

TERRESTRIAL RADIO EMISSION: AKR

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Abstract

Auroral kilometric radiation (AKR) is believed to come from a plasma instability associated with electron precipitation known as the electron-cyclotron maser. This emission mechanism has been evoked to explain circularly-polarized radio emissions from all of the outer giant planets. It calls for a coherent plasma instability near the electron cyclotron frequency based on the free energy in the loss-cone of an electron distribution. Recent observations within the Earth's AKR source region, however, indicate that the radiation grows from the free energy associated with a "shell" electron distribution rather than the loss-cone. Such distributions are created by electrons accelerated by parallel electric fields that travel into a region of stronger magnetic field as seen in the Earth's auroral zone. This recent finding suggests that the auroral zones of the giant outer planets may have potential structures and parallel electric fields similar to those of Earth.

1 Introduction

AKR, the strongest source of terrestrial radio emission, has been found to originate on auroral field lines where down-going electrons are accelerated [Gurnett, 1974, and references therein]. The circularly-polarized waves propagate primarily in the R-X mode and show strong temporal variations and fine spectral features [e.g. Viking observations, Bahnsen et al., 1987; Pottelette et al., 1992; Roux et al., 1993]. Radio wave and ray tracing analysis indicate that AKR is generated in regions of depleted plasma density near the electron cyclotron frequency (f_{ce}). It is natural to assume that the waves are generated from the free energy of the non-Maxwellian auroral electron distribution. One of the first widely-accepted growth mechanisms, put forth by Wu and Lee [1979], was a loss-cone instability with a weakly-relativistic treatment. This instability was later expanded and coined the electron-cyclotron maser instability [Melrose and Dulk, 1982]. Melrose and Dulk [1982] postulated the electron-cyclotron maser as a source for a number of radio emissions, including planetary radiation, solar microwave spikes associated with impulsive flares, radio emissions from binary systems, and narrow-band emissions from

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dwarf M flare stars. The loss-cone as the source of free energy for AKR, however, was not supported by two-dimensional particle simulations based on measured electron distributions [Pritchett, 1984; Pritchett and Strangeway, 1985]. Instead, it was suggested that a "shell distribution" [Winglee and Pritchett, 1986] produced by a parallel electric field may drive the electron-cyclotron maser. A study based on Viking satellite observations suggested that the free energy for AKR wave growth comes from electron distributions with $df/dv_{\perp} > 0$ [Louarn et al., 1990], many of whose conclusions are supported by observations that we present here. The purpose of this article is to review recent findings on terrestrial radio emissions and discuss how these findings may pertain of Jovian radio emissions. Satellite observations within the AKR source region [Ergun et al., 1998, 2000; Delory et al., 1998; Strangeway et al., 1998] and numerical simulations [Pritchett et al., 1999] suggest an important modification to the loss-cone electron-cyclotron maser process as put forth by Wu and Lee [1979] and Melrose and Dulk [1982]. The most important modification is that the emissions, as observed at Earth, do not draw their energy from a loss-cone instability, rather, the radiation results from an unstable "horseshoe" or "shell" distribution. The most far-reaching implication is that the electron-cyclotron maser is directly associated with parallel electric fields in a dipole magnetic field. These findings change several of the characteristics of the electron-cyclotron maser mechanism and may necessitate re-analysis of the Jovian and other planetary sources [see Zarka, 1992b, 1998, and references therein]. Under the shell instability, intense radio emissions may be continuous. A loss-cone is not required, so the radiation source may be high above the planetary surface. The generation is entirely in the X-mode with $k_{\parallel} = 0$ which implies that the radiation at the source should propagate close to 90° to the ambient magnetic field ($\mathbf{B}_0$).

