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Bounce-averaged Pitch-angle Diffusion by Electromagnetic Ion Cyclotron Waves in Multi-ion Plasmas *

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We present a study on the gyroresonant interaction between electromagnetic ion cyclotron waves and ring current particles in multi-ion (H^+, He^+, and O^+) plasmas. We provide a first evaluation of the bounce-averaged pitch angle diffusion coefficient $\langle D_{\alpha\alpha}\rangle$ for three typical energies of 50, 100 and 150 keV at $L \approx 3.5$, the heart of the symmetrical ring current. We show that in the H^+-band and He^+-band, $\langle D_{\alpha\alpha}\rangle$ can approach $\sim 10^{-4}\,s^{-1}$ for ion H^+, and $\sim 5\times 10^{-5}\,s^{-1}$ for ion He^+; meanwhile, in the O^+-band, $\langle D_{\alpha\alpha}\rangle$ can reach $\sim 10^{-5}\,s^{-1}$ for ions He^+ and O^+. The results above show that the EMIC wave can efficiently produce precipitation loss of energetic (~ 100 keV) ions (H^+, He^+ and even O^+), and such a wave tends to be a serious candidate responsible for the ring current decay.

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An active dynamic process occurring in the radiation belts of the Earth is considered to be the well-known cyclotron wave-particle interaction since it is responsible for stochastic acceleration and pitch angle diffusion of energetic particles.[1−7] During geomagnetic storms, fluxes of outer radiation belts electrons can vary substantially.[8] Such variations are found to be caused by wave-particle interactions,[9,10] together with drift resonance with ultra low frequency (ULF) waves.[11,12] It is well-known that the ring current strongly associated with geomagnetic storms usually occurs at locations between $L \sim 2$–9. Three dominant mechanisms are found to be responsible for the ring current decay: Coulomb collision processes, charge exchange, and pitch angle diffusion by electromagnetic ion cyclotron (EMIC) waves or whistler-mode waves.[13,14] He *et al.*[15] have presented an evaluation of local pitch angle diffusion by EMIC waves in a single hydrogen plasma and found that such waves can efficiently drive protons into the loss cone and yield the ring current decay. Jordanova *et al.*[16] analyzed the effect of heavy ions on local diffusion coefficients for resonance with obliquely propagated EMIC waves under the non-relativistic gyroresonant condition. They evaluated timescales for the scattering loss of ring current ions and found that resonance at energies of tens of keV can contribute to ion precipitation losses during geomagnetic storms. However, since the storm ring currents are primarily composed of positive ions (H^+, He^+, and O^+) with typical energy ~ 100 keV, and energetic particles usually bounce back and forth along the field line between mirror points, it is therefore essential to study bounce-averaged wave-particle interaction in a multi-ion plasma. This the primary purpose of this study.

For parallel-propagating EMIC waves in a multi-ion plasma, the refractive index $\mu = ck/\omega$ assumes the form:[17]

$$\mu^2 = 1 - \frac{\omega_{pe}^2}{\omega(\omega + |\Omega_e|)} - \sum_{\sigma=1}^{3} \frac{\omega_{p\sigma}^2}{\omega(\omega - \Omega_\sigma)}, \tag{1}$$

where k is the wave number, c is the speed of light in vacuum, ω_{pe} and $|\Omega_e|$ denote plasma frequency and gyrofrequency of electrons; $\sigma = 1, 2, 3$ denotes ions H^+, He^+ and O^+, respectively; $\omega_{p\sigma}$ and Ω_σ represent plasma frequency and gyrofrequency of ions. In this study, we restrict ourselves at the heart location ($L = 3.5$) of the symmetrical ring current, and choose H^+, He^+ and O^+ fractional ion number densities respectively as $\eta_1 = 0.7$, $\eta_2 = 0.2$, and $\eta_3 = 0.1$.[17]

Figure 1 shows the EMIC wave dispersion relation in the cases of $\rho = \omega_{pe}^2/|\Omega_e|^2 = 50$ and 100, respectively, corresponding to higher and lower geomagnetic activities. The three illustrated wave bands $0 < \omega < \Omega_{O^+}$, $\omega_{He^+} < \omega < \Omega_{He^+}$ and $\omega_{H^+} < \omega < \Omega_{H^+}$ correspond to the oxygen, helium, and hydrogen bands. The frequencies ω_{He^+} and ω_{H^+} denote the respective cut-off ($\mu = 0$) frequencies for helium and hydrogen bands. A parallel propagating EMIC wave is not presented in the stop-bands specified by $\Omega_{O^+} < \omega < \omega_{He^+}$ and $\Omega_{He^+} < \omega < \omega_{H^+}$.

