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A Study of Bit Condition for Generation Rx -Mode Waves: Interaction of Particles with Z/UH-Mode Waves

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Abstract

Interactions of charge particles with electromagnetic waves have important effects (linear and nonlinear) on the propagation of electromagnetic waves, and it can somewhat play a role in generation of the new mode waves. Besides, the particle energies can play an important role in causing instability in plasma. The values of parallel energy of the particles have been calculated so that they can satisfy the nonlinear coupling condition. Furthermore, a result for instability is presented and the initial parameters inferred from the observational data are used. The results show that the nonlinear coupling (particle-wave interaction) can be a candidate for the generation of RX mode wave in equatorial plasmasphere. Besides, the results show that energetic particles that participate in particle - wave interaction have an energy range from 0.058 to 10.23keV. This range of particle energy particle is in agreement with the observation.

Keywords: Particle energies, Instability, Nonlinear wave-particle.

1. Introduction

Charge particles are a main component of plasma environments such as solar wind, magnetosphere, plasmasphere and ionosphere. It is well known that the particles energies have an important role in transporting energy and in causing instability in plasma. The interaction of an energetic electron with a background plasma and the instabilities associated with this interaction have a long history of investigation (Pierce, 1948). Further, the particles can interact with electromagnetic waves, and somewhat this interaction can lead to the generation of the new mode waves. Lee et al. (1980) studied the amplification of electromagnetic waves via the cyclotron maser mechanism by a population of weakly relativistic electrons. They considered a low plasma frequency and found that the ordinary and extraordinary modes can be excited; Freund et al. (1983) applied that for the astrophysical plasma with different types of velocity distribution. By using a one-dimensional electromagnetic particle code with different values of the electron beam-to-plasma density ratio for the high density electron beams, Zhou et al. (1998) showed that these waves (high-frequency electromagnetic waves) can be excited and the nonlinear effects will occur. Usui et al. (2001) studied the nonlinear wave/wave-particle interaction associated with the microwave power transmission in space plasma by performing one-dimensional simulation with the electromagnetic PIC model.

Besides, energetic electrons with energies in the keV range are frequently observed in the equatorial plasmasphere and also, plasma waves are frequently observed in the equatorial plasmasphere. Based on simultaneous observations of plasma waves and energetic particles, it has been shown that electromagnetic waves are related to unstable particle distributions localized in equatorial regions (Kurth et al., 1980). Kalaee and Katoh (2015) simulations showed that electromagnetic Z- and RX-mode waves could be coupled by a nonlinear interaction, where the values of the parallel components of both two modes are the same.

In this work, the nonlinear coupling condition was also focused on, but with a purpose that the values of the parallel components of both two modes are not the same. In this case, the values of parallel energy of the particles that can satisfy the nonlinear coupling condition were calculated. Furthermore, a result for the instability is presented by using the initial parameters inferred from observational data obtained by the Akebono satellite around the plasma-wave generation region.

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2. Observations and Calculations

Typical observation events at the generation site of RX-mode waves analyzed in this study were found during the period from 3:30 UT ($L \approx 2.5$) to 3:55 UT ($L \approx 2.3$) on February 4, 1992, when the Akebono satellite passed through the storm time geomagnetic equator; see Figure 1. In Figure 1, four reference curves indicate the characteristic frequencies of RX mode wave cutoff, UHR, plasma frequency and Z-mode wave cutoff. The vertical dash line at the middle of the panel shows the magnetic equator. The initial parameters of the observation are given in Table 1 including plasma frequency, upper hybrid frequency, cutoff frequency of Z-mode and cutoff frequency of RX mode waves. All of them are normalized by cyclotron frequency ($f_{ce} = 65.5kHz$).

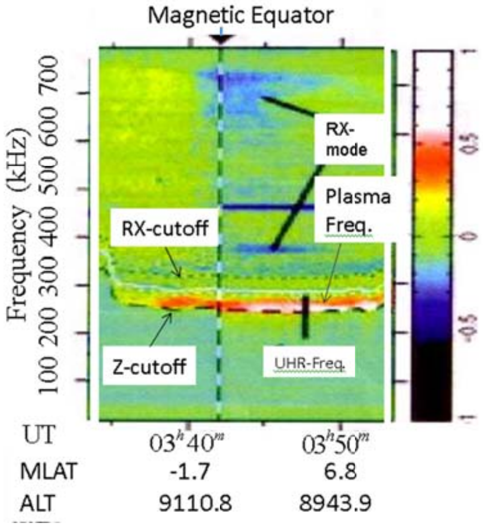


Figure 1. An example of the dynamic spectrum around the magnetic equator on February 4, 1992.

Table 1. The values of important frequencies from observation satellite that are used in the current work. All of them are normalized by cyclotron frequency.

