The generation and evolution of multi-band EMIC waves in the magnetosphere: hybrid simulations^[1]

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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; Zhang et al., 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].

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 sections 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 ($\mathbf{B}_0$). 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 Alfvén 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 $B_0 \approx 150 \text{ nT}$. 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 (~ 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 $\sim 5 \text{ keV}$ 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 $T_{j\parallel}/m_p V_A^2$ (where j denotes the species of particles, i. e. “c” for cold protons, “h” for hot protons, and “He” for helium ions), anisotropy $A_j (T_{j\perp}/T_{j\parallel}-1)$, and concentration n_j/n_e for all runs are listed in Table 1. Besides, the temperature of electrons is same with that of cold protons in each run.

3. Simulation Results

Figures 1(a) and 1(c) show the frequency-time spectrogram for Runs 1 and 2 respectively, with different proton anisotropies ($A_h=0.5$ for Run 1 and $A_h=3.5$ for Run 2). Figures 1(b) and 1(d) show the dispersion relation obtained from the 2-D FFT (fast Fourier transform) transforming of $\delta B_{\perp}/B_0$ during the period $\Omega_p t=0-200$ for Runs 1 and 2 respectively. The helium ion gyrofrequency is also denoted by the white dashed horizontal line in each panel. In order to highlight the spectral structures, the different color bars are used for Runs 1 and 2. The time period ($\Omega_p t=0-200$) is chosen in order to display the dispersion relation on the early linear stage of the cyclotron instability. The frequency-time spectrogram is obtained with the following method: we firstly calculate the wavelet power spectrum of the time series of $\delta B_y/B_0$ at 100 randomly selected x -grids, and the spectrum evolution exhibited in Figures 1(a) and 1(c) is the average result over these grids.

For Run 1, as shown in Figure 1(a), both the helium band and proton band are excited at $\Omega_p t \approx 100$, with a clear stop band between them. The dispersion relation in Figure 1(b) also shows two distinct bands separated by the helium ion gyrofrequency. According to the linear theory, the stop band around the helium ion gyrofrequency is contributed by the cyclotron damping of helium ions [Chen *et al.*, 2011; Lu *et al.*, 2006b]. Although the helium band slightly drifts to the lower-frequency waves, the two-band structure of EMIC waves can sustain until to the end of the simulation. For Run 2, as shown in Figure 1(c), both the helium and proton bands are also generated on the early linear stage, and merge together without a clear stop band between them. This is consistent with that the two dispersion curves of the helium and proton bands have merged together (Figure 1(d)). Compared with Run 1, the anisotropy of hot protons is much higher in Run 2, which can provide sufficient free energy to overcome the damping of helium ions and results in the growth of waves around the helium ion gyrofrequency. As time goes on, the frequencies of EMIC waves decrease so fast that only the helium band can be observed in the end (Figure 1(c)).

Figure 2, with similar format to Figure 1, presents the frequency-time spectrogram and dispersion relation for Runs 3 and 4 respectively. The two runs are different in that Run 3 ($n_{He}/n_e=0.1$) has a higher helium ion concentration than Run 4 ($n_{He}/n_e=0.01$). Here, it is worth noting that the change of the helium ion concentration also causes the change of the cold proton concentration, because of the requirement for electrical neutrality. For Run 3, two-band EMIC waves separated by a stop band can be generated in the early phase ($\Omega_p t < 100$) as shown in Figure 2(a), which is also

consistent with the dispersion curves in Figure 2(b). However, the proton band begins to drift to lower band after $\Omega_p t \approx 100$, and appreciable wave power can be observed within the stop band (Figure 2(a)). After $\Omega_p t \approx 200$, the proton band disappears in this system, and only the helium band survives, which still experiences the frequency decrease (Figure 2(a)). For Run 4, with much smaller concentration of helium ions, the damping due to helium ions is not enough to produce the stop band as shown in Figures 2(c) and 2(d). Similar to Run 3, both bands continuously drift to lower frequencies, and only the helium band residues in the end.

The effects of helium ion temperatures on the generation of multi-band EMIC waves are investigated by performing Run 5 ($T_{He}/mV_A^2 = 4.5 \times 10^{-4}$) and Run 6 ($T_{He}/mV_A^2 = 0.38$). The corresponding frequency-time spectrogram and dispersion relation shown in Figure 3 are in the format similar to Figures 1 and 2. For Run 5 in Figure 3(a), the stop band can be observed between the proton band and helium band initially for a very short time period ($\Omega_p t < 50$). After that, the proton band drifts to lower frequencies, fills the stop band, and ultimately merges into the helium band (Figure 3(a)). For Run 6 with hot helium ions, both the proton band and helium band are generated, but without a stop band (Figures 3(c) and 3(d)).