The gyroresonant condition for interaction between parallel EMIC waves and ions can be taken as

$$\omega - kv_\parallel = \Omega_\sigma/\gamma, \tag{2}$$

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where $v_\parallel = v\cos\alpha$ with speed v and local pitch angle α, γ is the resonant relativistic Lorentz factor.

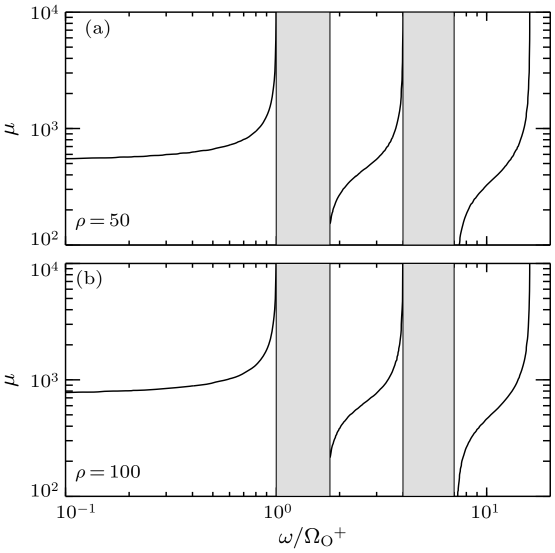

Fig. 1. Refractive index $\mu = ck/\omega$ plotted against the scaled wave frequency.

For a dipolar geomagnetic field model, the bounce-averaged pitch angle diffusion coefficient is given by[18]

$$\langle D_{\alpha\alpha}\rangle = \frac{1}{T_B}\int_0^{\lambda_m} D_{\alpha\alpha}\frac{\cos\alpha}{\cos^2\alpha_0}\cos^7\lambda d\lambda, \quad (3)$$

where α_0 is the equatorial pitch angle, $T_B \approx 1.30 - 0.56\sin\alpha_0$ is the normalized bounce period,[19] λ is the geomagnetic latitude, λ_m is the maximum latitude where wave exists; the local pitch angle diffusion coefficient $D_{\alpha\alpha}$ can be expressed by[20]

$$D_{\alpha\alpha} = \frac{\Omega_\sigma^2}{p^2}\Big(\frac{p^2}{\gamma^2}I_0 - 2\frac{cp}{\gamma}I_1\cos\alpha + c^2 I_2\cos^2\alpha\Big), \quad (4)$$

and

$$I_n = \pi\sum_{\omega_r}\Bigg\{\frac{B_\omega^2}{B_0^2}\Big(\frac{\omega_r}{ck_r}\Big)^n\Big|1 - \cos\alpha\frac{p}{\gamma}\frac{dk}{d\omega}\Big|_{\omega=\omega_r}^{-1}\Bigg\}, \quad (5)$$

where $n = 0, 1, 2$; ω_r (or k_r) obeys the resonant equation (2); $dk/d\omega$ is calculated by the dispersion relation (1) at each resonant frequency ω_r, B_ω^2 is the power spectral density of wave magnetic field, $B_0(\lambda)$ stands for the local geomagnetic field strength for a dipolar field model:

$$B_0(\lambda) = 3.12\times 10^4\frac{(1+3\sin^2\lambda)^{1/2}}{L^3\cos^6\lambda}\ \text{nT}. \quad (6)$$