2 AKR source region observations

Figure 1 displays wave and plasma observations of the AKR source region. The observations are from the Fast Auroral SnapshoT (FAST) satellite [Carlson et al., 1998, and references therein] as it was traveling across the Northern auroral zone from South to North at over 4000 km in altitude. The horizontal axis represents time (10 s in total) which can be also interpreted as distance (50 km in total). The satellite's velocity was ~ 5 km/s. The top panel (a) displays the electron energy flux (color) as a function of energy (vertical axis). There are intense fluxes at roughly 4 keV near the beginning of the plot, decreasing in intensity by the end of the plot. The electron fluxes were relatively evenly distributed in pitch angle (not displayed) except for a loss-cone at 180° (anti-earthward). The net motion of the electrons was therefore earthward. These precipitating electrons created visible auroral arcs. From $\sim 01:28:29$ UT to $\sim 01:28:31$ UT, marked as "density cavity" on the plot, there were almost no detectable electron fluxes between ~ 100 eV and ~ 1 keV. At that time, the spacecraft was within the auroral acceleration region often referred to as the "auroral cavity".

Panel (b) displays the results of two separate methods of determining the electron density. The solid trace is the density of >100 eV electrons derived from the electron fluxes (Panel a) which were measured by an electrostatic analyzer. We call this quantity the "hot" electron density. The derived density has approximately $\pm 25\%$ uncertainty. The

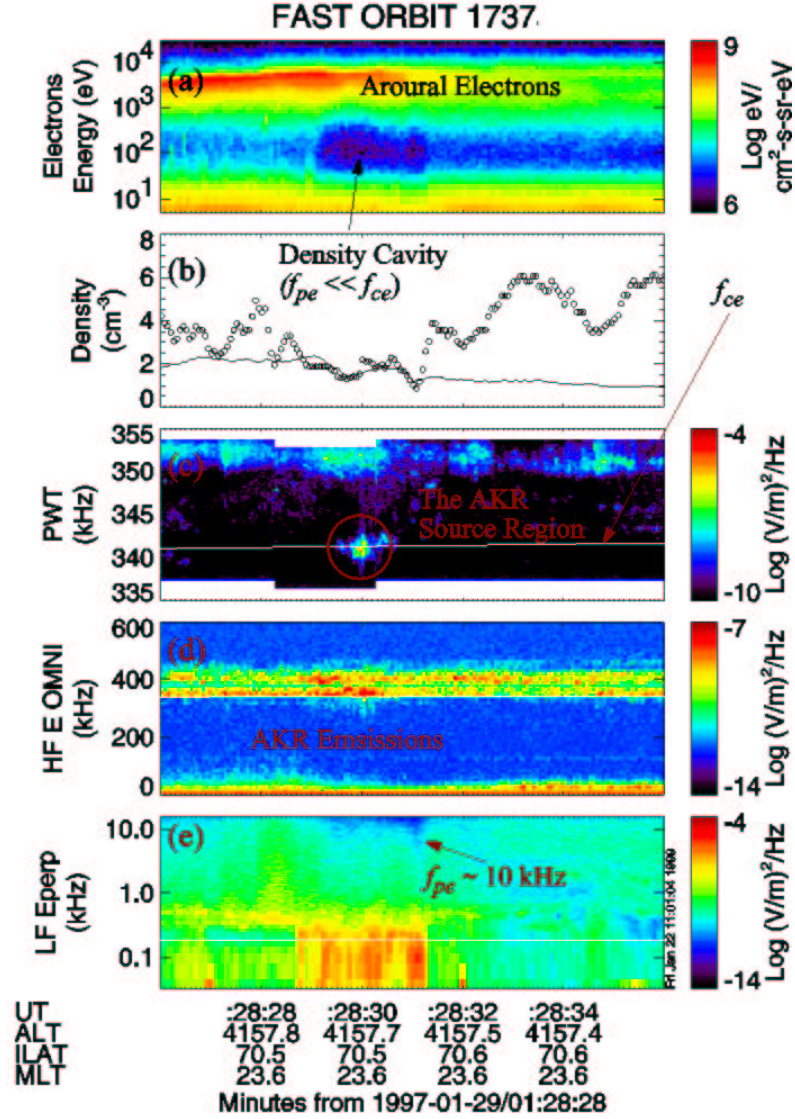


Figure 1: The AKR source region. (a) Electron energy flux versus energy and time. There are no measurable electron fluxes between ~ 100 eV and ~ 1 keV in the auroral cavity. The fluxes below ~ 100 eV are spacecraft photoelectrons. (b) The total electron density (circles) derived from fits to the whistler–Langmuir dispersion. The solid line is the hot (> 100 eV) electron density. (c) Wave power as measured by the Plasma Wave Tracker. The white line is f_{ce} (± 400 Hz). These data have spin modulations. The PWT covers a ~ 16 kHz band, the center frequency updated every 1 s. The emissions extend below f_{ce} . (d) High–frequency electric field power. The white line is f_{ce} . (e) The low–frequency electric field ave power. The white line is the H^+ cyclotron frequency.