Plasma Freq.	4.1
UHR Freq.	4.2
Z-mode Cutoff Freq.	3.63
Rx-mode Cutoff Freq.	4.63

As the first step, the analysis of the linear growth rate was performed. It was assumed that energetic electrons had a ring distribution (Nishimura et al., 2007; Li et al., 2010; Kalaee et al., 2013, 2015) in a momentum space,

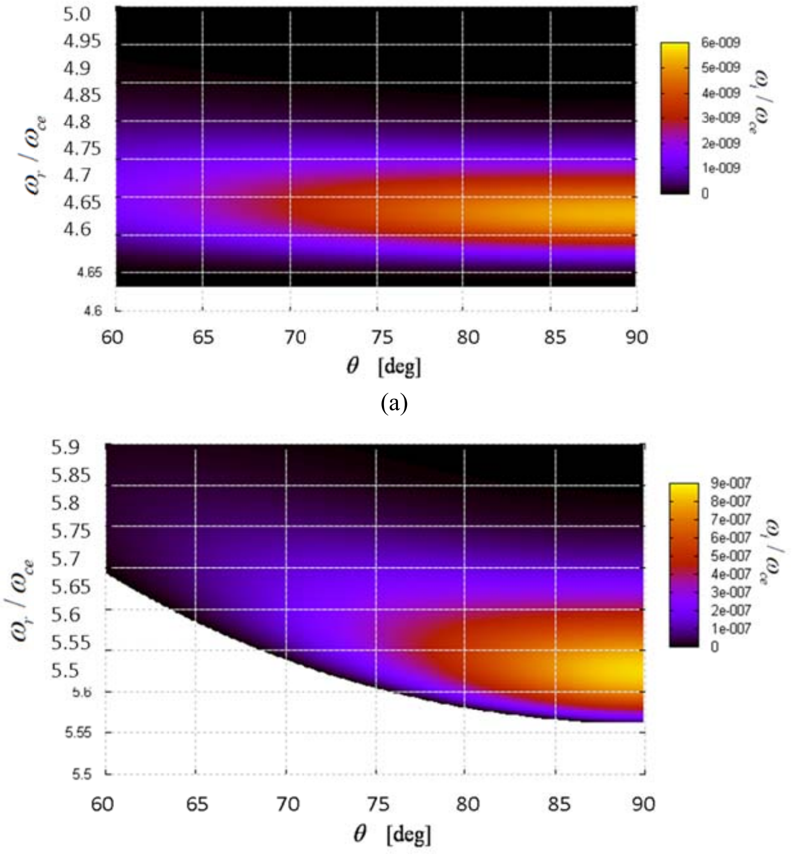
$$f_{\|}\left(u_{\|}, u_{\perp}\right) = \frac{n_h}{\sqrt{\pi^3} A_{\|} A_{\perp}^2 c^3} \exp\left(-\frac{1}{A_{\perp}^2}\left(\frac{u_{\perp}}{c} - \frac{u_{\perp 0}}{c}\right)^2 - \frac{1}{A_{\|}^2}\left(\frac{u_{\|}}{c} - \frac{u_{\|0}}{c}\right)^2 \right) \tag{1}$$

where A^2 is the variance of the normalized momentum, which corresponds to temperature, and $u_{\|0}$ and $u_{\perp 0}$ are the average momentum. The relativistic cyclotron resonance condition is given by

$$\gamma\omega_{\mathrm{r}} - k_{\|}u_{\|} - n\Omega_{ce} = 0 \tag{2}$$

where Ω_{ce}, γ, and n are the cyclotron frequency, the Lorentz factor, and the order of resonance, respectively. The parameters adopted for the ring distribution given by Equation (1) are $n_{\mathrm{h}} = 1/cc$, $u_{\perp 0}/c = 0.4 \sim$ 40 keV, $u_{\|0}$=0, and $A = A_{\|} = A_{\perp} = 0.1 = 17.5$ keV. The cold background component, $n_{\mathrm{c}} = 1000/cc$, and A=1.4×10^{-3}=1 eV were estimated in the Akebono/PWS analysis.

Figure 2a and Figure 2b show the growth rate of RX mode waves based on linear growth rates where $\omega_p/\omega_{ce} = 4.1$, with the ring-type distribution and with n = 5 and n= 6, respectively. The maximum value of growth rate is approximately, 6.0×10^{-9} and 9.0×10^{-7} for θ=90°. The RX mode frequencies are in the range from 4.65 ω_{ce} to 4.8 ω_{ce} and from 5.56 ω_{ce} to 5.75 ω_{ce}, in Figure 2a and Figure 2b respectively. However, the growth rates in both cases are weak and maybe another mechanism should be considered for the generation wave in this case.



