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The generation and evolution of multi-band EMIC waves in the magnetosphere: Hybrid simulations

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Abstract

Electromagnetic ion cyclotron (EMIC) waves have played an important role in loss and acceleration of charged particles in the magnetosphere. In this paper, with a 1-D hybrid simulation model, we have studied the generation and evolution of multi-band EMIC waves in a homogenous multi-ion (protons and helium ions) plasma, where the waves are excited by the anisotropic hot protons, and the effects of the anisotropy of hot protons, concentration, and temperature of helium ions on the excited EMIC wave spectrum are considered. In the early phase of the cyclotron instability, the multi-band EMIC waves with a clear stop band around the helium ion gyrofrequency are preferentially generated under the condition of a lower anisotropy of hot protons, smaller concentration of helium ions, and colder helium ions, which is consistent with the linear theory. What's more, it is found that both the frequencies and wave numbers of EMIC waves will decrease with time, which is then proved to be a quasi-linear process caused by the decrease of anisotropy of hot protons. Meanwhile, the standing density structures will be generated in the system, which is due to the coupling between counter-propagating EMIC waves. Our simulations suggest that the linear theory should be valid to describe both generation and evolution of EMIC waves in the Earth's magnetosphere.

Keywords: Electromagnetic ion cyclotron (EMIC) waves; Hybrid simulation; Anisotropy

1. Introduction

Electromagnetic ion cyclotron (EMIC) waves have long been believed to play a key role in reshaping the velocity distributions of charged particles in the magnetosphere (Thorne, 2010). One well known mechanism for the loss of relativistic electrons in the outer radiation belt is the pitch-angle scattering by EMIC waves (Thorne and Kennel, 1971; Lyons and Thorne, 1972; Summers and Thorne, 2005; Summers et al., 2007; Su et al., 2013; Ni et al., 2015; He et al., 2016). Through the resonant interactions, EMIC waves are able to scatter the relativistic electrons into the loss cone and result in the precipitation into the Earth's atmosphere, which has also been supported by many observational results (Bortnik et al., 2006; Miyoshi et al., 2008; Horne et al., 2009; Ukhorskiy et al., 2010; Carson et al., 2013; Usanova et al., 2014; Gao et al., 2015). Besides, EMIC waves can not only resonantly heat the Helium ions, especially in the perpendicular direction (Horne and Thorne, 1997; Omura et al., 1985; Zhang et al., 2010, 2011), but also scatter the ring current ions into the loss cone, which contributes to the decay of ring current (Cornwall et al., 1970; Jordanova et al., 2001; Xiao et al., 2012; Cao et al., 2016) and the formation of subauroral arcs (Jordanova et al., 2007; Yahnina et al., 2008; Yuan et al., 2010).

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In the magnetosphere, EMIC waves are generally generated due to the ion cyclotron instability driven by anisotropic ($T_\perp > T_\parallel$) energetic ring current protons (10–100 keV) (Cornwall, 1965; Lu et al., 2006a), resulted from either injections from the plasma sheet (Chen et al., 2010; Zhang et al., 2014) or strong compression on dayside magnetosphere by solar winds with large dynamic pressure (Anderson and Hamilton, 1993; Liu et al., 2012). They are preferentially detected in the dusk sector near the equatorial region where the ring current overlaps the high-density plasmasphere (Erlandson and Ukhorskiy, 2001; Jordanova et al., 2001) and dayside drainage plumes (Chen et al., 2009; Morley et al., 2009), and in the outer magnetosphere at high latitudes on the dayside (McCollough et al., 2010; Liu et al., 2012; Allen et al., 2015). Due to the presence of multiple ion species (H^+, He^+, and O^+), EMIC waves usually exhibit in three distinct bands: proton band with frequencies between f_p and f_{He}; helium band with frequencies between f_{He} and f_O; oxygen band with frequencies below f_O (where f_p, f_{He}, and f_O are the gyro-frequencies for proton, helium, and oxygen ions, respectively).