lower energy (< 100 eV) electron fluxes were not included because they were dominated by spacecraft photoelectrons. The circles in Panel (b) denote the density derived from fits of the electric field wave observations, representing the total density [Ergun et al., 1998; Strangeway et al., 1998]. Only fits that had better than $\pm 50\%$ uncertainty are

plotted. Outside of the auroral cavity, the hot and the total densities differ, indicating a substantial "cold" (< 100 eV) electron population. Inside the cavity, however, the two measurements agree within expected error. These observations imply that the dominant plasma constituents were the precipitating electrons and an anti-earthward ion beam [Ergun et al., 1998; Strangeway et al., 1998].

Panels (c), (d), and (e) show the electric field spectral power density as a function of frequency and time. Panel (d) displays the frequency span from 0 to 600 kHz at 15 kHz bandwidth and Panel (e) displays the frequency range from ~ 40 Hz to 16 kHz and 40 Hz bandwidth. The white line in Panel (d) is the electron cyclotron frequency (f_{ce}) and the white line in Panel (e) is the ion cyclotron frequency (f_{ci}). The wave power in these panels was derived from two orthogonal antennas in the spin plane, and therefore show little modulation at the spacecraft spin frequency. Panel (c) displays Plasma Wave Tracker (PWT) data which have a fine frequency resolution over a limited bandwidth that encompasses f_{ce} . The frequency axis is from 335 kHz to 355 kHz with 32 Hz resolution. The PWT has better than 50 Hz frequency stability. The white line is f_{ce} with no relativistic correction, called the "cold" electron cyclotron frequency. The PWT spectral power density was derived from a single antenna in the spacecraft spin plane, and therefore shows strong spin modulation. The spacecraft spin period was 5 s resulting with a modulation with a period of 2.5 s. This modulation indicates that the wave electric field was polarized perpendicular to the ambient magnetic field [Ergun et al., 1998].

At 01:28:30 UT, an emission of great intensity, $\sim 10^{-5}$ (V/m) ^{2} /Hz, is seen at ~ 340 kHz, just below f_{ce} (Panel c). Figure 2a shows a slice of the PWT data (from Figure 1c). The vertical axis is spectral power density and the horizontal axis is frequency, focusing on a narrow band about f_{ce} . The wave power has a clear peak between the relativistically corrected electron cyclotron frequency ($f_{cr} = f_{ce}/\gamma$) and the cold electron cyclotron frequency (f_{ce}). This event is interpreted as the AKR source. The source region is characterized by greatly increased power near f_{ce} , wave emissions between f_{ce} and f_{cr} , decreased plasma density, an absence of low-energy electrons fluxes, and an ion beam (not displayed). These criteria are similar to previously published criteria [Bahnsen et al., 1987; Roux et al., 1993; Ergun et al., 1998].

Figure 2b displays the two-dimensional electron energy flux taken at the same time as the frequency spectrum in Panel (a). The horizontal axis is the parallel (to $\mathbf{B}_0$) energy; the vertical axis is the perpendicular energy. The electron energy flux forms a "shell" at roughly 4 keV with a loss-cone. There are several interesting features of shell distributions, one of which is that all electrons have approximately the same energy, given that the energy from acceleration is greater than the source temperature. The effective mass (γm_e) and therefore the relativistically corrected gyro-frequencies ($f_{cr} = f_{ce}/\gamma$) of all electrons are nearly identical leading to a simple change in the plasma dispersion. Since the plasma frequency (f_{pe}) is much smaller than f_{cr} , the right cut-off is generally less than f_{ce} , so the R-X mode can propagate below f_{ce} .

