CHIN. PHYS. LETT. Vol. 26, No. 11 (2009) 119401

Evolution of Ring Current Protons Induced by Electromagnetic Ion Cyclotron Waves *

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(Received 7 April 2009)

We investigate the evolution of the phase space density (PSD) of ring current protons induced by electromagnetic ion cyclotron (EMIC) waves at the location $L = 3.5$, calculate the diffusion coefficients in pitch angle and momentum, and solve the standard two-dimensional Fokker–Planck diffusion equation. The pitch angle diffusion coefficient is found to be larger than the momentum diffusion coefficient by a factor of about 10^3 or above at lower pitch angles. We show that EMIC waves can produce efficient pitch angle scattering of energetic (~ 100 keV) protons, yielding a rapid decrement in PSD, typically by a factor of ~ 10 within a few hours, consistent with observational data. This result further supports previous findings that wave-particle interaction is responsible for the rapid ring current decay.

PACS: 94. 20. Wj, 52. 35. Hr, 94. 20. Ny, 94. 30. Xy

In recent years there has been a significant interest in magnetic storms owing to their severe effects on technological systems and geostationary orbiting spacecrafts. In particular, fluxes of electrons in outer radiation belts are found to change dramatically during geomagnetic storms, which is regarded as the result of wave-particle interactions,[1−7] and of drift resonance with enhanced ultra low frequency waves.[8,9]

The terrestrial ring current, which is the key element of geomagnetic storms in the near-Earth space, generally locates at geocentric distances between $\sim 2 - 9R_E$ with the heart location of the symmetrical ring current being at $L = 3.5$. The main carriers of the storm ring current are energetic (about tens of keV) positive ions (H^+, He^+, and O^+), which are trapped by the geomagnetic field and undergo an azimuthal drift. There are three primary loss processes for ring current ions: Coulomb collision processes and charge exchange, together with pitch angle diffusion by electromagnetic ion cyclotron waves.[10,11] The loss time associated with charge exchange and Coulomb drag are in the range of 1–100 days for ion energies above ~ 80 keV.[12] Meanwhile, the timescales for scattering of ions into the loss cone during resonant interactions with EMIC waves can be rapid, typically a few hours.[13] Most of the previous studies concentrated on computing only pitch angle diffusion coefficient to estimate the scattering rates by EMIC waves.[14−16] Using a one-dimensional (1-D) energy diffusion equation, Jordanova *et al.*[17] presented an initial simulating results of ring current evolution during a magnetic storms. To accurately model the competition of acceleration and loss due to wave-particle interaction, solution of a 2-D diffusion equation incorporating both pitch angle and energy diffusion coefficients is required. In this Letter, in order to help to analyze and predict the Earth's radiation environment, we investigate the evolution of the ring current protons by solving a 2-D pitch-angle energy diffusion equation.

EMIC waves with a typical frequency range 0.1–5.0 Hz are often found to occur in the plasmasphere along the duskside plasmapause[18] or within drainage plumes which form in the afternoon sector during storms. EMIC waves are excited during magnetic storms with typical broadband amplitudes in the range 1–10 nT.[15] The anisotropic distribution of low-energy (~ 10 keV) ring current hydrogen (H^+) convected from the magnetotail provides the free energy for EMIC wave excitation.[18]

The dispersion relation for parallel-propagating EMIC waves, in a hydrogen plasma can be written as

$$\mu^2 = \frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega + |\Omega_e|)} - \frac{\omega_p^2}{\omega(\omega - \Omega_p)}, \qquad (1)$$

where k is the wave number, c is the speed of light, Ω_p and $|\Omega_e|$ denote gyrofrequencies of protons and electrons; ω_p and ω_{pe} represent plasma frequencies of pro-

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*Supported by the National Natural Science Foundation of China Grant Nos 40874076, 40774079, 40774078 and 40774077, the Special Fund for Public Welfare Industry (meteorology) GYHY200806024, and the Visiting Scholar Foundation of State Key Laboratory for Space Weather, Chinese Academy of Sciences.

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tons and electrons.

The gyroresonant equation between field-aligned EMIC waves and protons can be expressed as

$$\omega - k v_{\parallel} = \Omega_p/\gamma, \tag{2}$$

where $v_{\parallel} = v\cos\alpha$ with v being the velocity and α being the pitch angle, γ is the resonant relativistic Lorentz factor.