In the following, for EMIC waves, based on the previous work[18] we adopt the standard Gaussian frequency band with a peak ω_m, a half width $\delta\omega$, a lower cutoff ω_1, and an upper cutoff ω_2:

$$B_\omega^2 = \begin{cases} B_n^2\exp[-(\omega-\omega_m)^2/\delta\omega^2], \\ \text{for}\ \ \omega_1 \le \omega \le \omega_2, \\ 0, \qquad \text{otherwise,} \end{cases} \quad (7)$$

with B_n^2 being the normalized parameter given by

$$B_n^2 = \frac{2B_t^2}{\sqrt{\pi}\delta\omega}\Big[\text{erf}\Big(\frac{\omega_2-\omega_m}{\delta\omega}\Big) + \text{erf}\Big(\frac{\omega_m-\omega_1}{\delta\omega}\Big)\Big]^{-1}, \quad (8)$$

where B_t is the wave magnetic field strength. Based on the previous work,[20,21] we choose the following representative values of wave parameters in Table 1 where $\delta\omega = (\omega_2-\omega_1)/4$ and $\omega_m = (\omega_1+\omega_2)/2$.

Table 1. Parameters for EMIC-ion interaction.

	H^+ band	He^+ band	O^+ band
L	3.5	3.5	3.5
λ_m	30	30	30
ω_1	$0.45\Omega_{H^+}$	$0.452\Omega_{He^+}$	$0.1\Omega_{O^+}$
ω_2	$0.95\Omega_{H^+}$	$0.998\Omega_{He^+}$	$0.9\Omega_{O^+}$
B_t	1 nT	1 nT	1 nT

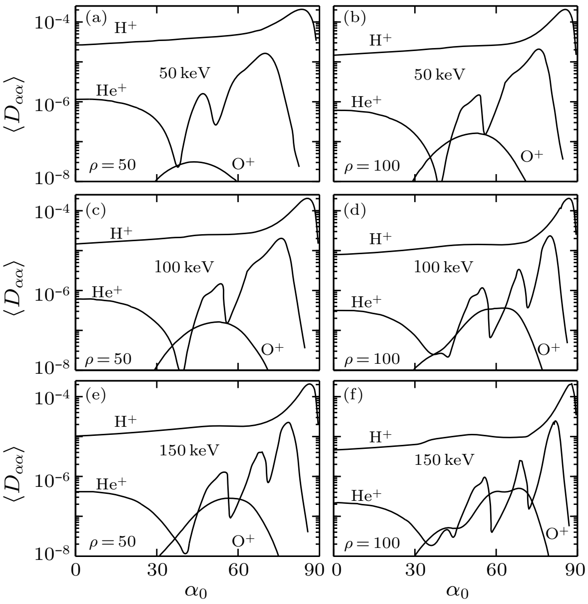

Fig. 2. Bounce-averaged pitch angle diffusion coefficient $\langle D_{\alpha\alpha}\rangle$ (s^{-1}) versus equatorial pitch angle α_0 due to interactions between ions with H^+ band for different indicated kinetic energies and plasma parameters (shown).

In Fig. 2, we plot the bounce-averaged pitch angle diffusion coefficient $\langle D_{\alpha\alpha}\rangle$ as a function of equatorial pitch angle α_0 due to interactions between H^+ band with ions (H^+, He^+ and O^+), for different indicated kinetic energies and plasma parameters $\rho = 50$ (left panels) and $\rho = 100$ (right panels). It is shown that the H^+ band can efficiently drive energetic ion H^+ into the loss cone since $\langle D_{\alpha\alpha}\rangle$ covers a wide range of pitch angles and even exceeds a value $\sim 10^{-4}\,\text{s}^{-1}$ for all three energies $E_k = 50, 100$ and 150 keV. However, the H^+ band is much less efficient in pitch-angle scattering ion He^+ and particularly ion O^+ since $\langle D_{\alpha\alpha}\rangle$ is found to be about one or two orders smaller than that for ion H^+.

Figure 3 shows $\langle D_{\alpha\alpha}\rangle$ for ions interacting with the He^+ band. Here $\langle D_{\alpha\alpha}\rangle$ is found to approach a peak value $\sim 5\times 10^{-5}\,\text{s}^{-1}$ (or above) for both ions H^+ and He^+, but a fairly smaller value for ion O^+. This result suggests that energetic H^+ and He^+ ions can be significantly scattered into the loss-cone by H^+ band but O^+ ion is much less effectively scattered.