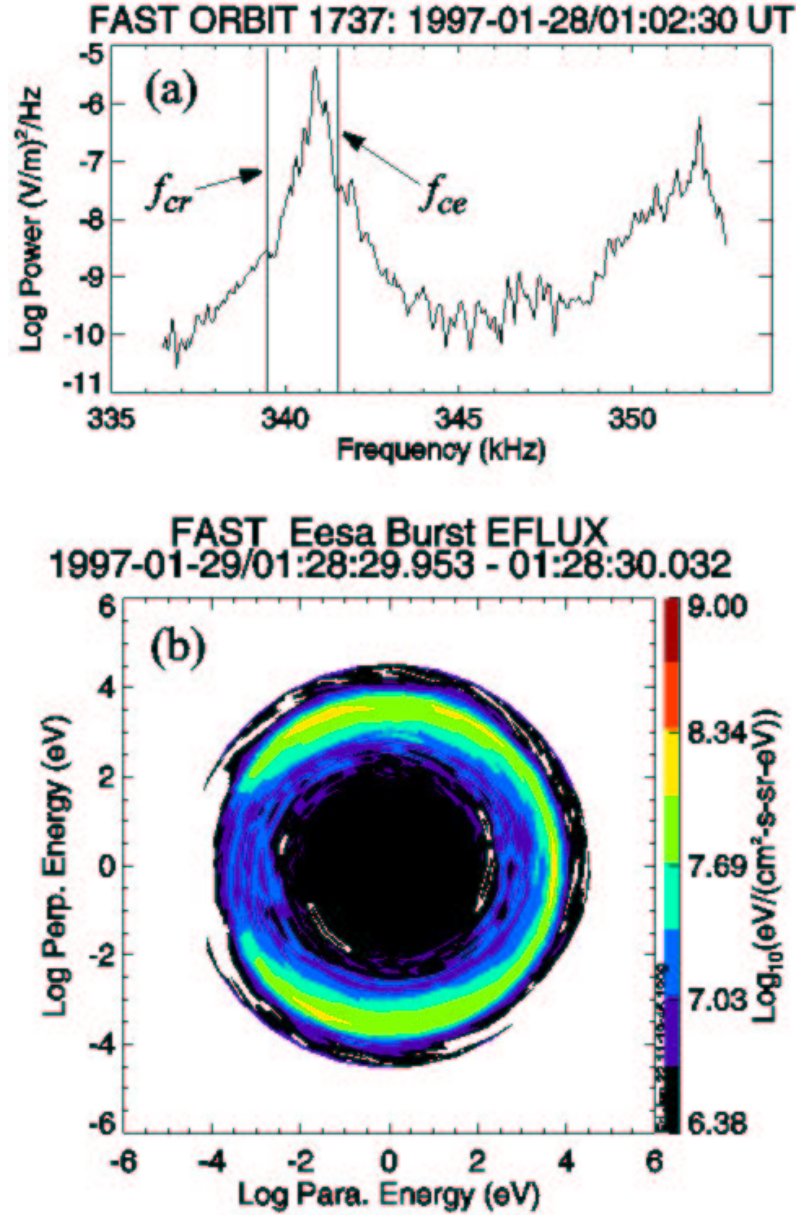


Figure 2: (a) The wave power versus frequency taken within the AKR source region in Figure 1. The peak is between f_{cr} and f_{ce} . (b) Two-dimensional electron energy flux in the AKR source region. Color indicates electron energy flux. One can see a clear horseshoe shape in distribution, which forms a partially-open shell in three dimensions.