In summary, for a lower anisotropy of ring current protons, smaller concentration of helium ions, and colder helium ions, the multi-band EMIC waves are preferentially generated with a stop band around the helium ion gyrofrequency in the early linear phase, which can confirm the theoretical work done by Chen et al. [2011]. However, both bands of EMIC waves tend to drift towards the lower frequencies, and in most of

our simulation runs, the proton band can drift across the stop band, and merge into the helium band.

Next, we focus on Run 3 to investigate the physical mechanism underlying the evolution of EMIC waves. Figure 4 shows the dispersion relations on the upper row, which are obtained from 2-D FFT transforming of $\delta B_{\perp}/B_0$ during the four time intervals $\Omega_p t=0-200$, $200-400$, $400-600$, and $600-800$, respectively. In addition, the linear dispersion relation at the middle time of each time interval is solved using the WHAMP code (<https://github.com/irfu/whamp>), based on the ion density and temperature derived from mean ion distributions over all grid cells. The corresponding dispersion curve and growth rate are plotted on the upper and bottom rows, respectively. The proton and helium bands are denoted by the black solid and dashed lines respectively. In the linear phase ($\Omega_p t=0-200$), it is found that both the proton band and the helium band are generated with a stop band between them, which can also be expected by the positive growth rates on both bands. After $\Omega_p t=200$, the growth rate of the proton band remains negative, meaning the proton band is damped in this system by cyclotron resonance with thermal helium ions. The helium band nearly reaches the marginal stability at small wave numbers ($kV_A\Omega_p^{-1}<0.25$) according to their quite small positive growth rates.

The time histories of temperatures of protons and helium ions are shown in Figure 5. From the top to the bottom, they are the temperature evolutions of cold background protons, helium ions and hot protons respectively. Compared with Figure 2(a), the proton band is generated while the anisotropy of hot protons decreases

roughly in the early phase ($\Omega_p t < 100$). And also, the temperature of cold protons is hardly changed during this period. After that the anisotropy of hot protons decreases slowly and the proton band begins to drift to lower band until $\Omega_p t \approx 200$. On the contrary, the cold protons are obviously heated in the parallel direction. After $\Omega_p t \approx 200$, the hot protons are nearly isotropic and the proton band disappears in this system. The development of the helium band is consistent with the evolution of anisotropy of the helium ions. The helium band is excited and developed while anisotropy of the helium ions continues to increase until $\Omega_p t \approx 200$. After $\Omega_p t \approx 200$, the helium band experiences the frequency decrease due to the decrease of the anisotropy. All of the above suggests that the time evolution of temperatures is quite consistent with the results obtained from the quasi-linear theory [Lu *et al.*, 2006b].

Figure 6 shows the evolutions of magnetic (a) and density (b) fluctuations for run3. Magnetic fluctuations are uniform during the linear growth stage ($T < 100$). After that, the strong magnetic fluctuations only occur at some specific locations, where waves propagate in both directions. Due to the existence of counter-propagating EMIC waves, the magnetic pressure are not uniform along the x axis, which can also be inferred from Figure 6(a). Then the parallel electric fields can be caused by the inhomogeneous magnetic pressure (not shown here). The parallel heating of cold protons shown in Figure 5 is mainly due to these parallel electric fields. As shown in Figure 6(b), the density fluctuations of ions along the x axis are very obvious, but they seem unchanged with the increase of time. In other words, these density fluctuations are just standing structures without propagation. What is more interesting is that the

strong standing density structures just occur in the region where the counter-propagating EMIC waves meet, indicating the standing density structures along the x axis may be caused by the counter-propagating EMIC waves.