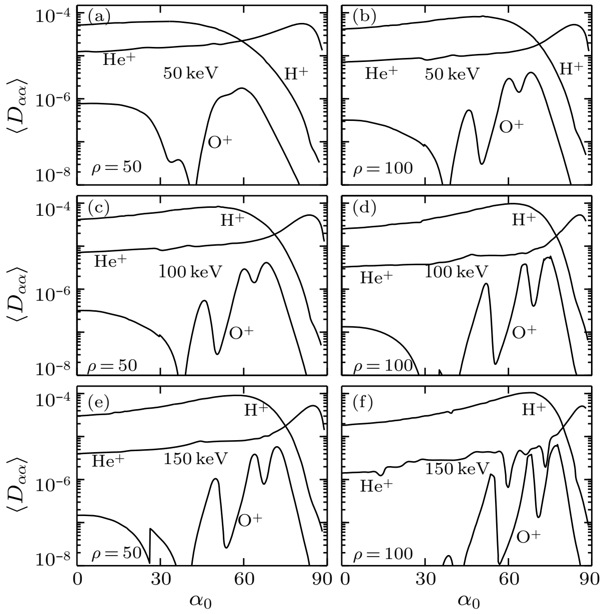

Fig. 3. The same as Fig. 2 but for the He^+ band.

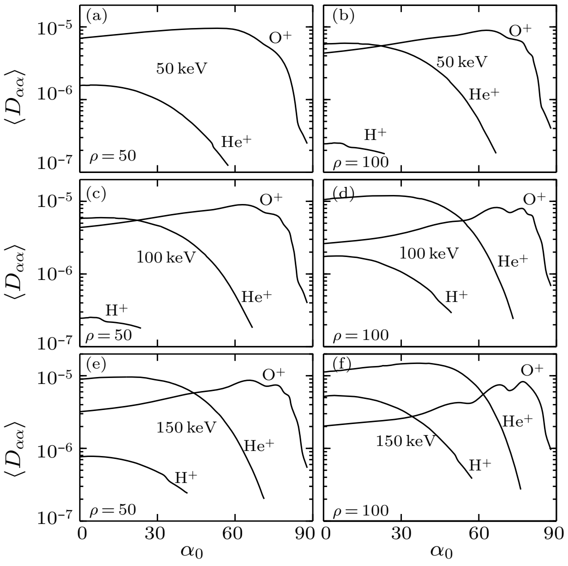

Fig. 4. The same as Fig. 2 but for the O^+ band.

Figure 4 presents the behavior of $\langle D_{\alpha\alpha}\rangle$ for ions in gyroresonance with the O^+ band. Clearly, the O^+ band has a potential for scattering energetic ions He^+ and particularly O^+ into the loss cone since $\langle D_{\alpha\alpha}\rangle$ can reach a peak value $\sim \times 10^{-5}\,s^{-1}$ for ions O^+ and He^+. However, ion H^+ is hard to be scattered by the O^+ band due to very small values of $\langle D_{\alpha\alpha}\rangle$.

It should be pointed out that the bounce-averaged pitch angle diffusion coefficients are found to be insensitive to the plasma parameter ρ in the cases of interest (see Figs. 2–4). Since the symmetrical ring current is present primarily within $L = 4$ during strong geomagnetic storms, while the asymmetrical ring current generally locates beyond $L = 4$, our results above demonstrate that the EMIC wave is one of the leading mechanisms responsible for the ring current decay.

In summary, we have provided a detailed investigation of gyroresonant interaction between EMIC waves and energetic ions in a multi-ion (H^+, He^+, and O^+) plasma. We have evaluated the bounce-averaged pitch angle diffusion coefficient for specified kinetic energy $E_k = 50$, 100 and 150 keV at $L \approx 3.5$, where the symmetrical ring current primarily occurs. EMIC waves are found to have great potentials for scattering energetic ions (H^+, He^+, and O^+) into the loss cone, and correspondingly result in precipitation loss at $L = 3.5$. The current results are tempting to support the previous work that cyclotron wave-particle interaction indeed provides a viable mechanism for the ring current decay.

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