3 The shell maser

The growth rate for the electron-cyclotron maser is derived by integrating $df/dv_{\perp}$ over a surface defined by the resonance condition [Melrose and Dulk, 1982]:

$$2\pi(f - sf_{ce})/\gamma = k_{\parallel}v_{\parallel}, \quad s = 0, +1, +2 \quad (1)$$

Two integration surfaces for the electron-cyclotron maser ($s = 1$) are drawn on Figure 3 (taken from another orbit). Contour 1 (blue) displays the integration surface of the loss-cone instability. The strongest wave growth requires a wave frequency ~ 1.5 kHz above f_{ce} and a finite $k_{\parallel}$ ($\sim -1 \times 10^{-3} m^{-1}$). Contour 2 (red), the integration surface of the shell instability, requires a wave frequency ~ 2.75 kHz below f_{ce} and $k_{\parallel} = 0$. The distribution shows evidence of wave growth from both the loss-cone and the shell instability. A positive slope, $df/dv_{\perp} > 0$ or $df/dv_{\parallel} > 0$, is seen at all pitch angles except in the region of the loss-cone. There is a statistically significant, but much weaker, $df/dv_{\perp} > 0$ in the loss-cone. These distributions, and the fact that the source region emissions are below f_{ce} , suggest that the shell maser can provide substantially stronger amplification than the loss-cone maser. The above analysis indicates that the growth mechanisms can be distinguished with observations of the wave polarization. Under the shell instability, the waves in the source region should be purely in the X-mode ($k_{\parallel} = 0$), whereas the loss-cone instability will produce emissions with a measurable $k_{\parallel}$. The wave electric field ($\Delta\mathbf{E}$) has been demonstrated to be purely perpendicular to $\mathbf{B}_0$ within experimental uncertainty, $\pm 4^\circ$ [Ergun et al., 1998]. The amplitude modulation in Figure 1c supports this conclusion. This finding confirmed that the waves were generated in the R-X mode, not the L-O mode.

To determine $k_{\parallel}$, we examine the polarization of the wave magnetic field ($\Delta\mathbf{B}$). In the X-mode $\Delta\mathbf{B}$ should be purely parallel to $\mathbf{B}_0$ whereas the loss-cone instability predicts $|k_{\parallel}/\mathbf{k}| \cong 0.13$ (Figure 3), in which case $\Delta\mathbf{B}$ should have a measurable perpendicular component. Figure 4 details the magnetic field wave polarization. Panel (a) shows the magnetic spectral power density. The dark line is f_{ce} . The magnetic field at high frequencies is measured with a single search coil and therefore is modulated at twice the spacecraft spin period. The phase of the modulation indicates that $\Delta\mathbf{B}$ is very near to $\mathbf{B}_0$. The electric field energy density is derived from two orthogonal antennas in the spin plane, and shows little modulation due to spacecraft rotation. The measured ratio of the magnetic to electric energy density ($\mathbf{B}^2 c^2 / \mathbf{E}^2$) is plotted in Panel (b) as circles. Superimposed on the plot, is a fit of $\mathbf{B}^2 c^2 / \mathbf{E}^2$ with $|k_{\parallel}/\mathbf{k}| = 0.1(6^\circ)$. This ratio is at the measurement uncertainty, given at the power level on the right side of the plot. On the left side of the plot, there is not enough power to determine the polarization accurately. These results demonstrate that the polarization angle of $\Delta\mathbf{B}$ was less than 6° from parallel to $\mathbf{B}_0$. Thus the observed emissions are inconsistent with the loss-cone instability and provide compelling evidence that the AKR emissions are generated from a shell maser.

An often discussed condition of the electron-cyclotron maser is the depth of the density cavity, typically expressed as $f_{pe}/f_{ce} < 0.1$ [e.g. Zarka, 1998]. As pointed out above, the electron mass is uniformly increased, so the relativistically corrected electron cyclotron frequency (f_{cr}) is decreased. The effective temperature of the plasma, although clearly non-Maxwellian, is also increased to $\sim \xi_{\Phi}$, the acceleration energy of the electrons. For a wave growth with $k_{\parallel} = 0$, the right cut-off must be less than the cold cyclotron frequency ($\omega_{right} < \omega_{ce}$). A necessary, but not sufficient, condition for the shell maser is then:

