic field. (i.e. with pitch angles close to 90°). The characteristic nonthermal feature of the electrons cannot be studied systematically over all the Viking AKR source crossing because of the long time required to obtain a complete distribution function (~ 20 s). However, a characteristic region of the inverted ‘V’ corresponding to the source has been identified by the mean of ion detectors and density probes.

2.3.2 *Upward-flowing ion beams*

Regions with upward field-aligned ion beams with energies from few hundred eV to few keV appeared to be also a substructure of the inverted ‘V’ precipitation crossings by Viking (Figure 2, panel c). These events are believed to be a signature of field-aligned electric potentials that are located below the satellite. It has been observed that the source coincide with these upward ion beams [Bahnsen et al., 1989; Louarn et al., 1990; Ungstrup et al., 1990]. Hilgers et al. [1991a] have shown from the examination of the 50 source crossings by Viking that this observation is indeed general. They have shown, in particular, that the few cases where no ions are detected can be explained by the fact that the ion detector was not looking in the direction of the field-aligned collimated beam when the source was crossed.

2.3.3 *Thermal electrons*

The electron density is rather low inside the auroral region. The typical values are of the order of 1 to 100 cm^{-3} according to the altitude. Occasionally, very low densities

have been observed. Calvert [1981a] proposed to explain the Hawkeye observations by the existence of a large-scale single auroral plasma cavity. However, the observations with S3-3 and Viking give evidence of smaller-scale plasma depletions. These depletions that are included in the region of inverted ‘V’, coincide with the period of observation of the upward field-aligned ion beams (Figure 2, panel a). The S3-3 has measured plasma densities as low as a few cm^{-3} . Recently, Hilgers et al. [1992], using the Viking Langmuir probe, have given evidence of thermal electron densities as low as 0.4 cm^{-3} (the probe current has been examined to remove the contribution of the photoelectrons guided by the magnetic field lines from the body or the booms of the satellite to the probe). Such low values show that the suprathermal electrons may be the dominant population. In this case, the probe current has to be interpreted for the measurement of the electron density. Assuming that the secondary emission is negligible at the surface of the probe, Hilgers [1991] has obtained upper bounds of the total electron density inside the acceleration structures. The corresponding values of the ratio of the plasma to the electron gyrofrequency versus the geocentric distance are displayed in Figure 3. Thus the maximum value of this ratio observed inside the sources is 0.14. A second important characteristic of the plasma depletion is the sharpness of their edges which may present a gradient spatial scale as low as 1.5 km [Hilgers et al., 1992], comparable to the Larmor radius of keV protons.

2.4 Synthetical view of the source structure

The above observations can be synthesized as follows. It appears that the sources are small scale structures. In particular, it can be observed directly that the extension perpendicular to the magnetic field is very small ($< 1^\circ$ in invariant latitude). The narrow bandwidth of the emission suggests that the extension parallel to the magnetic field is very small as well. These structures are included inside plasma depleted regions with sharply defined edges ($\sim 1.5 \text{ km}$). Inside them, the density is one to two orders of magnitude below the typical values in the surrounding region. They are substructures of inverted ‘V’ electron precipitations, where simultaneously upward-flowing field-aligned energetic ion beams are observed and where sometimes clear evidence for the disappearance of electrons below several hundreds of eV is given. The presence of downward-precipitating electrons is interpreted by the existence of a potential drop above the satellite and the upward field-aligned electron beams by the existence of a potential drop below the satellite that accelerates the ionospheric ions. The above characteristic features thus suggest that the sources are included inside an acceleration structure or between two such structures. This interpretation also accounts for the suppression of most of the thermal electrons inside the sources. The disappearance of the loss-cone-type reflected electrons and the enhancement of the trapped electron population are also explained, adding the hypothesis that the electrons undergo an increasing parallel electric field inside the acceleration structure [Eliasson et al., 1979; Louarn et al., 1990, 1991]. As a result, the source region is dominated by a low density suprathermal electron population with two characteristic non-thermal features: A downward electron beam and a ring-like distribution. Likely generated by these suprathermal electrons, an intense electromagnetic wave is observed with a lower cutoff frequency close, and sometimes below, the electron cyclotron frequency. This wave

