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Electron Cyclotron Maser Instability in the Sources of Saturn's Kilometric Radiation

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Abstract

Saturn's Kilometric Radiations (SKRs) are usually observed with characteristics of extraordinary-mode (X-mode) emissions at electron cyclotron frequency, excited via electron cyclotron maser instability (ECMI) of electron inside the source region. Previous studies on ECMI of SKR sources haven't employed appropriate dispersion relations. When considering the relativistic effect appropriately, the cut-off frequency of X mode could be modified, while the relativistic mode is present with considerable amounts of energetic electrons. Using particle-in-cell simulation, we studied the ECMI process in the SKR sources with parameters obtained with in situ measurement of Cassini mission. According to the previous reports, in the encounter of the SKR source, the density ratio of energetic electrons to total electrons $\frac{n_e}{n_0}$ was 24%, and the ratio of plasma frequency to electron cyclotron frequency $\frac{\omega_{pe}}{\Omega_{ce}}$ was 0.046. The simulation results suggest that with the observed parameters, X mode emissions cannot be directly amplified, while the non-escaping R mode is most unstable. We carried out further parametric studies with theoretical analysis and simulations, and found that X mode can be excited with the energetic electrons dominating (with density ratio over 90%). The properties of both R and X modes are consistent with the observed SKR emissions. The study provides new insight in to the ECMI processes of SKR.

1. Introduction

In strongly magnetized plasmas (with frequency ratio $\frac{\omega_{pe}}{\Omega_{ce}} \ll 1$, where ω_{pe} and Ω_{ce} represent the plasma frequency and electron gyro-frequency), electrons with strong anisotropy could generate X-mode emissions via gyro-resonance. Electron Cyclotron Maser Emission (ECME) has been widely applied to auroral radio emissions of magnetized planetary, including Earth, Jupiter, and Saturn [1, 2]. Saturn's kilometric radiatioins (SKRs) are usually observed with frequencies of kHz to MHz, close to the electron gyro-frequency of the source region.

With the in situ observation of Cassini, the properties of SKR sources have been extensively investigated [3]. The electrons in the source region consist of two components of electrons: energetic electrons with shell-like distribution and cold electrons with kappa or Maxwellian distribution[4]. Previous studies [5, 6] employed simplified dispersion relations of pure relativistic energetic electrons to calculate the growth rate of ECMI, and propose that X mode could be amplified. Nevertheless, the density ratio of energetic to total electrons (n_e/n_0) was fitted as 20%--24% with the in situ measurement. For plasmas consisting of both cold and energetic electrons, the dispersion relations are usually modified with the non-escaping relativistic (R) mode, being the most unstable [7]. This mode has not been considered in previous studies on ECMI of SKR sources.

In this paper, we performed theoretical analysis and numerical simulations to investigate the ECMI process excited by the electrons inside the SKR sources with the measured electron distribution functions and plasma parameters reported in earlier studies [6]. A parametric study on density ratio is carried out, to clarify the excitation of X-mode emissions of SKRs.

2. Theoretical analysis

We follow Pritchett's study [7, 8] to derive the dielectric tensors of plasmas, employing the electron velocity distribution functions as below

$$f = \left(1 - \frac{n_e}{n_0}\right)\delta(u_\perp)\delta(u_\parallel) + \frac{n_e}{n_0}\delta(u_\perp - u_r)\delta(u_\parallel) \quad (1)$$

Where n_e and n_0 represents the number density of energetic and total electrons, respectively, $u_r = 0.2\,c$ represents the momentum of energetic electrons with a ring distribution. With the derived dielectric tensors, we obtain the dispersion relation of the plasma waves and the growth rates of unstable modes with varying density ratio (Figure 1).