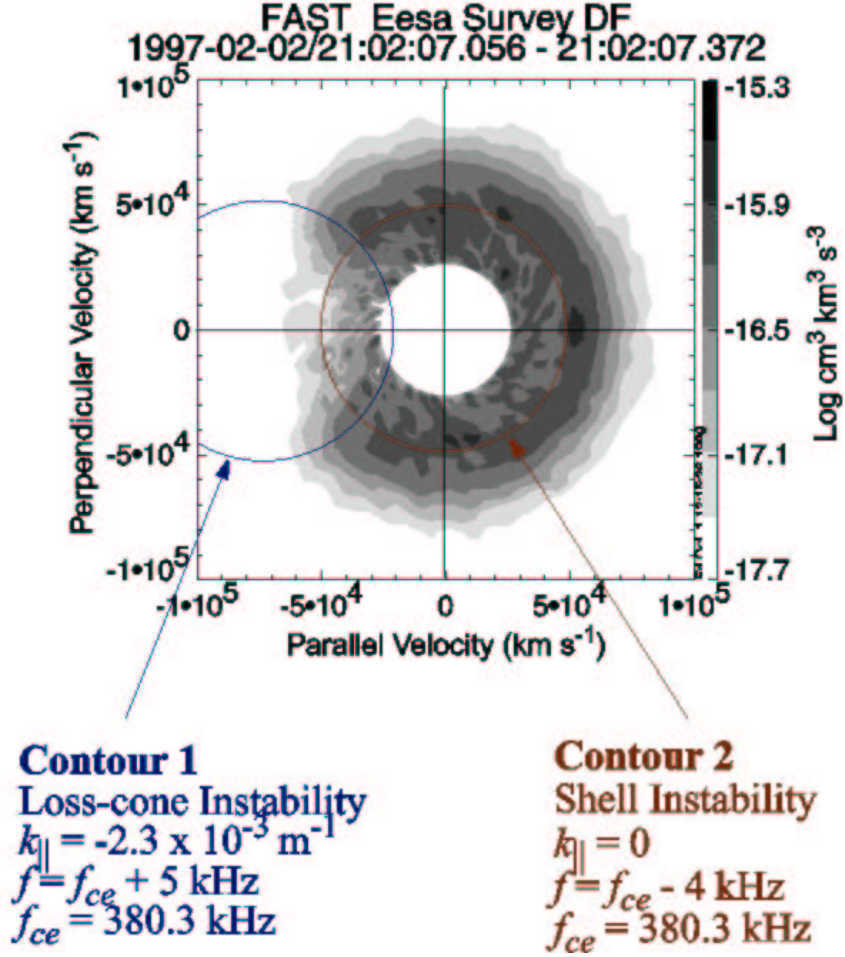


Figure 3: A two-dimensional electron distribution in an AKR source region. Darkness of shade indicates increased phase-space density. Electrons less than 1 keV have been removed. One can see a clear horseshoe shape in distribution, which forms a partially-open shell in three dimensions. The dashed lines represent integration surfaces to calculate wave growth. Contour 1 is optimized for the loss-cone maser, contour 2 for the shell maser.

$$\xi_{\Phi}/m_e c^2 > 2f_{pe}^2/f_{cr}^2, \quad \text{where } f_{cr} \gg f_{pe}. \quad (2)$$

Auroral electrons often have energies of roughly 10 keV, which results in the condition $f_{pe}/f_{ce} < 0.1$, identical to that quoted above. Interestingly, with lower electron energies the density cavity must be deeper, which may explain, in part, why intense AKR is associated with high energy electrons. The strong Jovian magnetic field makes this condition easy to satisfy for weak electron beams.