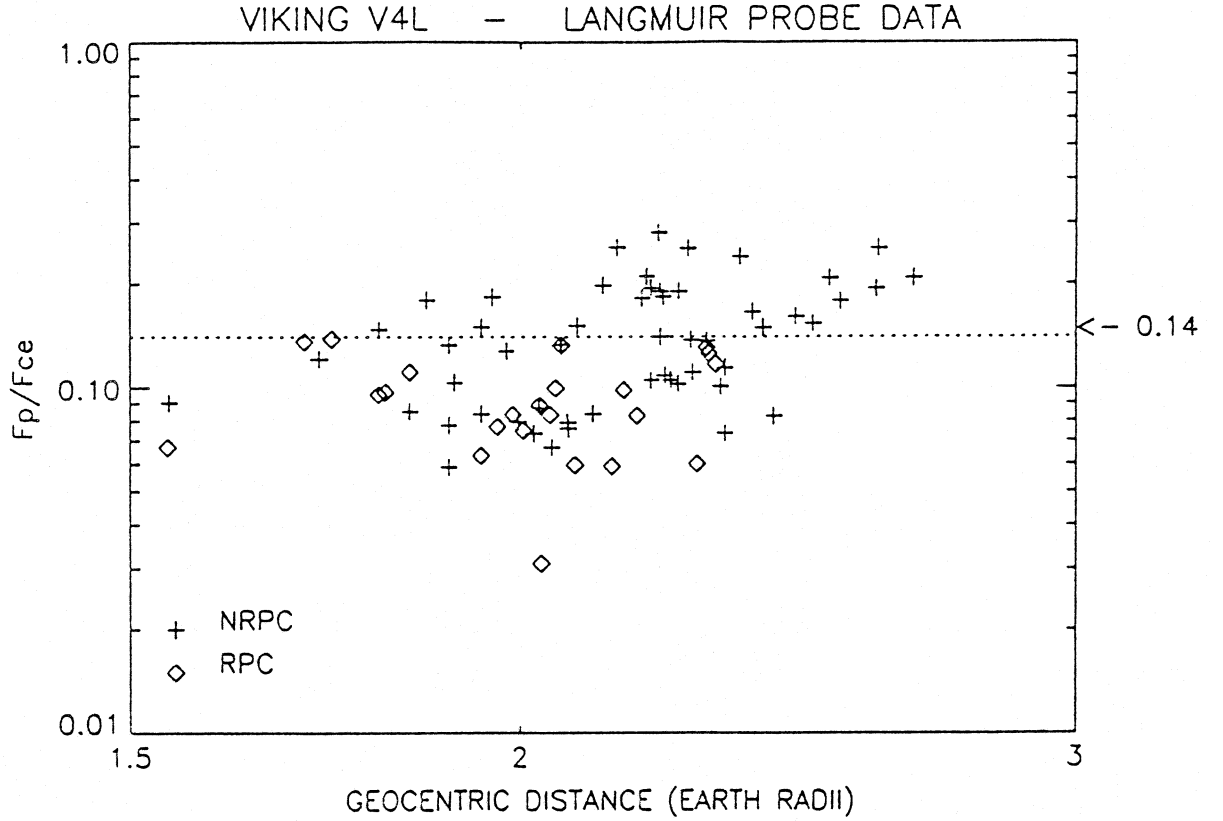


Figure 3: Estimate of the ratio f_p/f_{ce} inside the AKR sources (◇, radiating plasma cavity (RPC)) and inside the non radiating acceleration structures (+, non radiating plasma cavity (NRPC)) versus the geocentric distance (from Hilgers [1991]).

is guided over some distance in the structure with a polarization plane mainly transverse to the magnetic field.