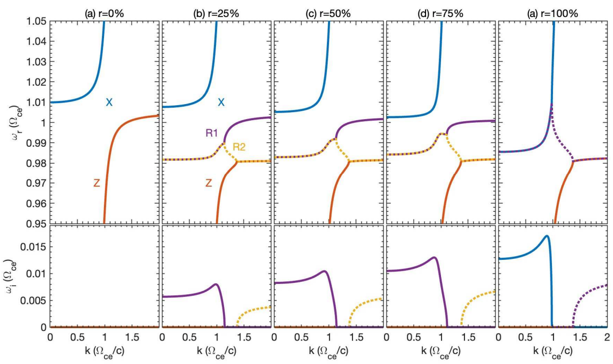

Figure 1. The dispersion relation (upper panels) and growth rates (lower panels) of extraordinary modes propagating perpendicularly to the background magnetic field with varying density ratio. The results are obtained by solving the dielectric tensors of linear theory analysis.

To simplify the equation, we consider the waves perpendicular to the ambient magnetic field. We find that with no energetic electrons, the dispersion relation is the same as the modes of magnetoionic theory of cold plasmas, containing escaping X mode and non-escaping Z mode waves. The growth rates of the two waves are zero, in the absence of free energy. With the existence of the energetic electron component ($\frac{n_e}{n_0} > 0$), two conjugate pairs of solutions emerge around the electron gyro-frequency. These two modes (R1 and R2) are both non-escaping modes with a resonance frequency of Ω_{ce} and $\frac{\Omega_{ce}}{\gamma}$ (γ refers to the Lorentz factor of energetic electrons), respectively. With large values of wave number k, R2 is coupled with Z mode. With $0 < \frac{n_e}{n_0} < 100\%$, the R modes are most unstable with a growth rate of ~0.01 Ω_{ce}, which rises with the abundance of energetic electrons. In this case, X mode cannot be amplified, with the cutoff frequency $\omega_X > \Omega_{ce}$.

With $\frac{n_e}{n_0} = 100\%$, the dispersion relation is significantly modified, with R mode and X mode coupled together with small values of k ($k < 1\,\Omega_{ce}/c$). The X-mode cutoff frequency (ω_X) is shifted lower than Ω_{ce}. Under this condition, X mode is most unstable with a growth rate over 0.015 Ω_{ce}.

3. PIC simulation

To study the ECMI of electrons inside the SKR sources self-consistently, we carry out 2D3V fully kinetic electromagnetic PIC simulations to investigate the wave amplification with the VDFs and plasma parameters of SKR sources obtained in the early reports. We employed the Vector-PIC (vPIC) code [9] developed by Los Alamos National Laboratory (LANL).

We perform simulation in the xOz plane with a uniform density and background magnetic field in the domain, employing periodical boundary conditions of fields and particles. The background magnetic field are along the z direction; the ratio of plasma frequency to electron cyclotron frequency $\frac{\omega_{pe}}{\Omega_{ce}}$ was 0.046. The domain is set with 2048×2048 grids, and the grid length was set with 0.019 λ_{DE}. We include two components of electrons: electrons with Maxwellian distribution representing the low-energy component (with thermal velocity of 0.01 c); the electrons with DGH distribution representing the energetic component. Note that all the parameters of energetic electrons are obtained by the in situ measurement as reported in the previous study [6]. The density ratio n_e/n_0 was fitted to be 24% in the SKR sources. For each component of electrons we employed 1000 macroparticles per cell and 500 for protons per cell, with a realistic proton-to-electron mass ratio of 1836. Charge neutrality was maintained.

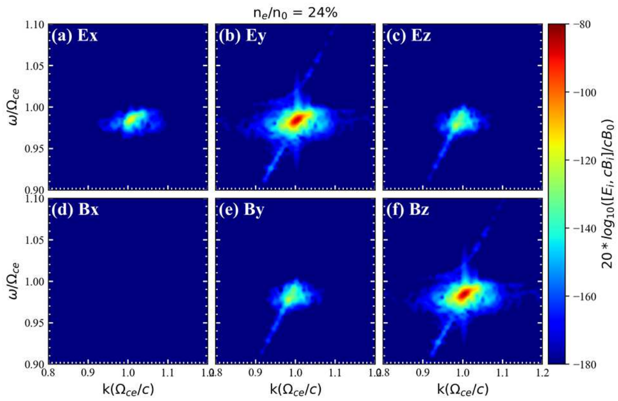

Figure 2. The $\omega - k$ dispersion relation along the perpendicular direction of six field components in the PIC simulation. The density ratio $\frac{n_e}{n_0} = 24\%$.

