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Ray tracing model of the AKR generation in the 3-D plasma cavity

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Abstract

Propagation and amplification of the auroral kilometric radiation (AKR) in a 3-D plasma cavity is investigated using the approximation of the geometrical optics, taking into account both the slightly relativistic electrons propagating inside a source region and cold background electrons. It is found that the most pronounced contribution to the AKR spectra is given by waves initially generated with a component of the group velocity directed to the Earth.

1. Introduction

Now it is reliably established that AKR sources are thin cavities oriented tangentially to the auroral oval and aligned with the background magnetic field [4, 6]. They have a small latitudinal width about several tens of kilometers as compared with their longitudinal extent on the order of thousand kilometers. Plasma of AKR sources is tenuous with electron population essentially composed of downward-going slightly relativistic particles. Peculiar feature of the electron distributions observed inside the sources is an accumulation of particles with high transverse energies about several KeV but low parallel velocities. The electron cyclotron maser instability [8] is widely accepted to be the fundamental mechanism responsible for generation of the terrestrial AKR, and similar radio emissions from the solar system's planets having their own magnetic field. The AKR is strongly polarized emission generally observed to be generated below the local electron gyrofrequency, and mainly propagating as the extraordinary X-mode waves [7]. There is a long-standing question arising in studies of cyclotron maser instability in a localized space region with a reduced density: how radiation generated below the cutoff frequency of the external cold plasma would escape from a source or, in other words, gets onto the branch of the cold plasma dispersion. The upward propagation of waves inside a source region due to the global magnetic field inhomogeneity until their frequency becomes higher than the cutoff frequency of surrounding plasma has been qualitatively discussed by Louarn and Le Quéau [4]. The role of magnetic field gradients in wave radiation outwards from a plasma cavity was emphasized by Cairns et al. [2]. Taking into account the occurrence of low frequency waves in the regions of the AKR generation, a wave escape from a thin plasma cavity with adiabatically slowly varying width was considered in [1], where was shown that there can exist localized regions from which the X-mode waves, growing in time, can be radiated outwards. However up to now, the factors influencing the AKR escape from a source are still not clearly understood.

2. Physical model

In the present study we use the ray tracing approximation in the 3-D finite cavity taking into account both background cold electrons and slightly relativistic electrons. Our objective is to investigate the wave amplification inside a plasma cavity, and estimate the wave intensity at the instant the wave leaves a source region. We assume that energetic electrons possess a ring distribution that does not significantly modified results obtained with the use of more realistic distributions [3]. The propagation of waves is investigated using the equations of the geometrical optics. The growth rate is found as a solution of the dispersion relation at every point along the ray path. The model density-depleted cavity has a small latitudinal width with the central invariant latitude $\theta_0 = 70^0$ and is aligned with the latitude. In spherical coordinate system a density profile of the background plasma is given by

$$n_{cold} = \frac{n_0}{(r/2R_E)^2}\left[1-\exp\left(-\frac{(\theta-\theta_0)^2}{\sigma_\theta^2}-\frac{(\varphi-\varphi_0)^2}{\sigma_\varphi^2}\right)\right]$$

and a density profile of source energetic electrons is given by

$$n_s = \frac{n_{s0}}{(r/2R_E)^2}\left[1-\exp\left(-\frac{(\theta-\theta_0)^2}{\sigma_\theta^2}-\frac{(\varphi-\varphi_0)^2}{\sigma_\varphi^2}\right)\right]$$

Here R_E is the Earth radius, n_0 is the density of cold background electrons at $r = 2R_E$ outside a cavity, n_{s0} is the density of energetic electrons at the centre of the cavity ($\theta_0 = 70^0$, $\varphi_0 = 0$) and $r = 2R_E$, σ_θ and σ_φ are the characteristic cavity widths in θ and φ directions. In our calculations we have used parameters adapted to the AKR generation region at $r = 2R_E$: the electron energy and density inside the source are taken ~4 KeV and 1cm $^{-3}$, respectively, and the background density outside the source is 5 cm $^{-3}$, $\sigma_\theta = 0.008$, $\sigma_\varphi = 0.23$. The ions are presumed to be immobile and to play the role of a neutralizing background. The dipolar magnetic field model is adopted in this study. Since the cyclotron maser instability driven by a ring or a shell-like electron velocity distribution has the largest growth rate for generation of X-mode waves near perpendicular to the magnetic field direction preferentially quasitangentially to source boundaries [4,6], we consider waves excited predominantly along the latitude.

3. Results and Conclusions

The time history of different waves launched from the center of the cavity at $r = 2R_E$ has been studied. It was found that wave dynamics strongly depends on their initial coordinates in the k -space. For some X-mode waves there is a possibility to be converted into the Z-mode waves and stay inside a cavity because there is an additional branch of the dispersion relation in the relativistic plasma connected together the X-mode and Z-mode waves. However the main part of waves escapes from a cavity as the X-mode waves. Although the largest growth rate for the X-mode emission is near perpendicular wave-normal angle in a homogeneous plasma, our results have shown that in the inhomogeneous plasma with a global magnetic field gradient the initial value of the wavevector component aligned with a local magnetic field plays an important role in a wave amplification. The most pronounced contribution to the AKR spectra is given by waves launched rather closely to the perpendicular to the magnetic field direction but with a sufficient wavevector component directed to the Earth (remind that the X-mode wave index N<1). Initially these waves propagate downward to the point where their radial group velocity becomes zero. After reflection they propagate upward inside a source region until their frequencies become larger than the cutoff frequency of the surrounding plasma. The longer a wave is inside a source, the more energy is gained. The amplification factor for waves excited with a wavevector directed upward from the Earth is far lower. All waves are refracted upward during their propagation inside a cavity and as they leave it. These model results are strongly supported by experimental observations demonstrating that the AKR radiating diagram is confined within 15 -25 degrees about the magnetic field vector in the source [5, 6].

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