The bicoherence index is used to quantitatively measure the phase coupling among two EMIC waves (k_0 and k^-) and the density fluctuation (k_s), which is close to 1 when these signals satisfy the resonance condition [Gao *et al.*, 2014; Gao *et al.*, 2016]. In this study, the resonant conditions, i.e. the strong phase coupling among three wave modes, are given by $k_0 = k_s + k^-$ and $f_0 = f_s + f^-$, where k_s (f_s) and k^- (f^-) denote the density mode and the EMIC mode, respectively. Here, one perpendicular component of magnetic fields and the density fluctuations of protons are chosen to calculate the bicoherence index. The bicoherence index is given by $bc(k_s, k^-, k_0) = |\langle \rho_{k_s} b_{k^-} b_{k_0}^* \rangle| / (\langle |\rho_{k_s} b_{k^-}|^2 \rangle \langle |b_{k_0}|^2 \rangle)^{1/2}$, which is calculated in the wave-number space with the complex power. The ρ_{k_s} denotes the density fluctuations, which is obtained by the FFT transforming of ion density. While, the b_{k^-} and b_{k_0} represent two EMIC wave modes, which are obtained by the FFT transforming of magnetic fields. And the bracket $\langle \bullet \rangle$ denotes an average over a time interval for the periods $260\text{-}290\Omega_p^{-1}$ for Run 3. In Figure 6(c), we can find that the dominant bicoherence index bc is about 1 with $k_s = -2k^-$, meaning that there exists the strong phase coupling among k_0 , k^- , and k_s ($k_0 = k_s + k^-$) along with the growth of density fluctuations. Due to the resonant condition $f_0 = f_s + f^-$, the frequency of the density mode is nearly zero, which are shown as the standing structure. It is natural that there exist standing density structures in the presence of forward and backward EMIC waves because of the formation of the beat

waves. Besides, as shown in Figures 6(a) and 6(b), the density fluctuations are generated just after the EMIC waves have gained the sufficient growth. So, we can conclude that the density fluctuations are just due to the coupling between two counter-propagating (i.e., with opposite wave numbers) EMIC waves. However, there is no obvious wave-wave coupling process related to the frequency drift. Therefore, it is another evidence that the frequency drift during the evolution of EMIC waves is due to the quasi-linear effect.

4. Conclusions

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. The principal results are summarized as follows:

1. The spectral structure and evolution of EMIC waves in a multi-ion plasma can be predicted by the linear cyclotron instability. Our simulation shows that the EMIC waves without stop band are favored by a higher proton anisotropy, smaller concentration of helium ions, and hotter helium ions, which confirms the theoretical work by Chen et al. [2011].
2. Both the frequencies and wave numbers of EMIC waves decrease with the time because of decreasing anisotropy of hot protons. The simulation suggests that the evolution of EMIC waves in the Earth's magnetosphere can be well described by the quasi-linear theory.
3. The strong magnetic fluctuations only occur at some specific locations, where

waves propagate in both directions. Meanwhile, the density fluctuations are also evident at those locations. Through the analysis of bicoherence index, the standing density structures will be generated in the system, which is due to the coupling between counter-propagating EMIC waves.

Previous hybrid simulations of Silin et al. [2011b] and Denton et al. [2014] have pointed out the frequency drift of EIMC waves. Silin et al. [2011b] have reported that this frequency drift is a nonlinear physical process, while Denton et al. [2014] considered it as a quasi-linear process due to the decreasing anisotropy of hot protons. In this study, we have employed a popular method, i.e., the bicoherence index, to check whether the nonlinear wave-wave couplings control the frequency drift. The frequency drift cannot be explained by the parametric instabilities, which have already been widely studied in the evolution of Alfvén/ion cyclotron waves in solar winds [Gao et al., 2013a; Gao et al., 2013b; Gao et al., 2014]. However, as shown in Figure 6, there is no obvious wave-wave coupling related to the frequency drift, except the couplings between counter-propagating EMIC waves. This result confirms that the frequency drift during the evolution of EMIC waves should be a quasi-linear process, which is mainly due to the decrease of anisotropy of hot protons.

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References

Allen, R. C., Zhang, J.C., Kistler, L. M., et al. A statistical study of EMIC waves

