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EMIC waves around the plasma-pause region

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Abstract

Electromagnetic ion-cyclotron (EMIC) instability has been studied using the general loss-cone distribution function by investigating the trajectories of charged particles and using the method of particle aspect analysis. A low β (ratio of plasma pressure to magnetic pressure) plasma consisting of resonant and non-resonant particles has been considered. It is assumed that the resonant particles participate in energy exchange with the wave, whereas non-resonant particles support the oscillatory motion of the wave. The wave is assumed to propagate parallel to the static magnetic field. The effects of steepness of loss-cone distribution with thermal anisotropy are discussed. The growth rate, perpendicular and parallel resonant energies of the particles and marginal instability condition are derived. The effect of general loss-cone distribution function is to enhance the growth rate of EMIC waves. The results are interpreted for the space plasma parameters appropriate to the plasma-pause region of the earth's magnetoplasma. The results of the work is consistent for EMIC emissions observation by SAMPEX and CRRES satellite around the plasma-pause region as reported by Bortnik et al. [Bortnik, J., Thorne, R.M., O'Brien, T.P., Green, J.C., Strongeway, R.J., Shprits, Y.Y., Baker, D.N., 2006. Observation of two distinct, rapid loss mechanisms during the 20 November 2003 radiation belt dropout event. J. Geophys. Res. 111, A12216, doi:10.1029/2006JA011802] and Xinlin et al. [Xinlin, Li., Baker, D.N., O'Brien, T.P., Xie, L., Zong, Q.G., 2006. Correlation between the inner edge of outer radiation belt electrons and the innermost plasmapause location. Geophys. Res. Lett. 33, L14107, doi:10.1029/2006GL026294].

Keywords: Electromagnetic ion-cyclotron instability; Loss-cone distribution; Thermal anisotropy; Plasma-pause region; Particle aspect analysis

1. Introduction

The outer boundary of the plasmasphere is referred to as the plasma-pause region where the plasma density has a steep gradient. Carpenter et al. (1971) reported the position of the plasma-pause related to the region of enhanced trapped energetic electrons. Xinlin et al. (2006) have renewed interesting features about the plasma-pause region. Moldwin et al. (2002) using CRRES satellite observations reported clear and sharp 'classic' isolated steep density gradients and that plasma-pause observations with significant structure or density cavities were more common. During storm times, the pitch angle scattering of the radiation belt electrons is more prominent near and just outside the plasma-pause where electromagnetic ion-cyclotron (EMIC) waves are also noticed Albert (2003).

EMIC waves play an important role in the overall dynamics of space plasmas. They not only act as a useful diagnostic of the relevant physical processes, but they can also affect the macroscopic plasma state by influencing the transport properties. These waves preferentially generated in high-density region. Horne and Thorne (1993) provided even faster loss of MeV electrons on the scale of hours which affects only relativistic electrons since resonant energies for interaction with EMIC waves are above 0.5 MeV (Summers and Thorne, 2003; Albert, 2003). Bortnik et al. (2006) have reported that rapid losses of the outer radiation belt electrons can be attributed to resonant wave particle interaction between a variety of plasma waves and energetic electrons (Kennel and Engelmann, 1966), which drive pitch angle scattering into the drift and bounce loss cone. The evidence of the presence of EMIC waves and associated thermal electron

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heating (Cornwall et al., 1970) at low latitudes is found indirectly through studies of thermosphere heating.

Spasojevic et al. (2004) reported that the sunward transport of ring current ions during distributed periods produces anisotropic ($T_\perp > T_\Pi$) particle distributions through adiabatic heating. Solar wind compressions of the magnetosphere can also increase the ion anisotropy (Anderson and Hamilton, 1993). The EMIC instability is derived by the thermal anisotropy of the hot ring current proton distribution in the outer magnetosphere. The thermal anisotropy is the free energy source for the EMIC instability. This instability has maximum growth rate at propagation parallel and anti parallel to the background magnetospheric magnetic field, so that protons are predominantly pitch angle scattered by the wave. Wave particle interactions strongly scatter particles only when the anisotropy is sufficiently strong to excite the instability. This pitch angle scattering acts to reduce the free energy source.