(a)

(b)

Figure 2. The growth rate of RX-mode waves where $\omega_p / \omega_{ce} = 4.1$, with the ring-type distribution a) for n=5 b) for n=6 .

In the second step of the calculation, the nonlinear coupling condition was considered

$$\left(\omega_{\mathrm{Rx}} - \omega_Z\right) - (k_{\|\mathrm{Rx}} - k_{\|Z}) \cdot \upsilon_{\|} = n\,\omega_{ce} \qquad (3)$$

where ω_{Rx} and ω_Z are angular frequency of Rx- mode and Z-mode waves, respectively, and ω_{ce} is the cyclotron frequency. $k_{\|Rx}$ and $k_{\|Z}$ are the wave vectors of RX mode and Z mode waves, respectively. $\upsilon_{\|}$ is the parallel component of the particle velocity, and n is an integer number. The relation between frequency and k vector is determined by dispersion relation. By assuming that the magnetic field is directed along z-axis, and that the wave vector, **k** , lies in the xz-plane; the dispersion relation of the plasma wave is determined by considering the condition of the non-trivial solutions of homogeneous equation, as:

$$\begin{vmatrix} S - n^2\cos^2\theta & -iD & n^2\cos\theta\sin\theta \\ iD & S - n^2 & \theta \\ n^2\cos\theta\sin\theta & 0 & P - n^2\sin^2\theta \end{vmatrix} = 0 \qquad (4)$$

where, $S = \dfrac{R+L}{2}$, $D = \dfrac{R-L}{2}$, $P = 1 - \dfrac{\omega_p}{\omega}$

and

$$R = 1 - \frac{\omega_p^2}{\omega^2}\left(\frac{\omega}{\omega + \omega_{ce}}\right) \qquad (5)$$

$$L = 1 - \frac{\omega_p^2}{\omega^2}\left(\frac{\omega}{\omega - \omega_{ce}}\right) \qquad (6)$$

A range of ω_p / ω_{ce} from 3.98 to 5.56 was considered, with the normal angle near to perpendicular ($\theta \approx 89^\circ$), for determination of k vector of $\omega_{Z/UH} / \omega_{ce} = 4.11$, and $\omega_{Rx} / \omega_{ce} = 5.65$ so that the equation (3) is satisfied.

3. Discussions and results

Figures 3 and 4 show the results of numerical calculation with n=1 and n=2, respectively. Both Figures show the parallel component of particle velocity in terms of ω_p / ω_{ce}, with $\theta \approx 89^\circ$ so that the equation (3) is satisfied. Furthermore, the right axis in each panel shows the parallel component of energetic particles in keV. Since $\omega_{Z/UH} / \omega_{ce} = 4.11$, so a range of plasma frequency can satisfy equation (3), which is shown in the elliptical short-line. The results show that with a decrease in the plasma frequency for satisfying equation (3), the parallel velocity increases from about 0.02c to 0.2c where c is the speed of light. This means that it needs a range of parallel component of energetic particles from about 0.058 to 10.23keV.

In Figure 4, all parameters are the same as Figure 3 except that n=2. Besides, in this case, a range of plasma frequency can satisfy equation (3) that is shown in the elliptical short-line. The results show that with the increase in the plasma frequency for satisfying equation (3), the parallel velocity increases from about 0.02c to 0.2c and accordingly the energy is of particles from 0.058 to 10.23keV.

Recently, a statistical study on the global distribution of super thermal electron (0.1-10 keV) fluxes using electron data from THEMIS (Time History of Events and Macroscale Interactions during Substorms) was accomplished by Li et al. (2010). Figure 4 shows the global distribution of the averaged electron energy flux inside the plasmasphere during quiet times $(AE^* < 100nT)$ and strong magnetic $(AE^* > 300nT)$ activity (Li et al., 2010). Moreover, they showed that inside the plasmasphere electron fluxes are larger and more stable at smaller L shells at higher energy (a few to 10 keV). This range of energetic particle is in agreement with our results; therefore, the results suggest that the nonlinear coupling (particle-wave interaction) can be a candidate for the generation of RX-mode wave in the equatorial plasmasphere.

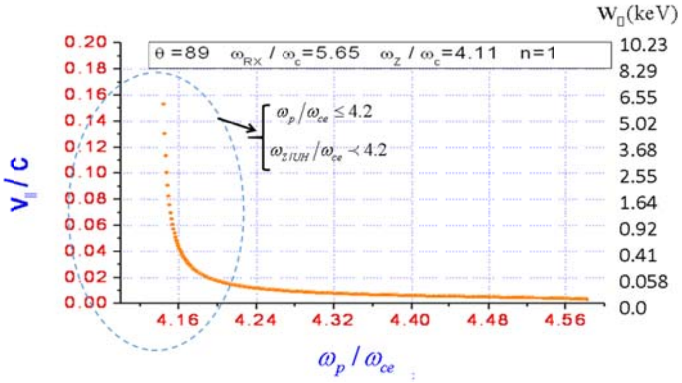


Figure 3. The parallel component of particle velocity in terms of ω_p / ω_{ce} , with n=1.