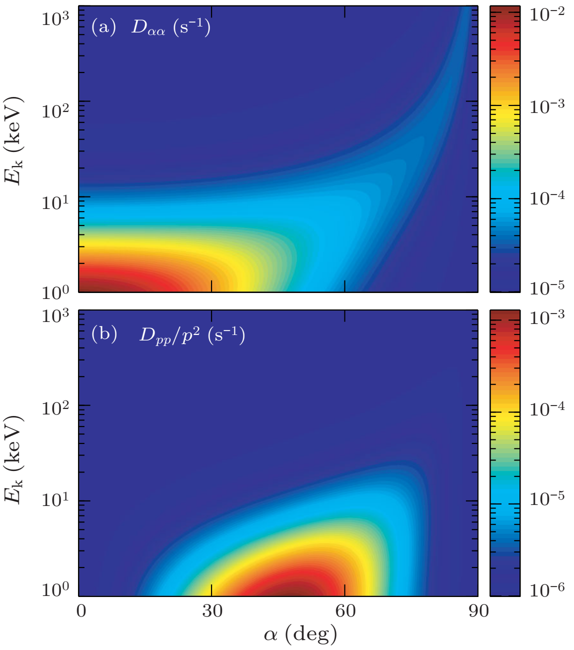

Fig. 1. Two-dimensional diffusion coefficients of pitch angle (a) and momentum (b) in units of (s^{-1}) at $L = 3.5$.

The 2-D Fokker–Planck equation for the phase space density f is expressed as

$$\frac{\partial f}{\partial t} = \frac{1}{\sin\alpha}\frac{\partial}{\partial\alpha}\Big(\sin\alpha D_{\alpha\alpha}\frac{\partial f}{\partial\alpha}\Big) + \frac{1}{p^2}\frac{\partial}{\partial p}\Big(p^2 D_{pp}\frac{\partial f}{\partial p}\Big), \tag{3}$$

where $D_{\alpha\alpha}$ and D_{pp}, denoting the pitch angle and momentum diffusion coefficients, are given by[19]

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

$$D_{pp} = c^2\Omega_p^2\sin^2\alpha I_2, \tag{5}$$

$$I_n = \frac{\pi}{2}\sum_{k_r}\frac{B_\omega^2}{B_0^2}\Big(\frac{\omega_r}{ck_r}\Big)^n\Big|1 - \cos\alpha\frac{p}{\gamma}\frac{dk}{d\omega}\Big|^{-1}_{k=k_r}, \tag{6}$$

where $n = 0, 1, 2$; ω_r (or k_r) satisfies the resonant equation (2); $dk/d\omega$ is calculated by the dispersion relation (1) at each resonant frequency ω_r, B_0 is the equatorial ambient magnetic field strength given by $B_0 = 3.12\times10^4/L^3$ nT.

In order to evaluate PSD evolution of energetic protons by wave-particle interaction, for EMIC waves power B_ω^2, a standard Gaussian frequency band is adopted, with a peak ω_m, a half width $\delta\omega$, a lower cutoff ω_1, and an upper cutoff ω_2:

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

with the normalized parameter B_n^2 defined by

$$B_n^2 = \frac{2B_t^2}{\pi^{1/2}\delta\omega}\Big[\mathrm{erf}\Big(\frac{\omega_2-\omega_m}{\delta\omega}\Big) + \mathrm{erf}\Big(\frac{\omega_m-\omega_1}{\delta\omega}\Big)\Big]^{-1}. \tag{8}$$

Here B_t is the wave magnetic field strength. Based on the previous works,[15−19] we choose the following parameters for the high geomagnetic stormtime properties of EMIC waves at $L = 3.5$. $\omega_1 = 0.1\Omega_p$, $\omega_2 = 0.9\Omega_p$, $\delta\omega = (\omega_2-\omega_1)/4$, $\omega_m = (\omega_2+\omega_1)/2$, $B_t = 3$ nT and $\rho = \omega_{pe}^2/|\Omega_e|^2 = 50$.