The observational study by Xinlin et al. (2006), Bortnik et al. (2006), Fuselier et al. (2004) and Spasojevic et al. (2004) provides the authensity to our theoretical model which describe the EMIC wave structure in plasma-pause region. The present analysis is based upon (Dawson's, 1961) theory of Landau damping which was further extended by Terashima (1967), Misra and Tiwari (1979), Varma and Tiwari (1992, 1993), Dwivedi et al. (2001, 2002), Shandilya et al. (2003, 2004), Mishra and Tiwari (2006), Ahirwar et al. (2006, 2007) to the analysis of electrostatic and electromagnetic instabilities. The whole plasma is considered to consist of resonant and non-resonant particles. Non-resonant particles support the oscillatory motion of the EMIC waves whereas, the resonant particles participate in the energy exchange with the wave. An EMIC wave starts at $t=0$, when the resonant particles are not disturbed. Using the particle trajectory in the presence of EMIC wave, the dispersion relation and growth rate are derived and discussed for different distribution indices and the thermal anisotropy around the plasma-pause. In the present study, we focus our attention to explain the EMIC wave generation and energy transfer in the plasma-pause region accordance to the observations by Solar, Anomalous, and Magnetospheric Particle Explorer [SAMPEX] and Combined Radiation and Release Experiment Satellite [CRRES] satellite.

2. Basic assumptions

The left-handed circularly polarized EMIC wave having angular frequency ω is defined by Ahirwar et al. (2006, 2007) as,

$$B_x = B\cos(kz-\omega t), \qquad B_y = B\sin(kz-\omega t). \tag{1}$$

When the system is co-moving with the wave, the electric field vanishes. Thus, the wave magnetic field has the form,

$$B = B_x(\cos kz)\boldsymbol{x} + B_y(\sin kz)\boldsymbol{y}, \tag{2}$$

where the following conditions are valid,

$$z^{\text{wave}} = z^{\text{lab}} - \left(\frac{\omega}{k}\right)t, \tag{3a}$$

$$v^{\text{wave}} = v^{\text{lab}} - \left(\frac{\omega}{k}\right). \tag{3b}$$

Since $ck/\omega \gg 1$, the magnetic field amplitude may be regarded identical in both systems. Considering the equation of motion of ions and the general loss-cone distribution function the energy calculations and derivation of growth rate are performed by Ahirwar et al. (2006, 2007).

The general loss-cone distribution function is expressed as (Ahirwar et al., 2006, 2007),

$$N(\bar{V}) = N_0 f_\perp(V_\perp) f_\Pi(V_\Pi), \tag{4}$$

where

$$f_\perp(V_\perp) = \left[\frac{V_\perp^{2J}}{\pi V_{T\perp}^{2(J+1)} J!}\right]\exp\left(-\frac{V_\perp^2}{V_{T\perp}^2}\right), \tag{5}$$

and $f_\Pi(V_\Pi)$ is defined by (Varma and Tiwari, 1992)

$$f_\Pi(V_\Pi) = \left(\frac{1}{\sqrt{\pi}V_{T\Pi}}\right)\exp\left(\frac{-V_\Pi^2}{V_{T\Pi}^2}\right), \tag{6}$$

where J is the distribution index and measures the steepness of the loss-cone feature (Tiwari and Varma, 1991, 1993; Varma and Tiwari, 1992). In the case of $J=0$ this represents a bi-Maxwellian distribution and for $J=\infty$ this reduces to the Dirac delta function (Tiwari and Varma, 1993). $V_{T\Pi}^2 = 2T_\Pi/m$ and $V_{T\perp}^2 = (J+1)^{-1}(2T_\perp/m)$ are the squares of parallel and perpendicular thermal velocities with respect to the external magnetic field.

3. Dispersion relation and particles energy

We consider the cold plasma dispersion relation for the EMIC wave as (Misra and Tiwari, 1979; Ahirwar et al., 2006, 2007),

$$\frac{c^2k^2}{\omega^2} = \left(\frac{\omega_{\text{pi}}^2}{\Omega^2}\right)\left(1-\frac{\omega}{\Omega}\right)^{-1}, \tag{7}$$

where $\omega_{\text{pi}}^2 = (4\pi N_0 e^2)/m_i$ is the square of plasma frequency for the ions and $\Omega = qB_0/mc$ is the ion-cyclotron frequency, m is the mass of the ion and q is the charge of ion and c is the velocity of light.

The wave energy density W_{w} per unit wavelength is the sum of the pure field energy and the changes in the energy of the non-resonant particles, i.e. the total energy per unit wavelength is given as

$$W_{\text{w}} = U + Wi, \tag{8}$$

where U is the energy of electromagnetic wave as defined by the expression (Misra and Tiwari, 1979) as

$$U = \left(\frac{1}{16\pi}\right)\left[\left(\frac{\text{d}}{\text{d}\omega}\right)(\omega\varepsilon_{ik})E_1^*E_k + |B|^2\right], \tag{9}$$