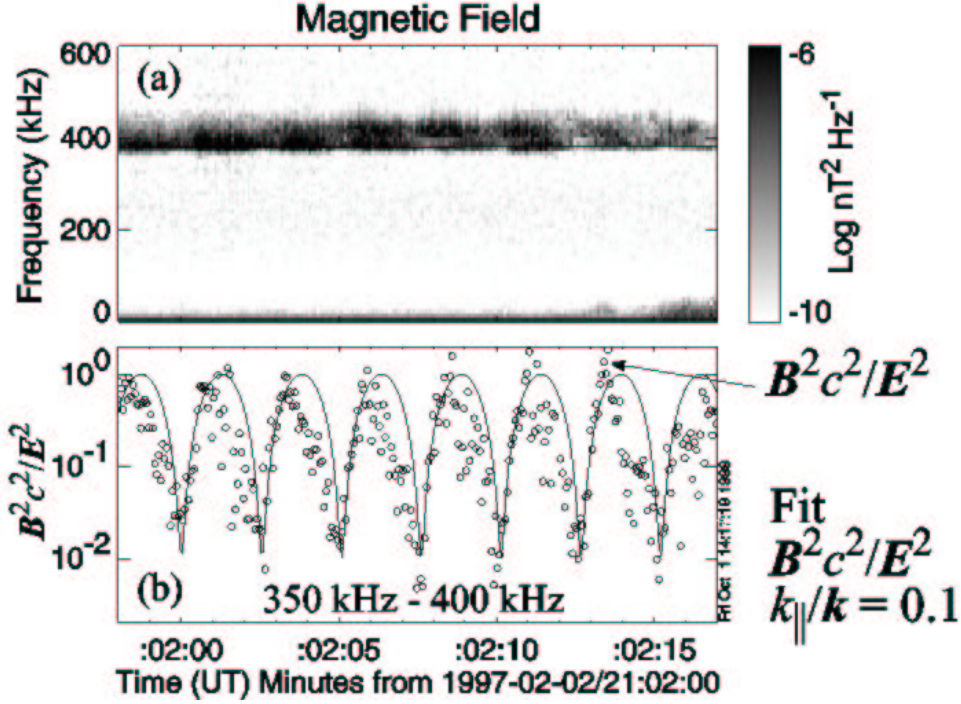


Figure 4: (a) The magnetic spectral power density. These data are from a single search coil in the satellite spin plane and therefore show strong spin modulation. The time span is 19 s. (b) The ratio of magnetic energy density and electric energy density (circles). The magnetic field energy density is spin modulated whereas the electric field energy density is from two antennas and therefore not modulated by spin. The solid line is the predicted ratio if $k_{\parallel}/k = 0.1$, the limit of uncertainty in the measurement. The uncertainty in the magnetic field polarization comes primarily from the compilation time of the frequency versus time spectrogram (64 ms). In that time, the satellite (5 s period) rotates 4.6° . Electrostatic pick up at ~ 400 kHz, can account for 2% (1°) uncertainty. The data indicate that the wave magnetic field is within $\sim 6^\circ$ of the ambient magnetic field.

4 Discussion

Observations of electron distributions and electromagnetic waves within the AKR source region allowed us to resolve the properties of electron–cyclotron maser instability. Since the theory of electron–cyclotron masers is well developed, we concentrate our discussion on the differences between the shell maser and the loss–cone maser. The convective growth limitation has been one of the more controversial aspects of the loss–cone driven electron–cyclotron maser [Omidi and Gurnett, 1982]. Under linear theory, a ray is amplified by a factor $e^{\beta\tau}$, where β is the growth rate and τ is the time that the ray can experience amplification. The latter value is as important as the growth rate. The loss–cone maser predicts an oblique group velocity with a component parallel to $\mathbf{B}_0$ of $\sim 0.1 c$. The motion along $\mathbf{B}_0$ causes the ray to go out of resonance (e.g., equation 1) with the maser since the ambient electron cyclotron frequency changes along the ray path. The observed bandwidths of AKR are ~ 1 kHz, so a change in f_{ce} of roughly 1 kHz will arrest growth.

Such a change, on Earth, occurs in ~ 8 km, limiting τ to ~ 0.3 ms. This implies that growth rates would have to exceed the wave bandwidth for significant amplification to occur which is an unphysical result. Furthermore, such large growth rates are not supported by observed distributions. The shell maser, on the other hand, does not suffer such a strong limitation. Since the emissions propagate perpendicular to $\mathbf{B}_0$, the ray can travel much farther before experiencing a significant change in the ambient magnetic field. These conclusions are supported by recent two-dimensional simulation results [Pritchett et al., 1999] that demonstrate that a loss-cone instability is considerably weaker than the shell instability.