We plot two-dimensional diffusion coefficients for EMIC waves in Fig. 1. The corresponding diffusion coefficients at different indicated energies are shown in Fig. 2. Figures 1 and 2 show that the values of diffusion coefficients are sensitively dependent on pitch angle and energy. Moreover, pitch angle diffusion coefficients are found to be higher than the momentum diffusion coefficient by a factor of $\sim 10^3$ or above at lower pitch angles, suggesting that pitch angle diffusion dominates over the energy diffusion in the interaction between ring current protons and EMIC waves.

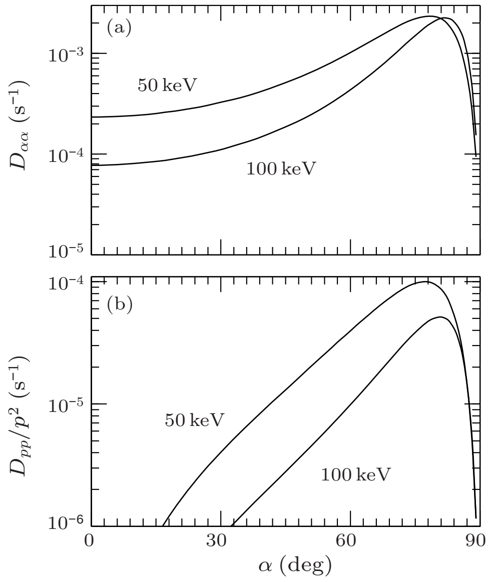

Fig. 2. Diffusion coefficients of pitch angle (a) and momentum at different indicated energies at $L = 3.5$.

Using the above parameters, we evaluate the temporal evolution of proton phase space density (PSD) by solving the 2-D Fokker–Plank equation. The numerical algorithm is implemented using a split operator technique and an unconditionally stable, implicit numerical scheme. The numerical grid is set to be 101 × 101 and uniform in pitch angle and natural logarithm of momentum. The initial distribution of protons is modeled by a kappa-type distribution function[20]

$$f_0^\kappa(p_{||},p_\perp)=\frac{\Gamma(\kappa+l+1)}{\pi^{3/2}\theta^{3/2}\kappa^{(l+3/2)}\Gamma(l+1)\Gamma(\kappa-1/2)} \cdot\left(\frac{p_\perp}{\theta}\right)^{2l}\left[1+\frac{p^2}{\kappa\theta^2}\right]^{-(\kappa+l+1)}, \tag{9}$$

where l is the loss-cone index, θ^2 is the effective thermal parameter scaled by m_pc^2 ($\sim$ 938 MeV), κ is the spectral index, and Γ is the gamma function. Considering that EMIC waves efficiently resonate with energetic ($\sim$ 10 to $\sim$ 100 keV) protons, we assume that f =const at the lower boundary (E = 1 keV), and f =const at the upper boundary (E = 1 MeV); f = 0 at the loss-cone $\alpha = \alpha_L$, and $\partial f/\partial\alpha = 0$ at $\alpha = 90°$.[21]