We perform fast Fourier transform (FFT) analysis on the six field components, to study the wave amplification. We show the $\omega - k$ dispersion diagrams along the perpendicular directioin ($\theta_{kB} = 90°$, the angle between wave vector and background magnetic field). With the reported parameters, the strongest waves are amplified with the frequency ~0.98 Ω_{ce}, which are most intense in Ey and Bz components, indicating a significant transverse electromagnetic wave. This mode can be identified as R mode, in accordance with the theoretical analysis. However, no significant growth of X mode can be observed in the simulation.

We further performed parametric study of the density ratio. With n_e/n_0 of 10%, 24%, 50%, 70%, 90%, and 100%, we perform PIC simulation (with other parameters fixed) and carry out FFT analysis on each field component. Figure 3 presents the results of Ey component of all the cases, since the amplified waves are most significant in this component. For cases with $\frac{n_e}{n_0} < 90\%$, R mode is the most intense wave. With the increasing value of the density ratio, the growth of R mode gets more significant, and expands in the $\omega - k$ domain, approaching the X mode dispersion.

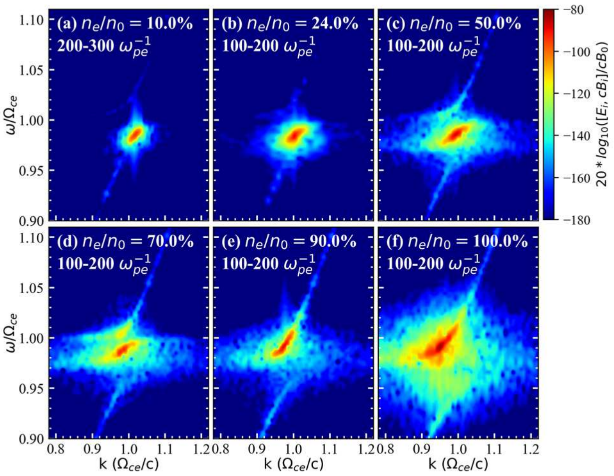

Figure 3. The $\omega - k$ dispersion relation of Ey component obtained in the PIC simulation, with $\theta_{kB} = 90°$, density ratio $\frac{n_e}{n_0}$ varying from 10% to 100%.

In the rest cases, energetic electrons get dominant ($\frac{n_e}{n_0} =$ 90% and 100%) in the plasma system, the R mode and X mode merge together, and grows significantly. The modified X mode has a lower cutoff frequency $\omega_X \sim 0.97\ \Omega_{ce}$. The energy conversion rate of X mode (the ratio between the energy of X-mode wave and initial kinetic energy of total electrons) was 3%. We note that, in all the cases, the amplified X and R modes exhibit similar features, such as frequency, wave number, and wave fields.

4. Summary and Discussion

To clarify the ECMI processes in the SKR sources, we performed theoretical analysis and PIC simulation with the reported parameters of electrons and plasmas of the in situ observation of Cassini mission. We find that with the measured density ratio of energetic to total electrons $\frac{n_e}{n_0} =$ 24%, the ECMI mainly generate non-escaping R mode, while X mode cannot grow. X mode emissions can be amplified only with the energetic electrons are dominant in the system ($\frac{n_e}{n_0} \geq 90\%$). The results can be explained well with the analysis of plasma kinetic theory.

With the measured parameters, we got significant excitation of the trapped R mode, which may not explain the SKR phenomena. We note that the CAPS/ELS instruments onboard Cassini spacecraft measures the electrons in a long duration (3 min to cover the whole pitch angle). The ECMI process, however, usually happens in much smaller time scales (100 Ω_{ce}^{-1}), and the electron VDFs diffuse accordingly. The measured electrons may not be the direct driver of ECMI of the sources.

We note that in our simulation, the amplified R and X modes exhibit similar characteristics. With the in situ observation, it would be hard to distinguish these two modes. This study raise questions on distinguishing the sources of escaping SKR emissions and the non-escaping R-mode fluctuation with the in situ measurement.

5. Acknowledgements

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