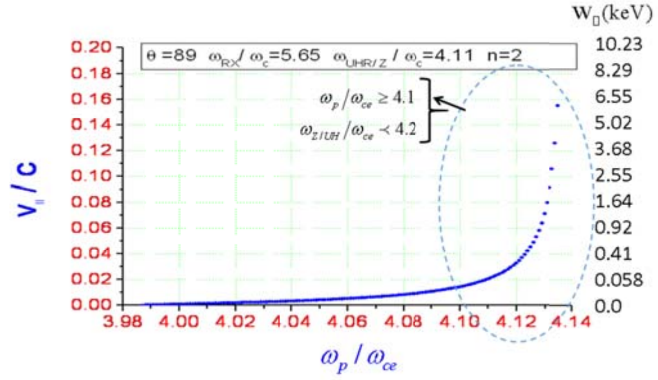


Figure 4. The parallel component of particle velocity in terms of ω_p / ω_{ce} , with n=2.

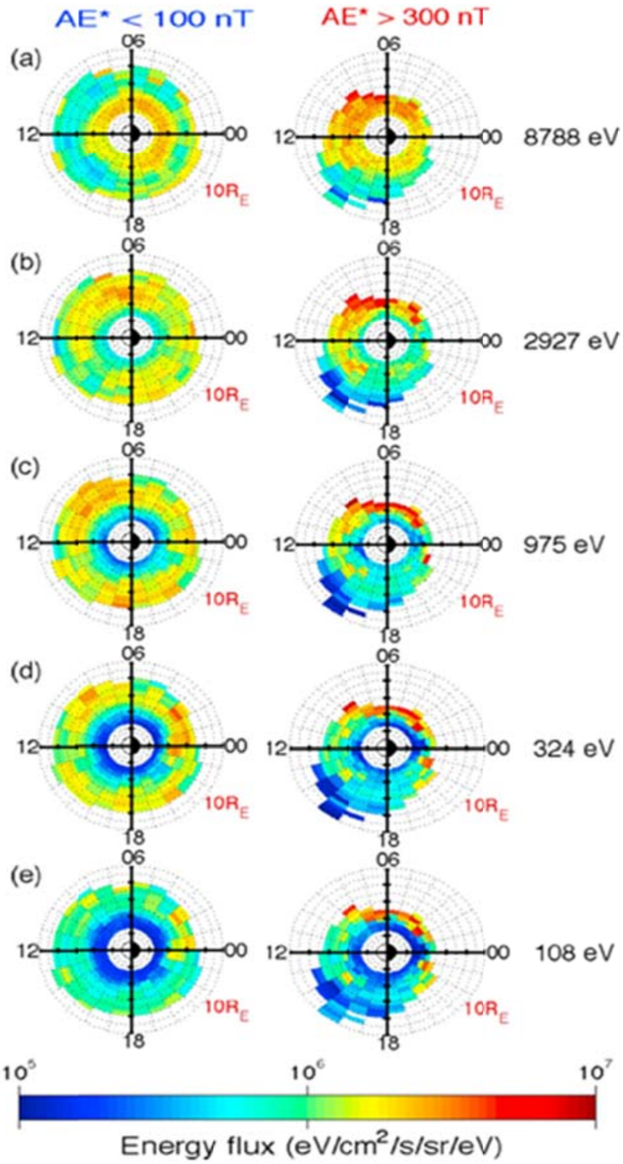


Figure 5. Global distribution of the averaged electron energy flux inside the plasmasphere during two levels of magnetic activity, (quiet and strong magnetic activity). Different rows indicate electrons with different energies (Li et al., 2010).

4. Conclusions

This work is focused on the nonlinear coupling condition, but with a purpose that the values of the parallel components of both two modes are not the same. In this case, the values of parallel energy of the particles that can satisfy the nonlinear coupling condition were calculated. Furthermore, a result for the instability was presented. The initial parameters inferred from observational data obtained by the Akebono satellite around the plasma-wave generation region were used. Results of this investigation indicate that the growth rate of this type of wave is weak, and the instability cannot generate strong Rx-mode waves. The results also show that the nonlinear coupling (particle-wave interaction) can be a candidate for the generation of RX mode wave in equatorial plasmasphere. Besides, the results show that energetic particles that participate in particle-wave interaction have the range energy from 0.058 to 10.23keV. This range of energetic particle is in agreement with the observation.

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