- observed by Cluster: 1. Wave properties, *J Geophys Res*,120, 5574-5592, 2015.
- Anderson, B. J., Hamilton, D. C. Electromagnetic Ion-Cyclotron Waves Stimulated by Modest Magnetospheric Compressions, *J Geophys Res*,98(A7), 11369-11382, 1993.
- Bortnik, J., Thorne,R. M., O'Brien,T. P.,et al. Observation of two distinct, rapid loss mechanisms during the 20 November 2003 radiation belt dropout event, *J Geophys Res-Space*, 111(A12), A12216,2006.
- Cao, X., Ni B. B., Liang, J., et al. Resonant scattering of central plasma sheet protons by multi-band EMIC waves and resultant proton loss timescales, *J Geophys Res-Space*, 121, 1219-1232,2016.
- Carson, B. R., Rodger, C. J., Clilverd, M. A. POES satellite observations of EMIC-wave driven relativistic electron precipitation during 1998-2010, *J Geophys Res-Space*,118(1), 232-243, 2013.
- Chen, L. J., Thorne, R. M., Bortnik, J. The controlling effect of ion temperature on EMIC wave excitation and scattering, *Geophys Res Lett*,38, L16109, 2011.
- Chen, L. J., Thorne, R. M., Horne, R. B. Simulation of EMIC wave excitation in a model magnetosphere including structured high-density plumes, *J Geophys Res*,114, A07221, 2009.
- Chen, L. J., Thorne, R. M., Jordanova, V. K., et al. Global simulation of EMIC wave excitation during the 21 April 2001 storm from coupled RCM-RAM-HOTRAY modeling, *J Geophys Res*, 115, A07209, 2010.
- Cornwall, J. M., Cyclotron Instabilities and Electromagnetic Emission in Ultra Low

Frequency and Very Low Frequency Ranges, *Journal of Geophysical Research*, 70(1), 61,1965.

Cornwall, J. M., Coroniti, F. V., Thorne, R. M. Turbulent Loss of Ring Current Protons, *Journal of Geophysical Research*, 75(25), 4699, 1970.

Denton, R. E., Jordanova, V. K., Fraser, B. J. Effect of spatial density variation and O⁺ concentration on the growth and evolution of electromagnetic ion cyclotron waves, *Journal of Geophysical Research: Space Physics*, 119(10), 8372-8395, 2014.

Erlandson, R. E., Ukhorskiy, A. J. Observations of electromagnetic ion cyclotron waves during geomagnetic storms: Wave occurrence and pitch angle scattering, *J Geophys Res*, 106(A3), 3883-3895, 2001.

Gao, X., Lu, Q. M., Bortnik, J., Li, W., et al., Generation of multiband chorus by lower band cascade in the Earth's magnetosphere, *Geophysical Research Letters*.43, 2343-2350,2016.

Gao, X., Li, W., Bortnik, J., Thorne, R. M., et al., The effect of different solar wind parameters upon significant relativistic electron flux dropouts in the magnetosphere, *Journal of Geophysical Research: Space Physics*.120, 4324-4337,2015.

Gao, X. L., Lu, Q. M., Li, X., et al. Ion Dynamics during the Parametric Instabilities of a Left-Hand Polarized Alfvén Wave in a Proton-Electron-Alpha Plasma, *Astrophys J*,780(1),56, 2014.

Gao, X. L., Lu, Q. M., Li, X., et al. Parametric instability of a monochromatic Alfvén wave: Perpendicular decay in low beta plasma, *Phys Plasmas*, 20(7), 072902, 2013a.

Gao, X. L., Lu, Q. M., Tao, X., et al. Effects of alpha beam on the parametric decay of

a parallel propagating circularly polarized Alfvén wave: Hybrid simulations, *Phys Plasmas*, 20(9), 092106, 2013b.

Halford, A. J., Fraser, B. J. and Morley, S. K. EMIC wave activity during geomagnetic storm and nonstorm periods: CRRES results, *J Geophys Res*, 115, A12248, 2010.

Halford, A. J., Fraser, B. J., Morley, S. K. EMIC waves and plasmaspheric and plume density: CRRES results, *J Geophys Res*, 120(3), 1974-1992, 2015.

He, F. M., Cao, X., Ni, B. B., et al. Combined Scattering Loss of Radiation Belt Relativistic Electrons by Simultaneous Three-band EMIC Waves: A Case Study, *J. Geophys. Res. Space Physics*, 121, 4446-4451, 2016.

Horne, R. B., Lam, M. M. and Green, J. C. Energetic electron precipitation from the outer radiation belt during geomagnetic storms, *Geophys Res Lett*, 36, L19104, 2009.

Horne, R. B., and Thorne, R. M. Wave heating of He⁺ by electromagnetic ion cyclotron waves in the magnetosphere: Heating near the H⁺-He⁺ bi-ion resonance frequency, *J Geophys Res*, 102(A6), 11457-11471, 1997.

Jordanova, V. K., Farrugia, C. J., Thorne, R. M. et al., Modeling ring current proton precipitation by electromagnetic ion cyclotron waves during the May 14-16, 1997, storm, *J Geophys Res*, 106(A1), 7-22, 2001.