3 Significance for the AKR study

3.1 Generation mechanism

The observations inside the sources have of course the greater advantage of putting some constraints on the mechanism of generation. Let us summarize them. An electromagnetic mode is generated at frequencies very close to the electron gyrofrequency inside a region of energetic particles with several kinds of anisotropies in their velocity distribution, the most salient feature being a ring-like distribution. The density of these electrons is at least of the same order as the thermal electron core that may, however, exist in such a structure. This mode is plane polarized with a direction of polarization almost perpendicular to the magnetic field. Observations also suggest that the waves have a lower cutoff frequency very close to the electron gyrofrequency (within a few percent) and occasionally below. The intensity is very variable from one event to another. The typical value for the instantaneous conversion rate of the flux of energy from particles to waves is of the order of 10^{-5} and sometimes as high as 10^{-3} .

The generation mechanism should be particularly efficient to explain the highest conversion rates observed and should lead directly to the generation of an electromagnetic mode. This eliminates the generation mechanisms relying on conversion of primarily generated electrostatic waves [Oya, 1974; Jones, 1977].

Among the direct mechanisms, the one which fits best the observations of the AKR, is the Cyclotron Maser Instability (CMI hereafter) proposed by Wu and Lee [1979]. This instability relies on a coherent cyclotron interaction between the wave electric field and energetic electrons having perpendicular energy in excess. Such property is characterized on the electron velocity distribution by the presence of strong positive gradients with respect to the perpendicular velocity ($\partial f / \partial v_{\perp} > 0$).

In their original theory, Wu and Lee proposed that the reflected loss-cone type electrons constitute the free energy source. However, the Viking observations have shown that, whereas the loss cone type electrons are observed in almost all the regions of inverted 'V' precipitation, the generation indeed occurs in a restricted region of the inverted 'V'. According to Louarn et al. [1990], this restricted part could be characterized by a very different kind of velocity distribution with essentially quasi-trapped type electrons.

The trapped electrons interact coherently with an extraordinary mode if its lower cutoff is low enough. However, when hot plasma is the dominant population and is taken into account in the propagation, the X mode lower cutoff frequency significantly decreases and can even be below the electron gyrofrequency [Strangeway, 1985; Le Quéau and Louarn, 1989]. In that case, the instability can take place at a very low group velocity (at $k \simeq 0$ for instance). The resulting amplification lengths are short which fits better the small size of the source.

Even if the mechanism of the instability seems to be well identified, several important problems are still to be solved. First, the Viking observations show clearly that the perpendicular gradients should play a significant role in the distribution of the wave field that is allowed to propagate inside the source and to be radiated outside. Secondly, for a wave very close to the cutoff frequency, the resonance condition is very sensitive to the variations of the geomagnetic field, and thus the magnetic field gradients must be taken into account. Their effect is to limit the altitude region where the waves and the particle may interact coherently [Le Quéau et al., 1985]. The mechanism of saturation of the instability is not identified. The parameters that govern the observed wave intensity are not known and the wave level cannot be accounted for quantitatively.

3.2 Radiation of the energy

In the preceding section, we have shown that electromagnetic waves are generated very close to the electron gyrofrequency, inside a density depletion limited by sharp density gradients. In that case, only ordinary mode and Z mode can escape from the plasma depletion at the altitude of generation. Before escaping, the X mode should propagate upward until the density of the surrounding plasma and the electron gyrofrequency decrease sufficiently for the cutoff of the X mode outside of the source to become smaller

than the wave frequency. For the source most often encountered by Viking, a rough calculation gives an upward propagation of a few tens of kilometers before escaping. Mode conversion can occur at the gradients. We have seen that the guided mode inside the structure is probably a hot plasma extraordinary supraluminous mode. Part of the energy of this mode is possibly converted into O and Z modes. The conversion rates calculated with a cold plasma X mode inside the sources account for the relative intensity of the X mode and O mode outside the sources [Hayes and Melrose, 1986]. Other conversion processes have been considered. In a particular structure used for a plasma simulation by Pritchett [1986], successive conversion from X to Z mode and then into X mode again was considered.