One can carry out a similar analysis of the emissions from Jupiter. The loss-cone instability would not be affected by spatial gradients of the ambient magnetic field for the HOM (Jovian hectometer-wavelength) emissions which are produced at several R_J in altitude. On the other hand, the loss-cone at those altitudes would be extremely narrow, and one would expect the loss-cone maser to saturate rapidly. The DAM (Jovian decameter-wavelength) emissions, however, are generated at lower altitudes. The convective growth limitation may come into play for narrow-band width emissions. An important implication of the recent AKR observations is that the most powerful planetary radio emission process is associated with a parallel electric field in a dipole magnetic field geometry. There are two conditions for direct amplification of electromagnetic waves by the electron-cyclotron maser [Wu and Lee, 1979]. The unstable distribution needs to be created and a low plasma density such that $f_{pe} \ll f_{ce}$ is required. The parallel electric fields set up both of the necessary conditions for direct amplification of electromagnetic waves. Planetary auroral radiation has been observed from all of the magnetized outer planets [Zarka, 1992b, 1998] which includes Jovian decametric and hectometric radiation. Most of the planetary radiation models are derived from the auroral AKR model and incorporate the electron-cyclotron maser. These models include acceleration of electrons by a parallel electric field in a dipole magnetic geometry. The application of the shell maser to planetary emissions is particularly compelling in the light of the FAST satellite observations. The shell instability, however, appears more feasible because it is now proven as the source of terrestrial radiation; it is a more powerful source, and is directly associated with particle acceleration. The shell maser and the loss-cone maser are nearly impossible to distinguish from remote observations. The differences are quite subtle. The shell instability calls for generation entirely in the X-mode with $k_{\parallel} = 0$. Emissions from the shell maser propagate at 90° from $\mathbf{B}_0$ in the source region, whereas the loss-cone maser emissions propagate at an oblique angle. Terrestrial AKR, however, show strong beaming patterns indicating strong refraction. Ray refraction can confound an interpretation of remote observations. The shell maser emissions are slightly below f_{ce} and the loss-cone maser is slightly above, an distinguishable difference if observed remotely. Both types of masers are expected to produce narrow-band width emissions. There are two possibly detectable differences. The shell maser can produce strong, continuous emissions whereas the loss-cone maser is expected to saturate rapidly, and the shell maser can produce emissions high above the planetary surface where the loss-cone is too narrow to support a strong instability. The shell instability can explain the Jovian emissions at high-altitude [Zarka et al., 2001a].

5 Conclusions

The electron–cyclotron maser is a well–suited mechanism to explain high intensities, high degrees of circular polarization, and narrow bandwidth emissions of planetary radiation. The FAST satellite observations have now provided conclusive evidence that the electron–cyclotron maser driven by a shell instability is responsible for the coherent generation of AKR. The radiation source region must be in a depleted cavity, such that the right cut–off is below f_{ce} ($f_{right} < f_{ce}$). The condition for growth is given by $\xi_{\Phi}/m_e c^2 > 2f_{pe}^2/f_{ce}^2$, where $f_{pe} \ll f_{ce}$. A magnetic mirror is required so that the electrons adiabatically evolve to higher pitch angles forming a shell. Simulations and observations do not support the loss–cone as the free energy source, and demonstrate that the shell maser is a far more powerful radiation source.

Under the shell maser, amplification occurs at frequencies between f_{ce}/γ and f_{ce} . The bandwidth of the radiation depends upon the acceleration potential, limited roughly by $(\gamma - 1)/\gamma$. Growth occurs in the X–mode with $k_{\parallel} = 0$. Particle acceleration is from parallel electric fields; it is very difficult to envision any other acceleration mechanism that creates the shell distributions and the density depleted cavities. The shell instability appears to be a feasible mechanism for many sources of planetary radiation. It is now proven as the source of terrestrial radiation. It has been shown to be a more powerful source through simulations, it does not suffer from severe convective growth limitations, it can explain continuous emissions and emissions at high altitude, and is directly associated with particle acceleration. The outer planet observations need to be re–analyzed in the light of these new findings.

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