The spectra of EMIC waves often show multi-band structures with clear stop bands at local ion gyrofrequencies (Halford et al., 2010; Meredith et al., 2014; Zhang et al., 2014). Different bands may merge together without stop bands (Lee et al., 2012), and single-band EMIC waves are also observed frequently (Zhou et al., 2013; Meredith et al., 2014; Zhang et al., 2014). The spectral structures of EMIC waves not only reflect the local plasma conditions, but also are important for modeling the wave-particle and wave-wave interactions. However, the formation of EMIC spectral structures is still an open question. Considering the warm plasma effects in the linear theory, Chen et al. (2011) and Silin et al. (2011a) have studied the plasma conditions where the stop bands will and will not exist. Furthermore, both Silin et al. (2011b) and Denton et al. (2014) have found the evolution (frequency drift) of EMIC waves in their hybrid simulations, and pointed out that it is also necessary to estimate the characteristics of expected wave spectra in the magnetosphere.

In this paper, with 1-D hybrid simulations, we investigate the generation and evolution of multi-band EMIC waves excited by the temperature anisotropy of hot protons in the magnetosphere. It is found that the spectral structures of excited EMIC waves are closely dependent on the initial plasma condition, which confirms the theoretical work by Chen et al. (2011). However, the excited EMIC waves will then experience a frequency drift after the saturation of instabilities, which has been further studied to determine whether it is a linear or nonlinear process. We organize this paper as follows. In Section 2 we describe the hybrid simulation model used in this study and the initial input of plasma parameters. Section 3 shows the generation of multi-band EMIC waves in the linear phase and presents the analysis of the evolution of EMIC waves. In Section 4, we summarize and further discuss our principal results.

2. Hybrid model and plasma initialization

A 1-D hybrid simulation model with periodic boundary condition is used to investigate the generation and evolution of EMIC waves in a multi-ion species plasma. In hybrid simulations, the ions are treated as macro-particles, while electrons are described as massless fluid (Winske, 1985; Quest, 1988; Lu et al., 2006b). The simulations allow for one spatial direction, which is parallel to the background magnetic field ($\boldsymbol{B}_0$). In our simulations, all the physical quantities will be normalized by the corresponding characteristic physical quantity. The plasma number density is normalized by the initial uniform electron density n_e, the magnetic field is normalized by the background magnetic field B_0, and the velocity is normalized by the background Alfven velocity $V_A = B_0/(\mu_0 n_e m_p)^{1/2}$. The units of time and space are the reciprocal of proton cyclotron frequency $\Omega_p{}^{-1} = m_p/eB_0$, and the proton inertial length V_A/Ω_p, respectively. The number of grid cells is $n_x = 512$ with size $\Delta x = 1.0 V_A/\Omega_p$. The time step is $\Delta t = 0.01\Omega_p^{-1}$, and the simulation time is $1000\Omega_p^{-1}$.

Six runs are performed in this study, which are all assumed to occur at $L = 6$ with the background magnetic field $B_0 \approx 150$ nT. Since EMIC waves are preferentially generated in regions with the high cold plasma density (Chen et al., 2009; Halford et al., 2015), the ratio between the plasma frequency (ω_{pe}) and the electron gyrofrequency (Ω_e) is set as a typical value ($\sim$10) in the plasma plume, which is a key parameter for the wave generation. Therefore, the unit of temperature ($m_p V_A{}^2$) in the simulations is corresponding to $\sim$5 keV in the real magnetosphere. Nearly all the parameters in Table 1 are chosen based on the previous observations in the Earth's magnetosphere, so they are quite consistent with the real conditions. Although there may exist three ion species (H^+, He^+, and O^+) in the magnetosphere, only protons and helium ions are considered in our simulations. The existence of oxygen ions may bring another stop band around the oxygen gyrofrequency if the plasma condition allows, which could separate the EMIC spectrum into three bands. However, the oxygen ions in the Earth's magnetosphere usually have a very low concentration, and the oxygen band EMIC waves are relatively uncommon. Moreover, we believe that the existence of oxygen ions will not change our main conclusion about the stop band around the Helium ion gyrofrequency. Therefore, only protons and helium ions are considered in our simulations, and leave the effects of oxygen ions on the generation and evolution of EMIC waves as another separate study. Besides, the protons consist of two distinct components, the cold background protons and the anisotropic ring current protons. For each ion species, there are an average of 900 macro-particles uniformly allocated in every cell. The parallel temperature

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