Observations of the AKR outside the sources have shown that the AKR is beamed in a hollow cone [Benson and Calvert, 1979; Calvert, 1981*a, b*] and that it mainly propagates in extraordinary luminous mode, although weaker O and Z modes are observed [Oya and Morioka, 1983]. Attempt was made to deduce directly the wave characteristics inside the sources from remote observations. The present section has shown, however, that these two properties of the AKR are likely directly related to the presence of the sharp gradients at the edge of the sources.

4 Discussion and conclusion

Since the AKR is generated by precipitating electrons, it is a marker of the acceleration processes. Furthermore, the basic mechanism of the instability requires anisotropies in the electron velocity distribution that are related to the geomagnetic topology. It has been shown that the electric field topology also plays a significant role in the creation of the microscopic properties of the plasma, that lead to AKR generation. Two main effects, that increase the efficiency of the CMI, have been associated with the possible presence of a magnetic field-aligned potential drop. The first one prevents the cold ionospheric and backscattered electrons from reaching the source altitude and then to deplete the source region of cold plasma. The second one modifies the electron velocity distribution along the edge of the loss cone, especially by enhancing the perpendicular energy at low parallel velocity. This has been illustrated by [Wu et al., 1982]. These authors have tested different simple, realistic, but non self-consistent models of auroral field lines (including suprathermal and thermal electron densities, mean energy, potential repartition and magnetic topology). They found that a very efficient topology is obtained when the parallel potential drop is confined at rather low altitude (between 4000 and 6000 km altitude). Figure 4 shows the amplification distance obtained for such a model versus the altitude. This model accounts easily for the AKR maximum intensity around 200 kHz. It is interesting to notice that in the study of Wu et al. [1982] a strong wave growth rate was obtained below the gyrofrequency with a wave vector perpendicular to the magnetic field; this was attributed to the ‘may be not realistic distribution function’ that as a matter of fact presented strong gradients $\partial f / \partial v_{\perp} > 0$ along the $v_{\parallel}$ axis. This region of the velocity space should be empty of electrons according to a static model of Chiu and Schulz [1978]. However, Louarn et al. [1990] have shown that a particular geometry or time variation of the ambient electric field efficiently fills this phase space

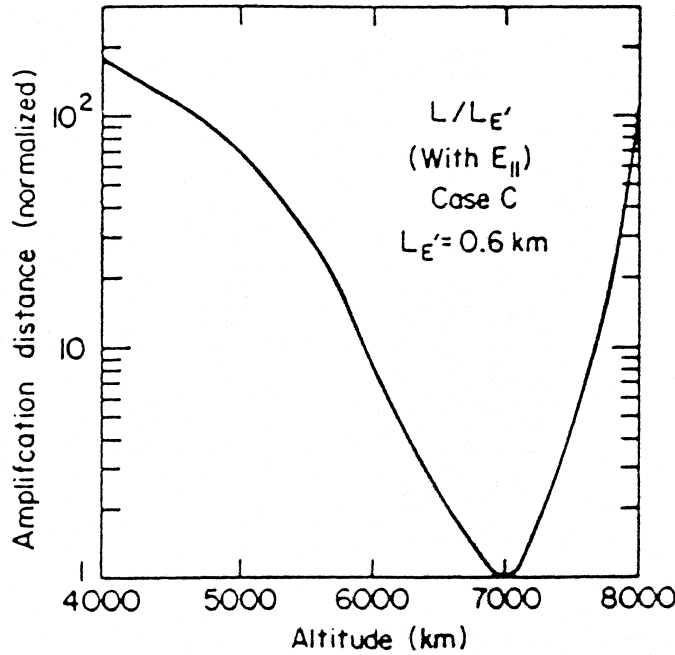


Figure 4: Normalized amplification distance versus the altitude, with a model of auroral field line and double loss-cone electron velocity distribution (see text for more explanations) from Wu et al. [1982].

region, giving rise to the so-called quasi-trapped electrons. Figure 5 shows the resulting distribution obtained by these authors inside a simple model of acceleration structure. Only little is known about this population, its origin and may be its role in maintaining a large scale potential drop. The fact that they seem to be a likely free energy source for the CMI suggests that the AKR is indeed a direct marker of such a population and thus of the topology and/or the dynamics of the acceleration region.