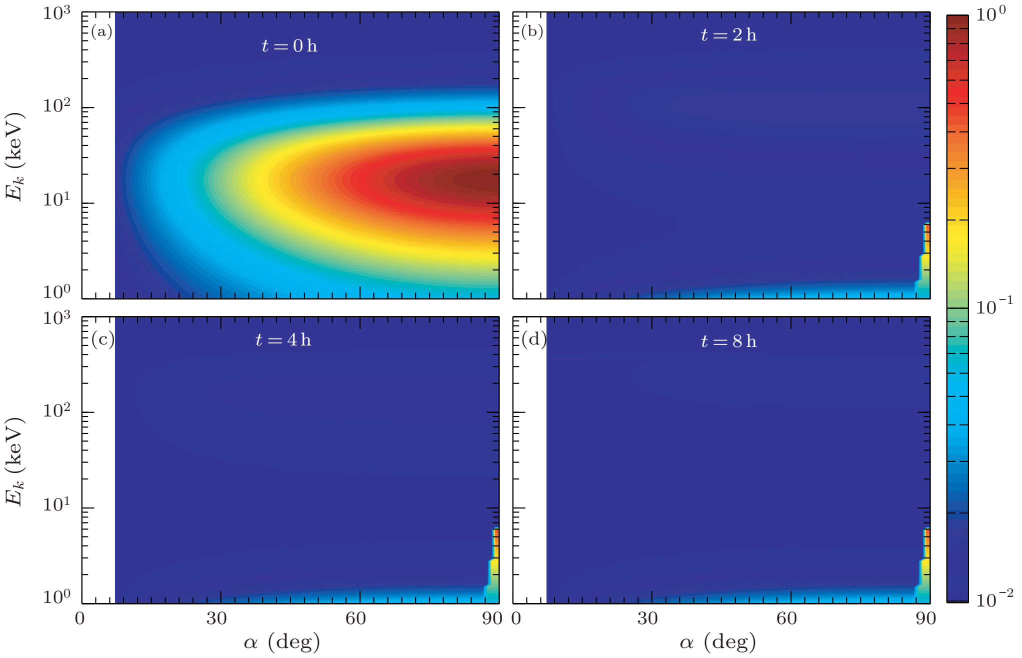

Fig. 3. Proton PSD (arbitrary units) at t = 0, 2, 4, 8 h from a numerical solution to the diffusion equation. The initial and boundary conditions are discussed in the text. The white area marks the loss cone.

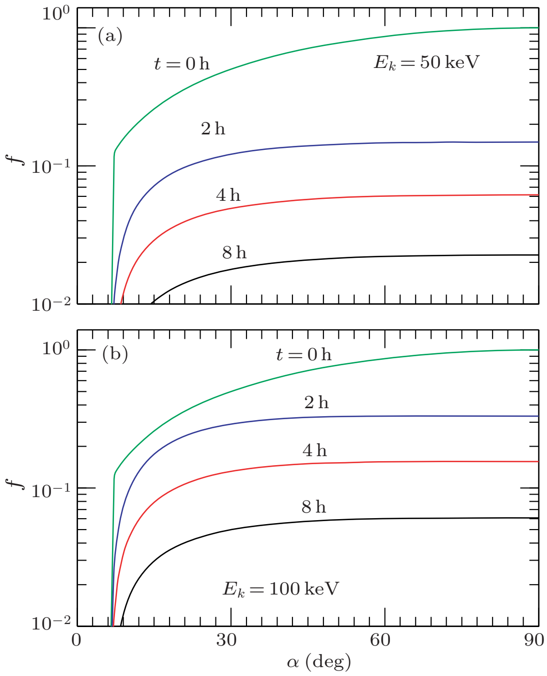

Fig. 4. Proton PSD as a function of pitch angle α at E_k = 50 keV (a) and 100 keV (b), at different indicated hours.

We take the parameters $\theta^2 = 10^{-4}$, $l = 0.5$ and $\kappa = 3$, and use those diffusion rates in Figs. 1 and 2 as an input to model the PSD evolution due to EMIC waves. The evolution of PSD as a function of pitch angle and kinetic energy is shown in Fig. 3, and the corresponding evolution of PSD for indicated energy is presented in Fig. 4. It is demonstrated that PSD of ring current protons decays with time very rapidly, particularly by a factor of 10 after about two hours for 50 keV and four hours for 100 keV. This result gives a further support that EMIC waves indeed induce efficient precipitation loss of protons, and eventually leading to the rapid ring current decay during geomagnetic storms.

It should be pointed out that the ion O$^+$ also contributes significantly to the ring current. In general, the diffusion coefficient associated with ion O$^+$ $D \propto \Omega_{o^+} \propto 1/m_{o^+}$ (see Eqs. (4)–(6) or Ref. [19]), and the loss time scale $\tau_L \propto 1/D \propto m_{o^+}$ (where Ω_{o^+} and m_{o^+} are the gyrofrequency and the mass of ion O$^+$ respectively). Hence, the scattering precipitation loss of ion O$^+$ by EMIC waves is much less efficient under the same conditions since the mass of oxygen is 16 times higher than the mass of proton. Further, in the current study we only concern with the effect of H$^+$-band on the ring current decay. We leave the contribution of He$^+$-band and O$^+$-band to a future study.

In summary, we have investigated the evolution of the phase space density of ring current protons driven by EMIC waves at the location $L = 3.5$. We solve the standard 2-D Fokker–Planck diffusion equation incorporating diffusion coefficients in pitch angle and momentum. Our simulations clearly show that EMIC waves can yield efficient precipitation loss of energetic (~ 100 keV) protons, eventually leading to a rapid ring current decay.

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