Jordanova, V. K., Spasojevic, M., Thomsen, M. F. Modeling the electromagnetic ion cyclotron wave-induced formation of detached subauroral proton arcs, *J Geophys Res*, 112(A8), A08209, 2007.

Lee, J. H., Chen, L. J., Angelopoulos, V., et al. THEMIS observations and modeling of multiple ion species and EMIC waves: Implications for a vanishing He⁺ stop band,

J Geophys Res,117, A06204, 2012.

Liu, Y. H., Fraser, B. J., Menk, F. W. Pc2 EMIC waves generated high off the equator in the dayside outer magnetosphere, *Geophys Res Lett*, 39, L17102, 2012.

Lu, Q. M., Guo, F., Wang, S. Magnetic spectral signatures in the terrestrial plasma depletion layer: Hybrid simulations, *J Geophys Res*,111, A04207, 2006a.

Lu, Q. M.,Xia,L. D. AndWang S. Hybrid simulations of parallel and oblique electromagnetic alpha/proton instabilities in the solar wind, *J. Geophys. Res.*, 111, A09101, 2006b.

Lyons, L. R., Thorne, R. M. Parasitic Pitch Angle Diffusion of Radiation Belt Particles by Ion-Cyclotron Waves, *J Geophys Res*,77(28), 5608, 1972.

McCollough, J. P., Elkington,S. R., Usanova,M. E. et al., Physical mechanisms of compressional EMIC wave growth, *J Geophys Res*, 115, A10214,2010.

Meredith, N. P., Horne, R. B., Kersten, T., et al. Global morphology and spectral properties of EMIC waves derived from CRRES observations, *J Geophys Res*,119(7), 5328-5342, 2014.

Miyoshi, Y., Sakaguchi, K., Shiokawa, K., et al. Precipitation of radiation belt electrons by EMIC waves, observed from ground and space, *Geophys Res Lett*,35(23), L23101, 2008.

Morley, S. K., Ables, S. T., Sciffer, M. D., et al. Multipoint observations of Pc1-2 waves in the afternoon sector, *J Geophys Res*, 114, A09205, 2009.

Ni, B. B., Cao, X., Zou, Z. Y., et al. Resonant scattering of outer zone relativistic electron by multiband EMIC waves and resultant electron loss time scales, *J Geophys*

Res, 120, 7357-7373, 2015.

Omura, Y., Ashourabdalla. M., Gendrin, R., et al. Heating of Thermal Helium in the Equatorial Magnetosphere - a Simulation Study, *J Geophys Res*, 90, 8281-8292, 1985.

Quest, K. B. Theory and Simulation of Collisionless Parallel Shocks, *J Geophys Res*, 93(A9), 9649-9680, 1988.

Silin, I., Mann, I. R., Sydora, R. D., et al. Warm plasma effects on electromagnetic ion cyclotron wave MeV electron interactions in the magnetosphere, *J Geophys Res*, 116, A05215, 2011a.

Silin, I., Sydora, R. D., Mann, I. R., et al. Nonlinear evolution of electromagnetic ion cyclotron waves, *Phys Plasmas*, 18(4), 042108, 2011b.

Su, Z. P., Zhu, H., Xiao, F. L., et al. Latitudinal dependence of nonlinear interaction between electromagnetic ion cyclotron wave and radiation belt relativistic electrons, *J Geophys Res-Space*, 118(6), 3188-3202, 2013.

Summers, D., Ni, B., Meredith, N. P. Timescales for radiation belt electron acceleration and loss due to resonant wave-particle interactions: 1. Theory, *J Geophys Res-Space*, 112(A4), A04206, 2007.

Summers, D., Thorne, R. M. Relativistic electron pitch-angle scattering by electromagnetic ion cyclotron waves during geomagnetic storms, *J Geophys Res*, 110(A1), A01208, 2005.

Thorne, R. M. Radiation belt dynamics: The importance of wave-particle interactions, *Geophys Res Lett*, 37, L22107, 2010.

Thorne, R. M., and Kennel, C. F. Relativistic Electron Precipitation during Magnetic

Storm Main Phase, *J Geophys Res*, 76(19), 4446, 1971.

Ukhorskiy, A. Y., Shprits, Y. Y., Anderson, B. J., et al. Rapid scattering of radiation belt electrons by storm-time EMIC waves, *Geophys Res Lett*, 2010, 37, L09101.

Usanova, M. E., et al., Effect of EMIC waves on relativistic and ultrarelativistic electron populations: Ground-based and Van Allen Probes observations, *Geophys Res Lett*, 41(5), 1375-1381, 2014.