In conclusion, the Viking observations appear very fruitful for the understanding of the planetary radio emissions. This is due to the possibility of ‘in situ’ observations for the closest radio source, the Earth. These observations allowed to determine the specific characteristics of the emitting plasma, namely: Low value of the ratio plasma to electron gyrofrequency $f_p/f_{ce} \leq 0.14$, typical energy of electrons above ~ 1 keV and a significant electron density compared to the thermal electron core, if any. Further they allowed to determine the following characteristics of the locally generated waves, namely: Electromagnetic mode with a frequency very close to the electron gyrofrequency, with a lower cut-off frequency sometimes below f_{ce} , and with a plane polarization nearly perpendicular to the geomagnetic field. They suggest that a characteristic nonthermal feature of the electron velocity distribution function is an enhanced flux of keV electrons at $\sim v_{||} = 0$ (quasi trapped electrons). These results show that the CMI is the most relevant mechanism to explain the AKR generation, provided that hot plasma effects are taken into account for the wave dispersion properties.

Moreover, the Viking observations enlightened the close link, although still not fully understood, between the acceleration processes and the AKR generation. It has been found that the sources are distributed in a multitude of small-scale structures that coincide with acceleration structures. It turns out that the parameters describing the plasma at the origin of the AKR emission are not the ones of a broad region of the magnetosphere. If this fact limits the applicability of AKR for remote sensing of the Earth environment, it of-

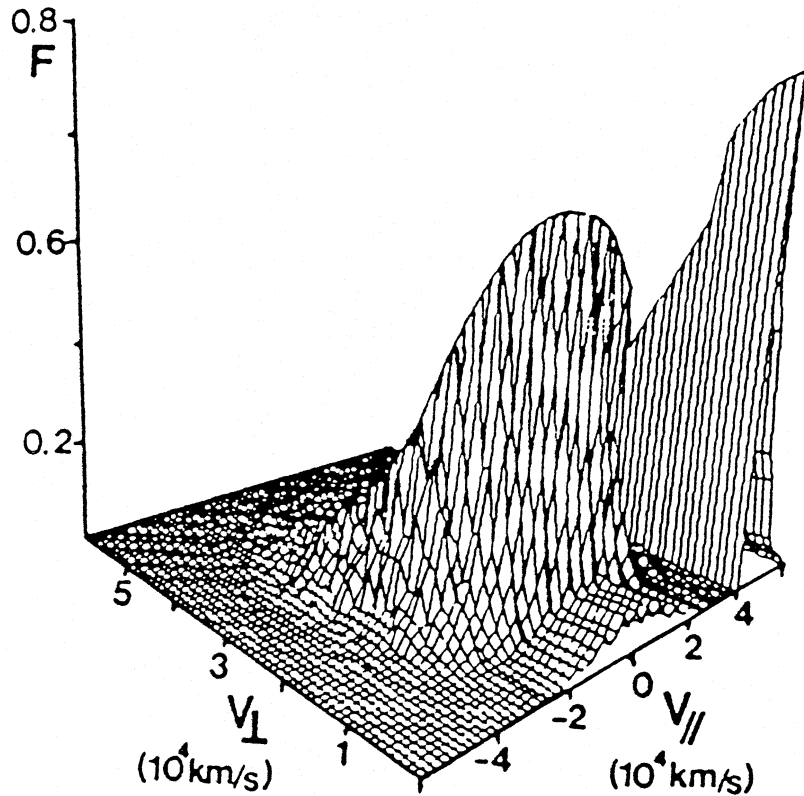


Figure 5: Distribution function obtained inside an acceleration structure, by a simulation in which it is assumed that the electrons experience an increasing field-aligned potential drop (from [Louarn et al., 1991]).

fers nevertheless the perspective of remotely diagnose the electronic distribution functions resulting from the complex auroral processes of the terrestrial magnetosphere.

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