Winske D. Hybrid Simulation Codes with Application to Shocks and Upstream Waves, *Space Sci Rev*, 42, 53-66, 1985.

Xiao F L, Yang C, Zhou Q H, et al. Nonstorm time scattering of ring current protons by electromagnetic ion cyclotron waves, *J Geophys Res*, 117, A08204, 2012.

Yahnina, T. A., Frey, H. U., Bosinger, T. and Yahnin, A. G. Evidence for subauroral proton flashes on the dayside as the result of the ion cyclotron interaction, *J Geophys Res*, 113(A7), A07209, 2008.

Yuan, Z. G., Deng, X. H., Lin, X., et al. Link between EMIC waves in a plasmaspheric plume and a detached sub-auroral proton arc with observations of Cluster and IMAGE satellites, *Geophys Res Lett*, 37, L07108, 2010.

Zhang, J. C., Kistler, L. M., Mouikis, C. G., et al. A case study of EMIC wave-associated He⁺ energization in the outer magnetosphere: Cluster and Double Star 1 observations, *J Geophys Res*, 115, A06212, 2010.

Zhang, J. C., Kistler, L. M., Mouikis, C. G., et al. A statistical study of EMIC wave-associated He⁺ energization in the outer magnetosphere: Cluster/CODIF observations, *J Geophys Res*, 116, A11201, 2011.

Zhang, J. C., et al. Excitation of EMIC waves detected by the Van Allen Probes on 28 April 2013, *Geophys Res Lett*, 41(12), 4101-4108, 2104.

Zhou, Q. H., Xiao, F. L., Shi, J. K., et al. Excitation of electromagnetic ion cyclotron waves under different geomagnetic activities: THEMIS observation and modeling, *J Geophys Res*, 118(1), 340-349, 2013.

Table captions:**Table 1.**Initial plasma parameters for six runs.

Run	$T_{cp//}$	A_{cp}	n_{cp}/n_e	$T_{hp//}$	A_{hp}	n_{hp}/n_e	$T_{he//}$	A_{he}	n_{he}/n_e
1	2.25eV	0	0.87	25keV	0.5	0.1	290eV	0	0.03
2	2.25eV	0	0.87	25keV	3.5	0.1	290eV	0	0.03
3	2.25eV	0	0.8	25keV	1.5	0.1	290eV	0	0.1
4	2.25eV	0	0.89	25keV	1.5	0.1	290eV	0	0.01
5	2.25eV	0	0.87	25keV	1.5	0.1	2.25eV	0	0.03
6	2.25eV	0	0.87	25keV	1.5	0.1	1.9keV	0	0.03

Figure captions:

Figure 1. The frequency-time spectrogram for (a) Run 1 and (b) Run 2. The dispersion relation obtained from the 2-D FFT (fast Fourier transform) transforming of $\delta B_{\perp}/B_0$ during the period $\Omega_p t=0-200$ for (c) Run 1 and (d) Run 2. The white lines denote the helium ion gyrofrequency.

Figure 2. The frequency-time spectrogram for (a) Run 3 and (b) Run 4. The dispersion relation obtained from the 2-D FFT (fast Fourier transform) transforming of $\delta B_{\perp}/B_0$ during the period $\Omega_p t=0-200$ for (c) Run 3 and (d) Run 4. The white lines denote the helium ion gyrofrequency.

Figure 3. The frequency-time spectrogram for (a) Run 5 and (b) Run 6; The dispersion relation obtained from the 2-D FFT (fast Fourier transform) transforming of $\delta B_{\perp}/B_0$ during the period $\Omega_p t=0-200$ for (c) Run 5 and (d) Run 6. The white lines denote the helium ion gyrofrequency.

Figure 4. Upper row: The dispersion relations obtained from 2-D FFT transforming of $\delta B_{\perp}/B_0$ during the period $\Omega_p t=0-200$, $200-400$, $400-600$, and $600-800$, respectively. And the dispersion curves at the middle time of each period obtained from the linear theory are also over plotted. Bottom row: The growth rate obtained from the linear theory. The proton band and helium band are denoted by the black solid and dashed lines respectively.

Figure 5. The time histories of temperatures of protons and helium ions.

Figure 6. The evolutions of magnetic (a) and density (b) fluctuations for run3. Magnetic fluctuations are uniform during the linear growth stage ($T < 100$). Figure 6c shows the bicoherence index, where k_s and k^- denote the density mode and the EMIC mode, respectively.