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Probing the Magnetosphere through Magnetoseismology and Ultra-Low-Frequency Waves

Key Points:

- The effects of polarization reversal at the crossover frequencies on the particle scattering by EMIC waves are investigated
- While polarization reversal causes obvious changes in H^+ band-induced scattering rates, scattering by the He^+ band is almost unaffected
- Polarization reversal of H^+ band increases the scattering rates of >4 MeV electrons and decreases those of 10–50 and >100 keV protons

Supporting Information:

- Supporting Information S1

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Effects of Polarization Reversal on the Pitch Angle Scattering of Radiation Belt Electrons and Ring Current Protons by EMIC Waves

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Abstract In this study, we investigate the effects of polarization reversal of electromagnetic ion cyclotron (EMIC) waves at the crossover frequencies on computations of bounce-averaged pitch angle diffusion coefficients of radiation belt electrons and ring current protons. We find that inclusion of polarization reversal can cause significant changes of H^+ band-induced particle diffusion coefficients, while scattering by the He^+ band is almost unaffected. Our results show that the pure L-mode approach, which has been widely implemented in previous studies, tends to underestimate the diffusion coefficients of ultrarelativistic (>4 MeV) electrons and overestimate those of 10–50 and >100 keV protons caused by H^+ band EMIC waves. Especially for >100 keV protons, the differences in diffusion coefficients can be larger by an order of magnitude. We confirm that the polarization reversal can contribute importantly to the scattering loss of radiation belt electrons and ring current protons by H^+ band EMIC waves.

1. Introduction

Electromagnetic ion cyclotron (EMIC) waves are frequently observed in the Earth's magnetosphere and usually occur in three emission bands (H^+ , He^+ , and O^+) separated by ion gyrofrequencies (Meredith et al., 2014; Min et al., 2012; Saikin et al., 2015; Wang et al., 2017; Zhang et al., 2016). It has been long recognized that EMIC waves play a crucial role in the Earth's magnetospheric particle dynamics. Via cyclotron resonant interactions, EMIC waves can efficiently scatter radiation belt electrons (Albert & Bortnik, 2009; Cao, Ni et al., 2017; Cao, Shprits et al., 2017; Engebretson et al., 2018; Miyoshi et al., 2008; Shprits et al., 2016, 2017; Su et al., 2017; Summers & Thorne, 2003) and ring current protons (Cornwall et al., 1970; Summers, 2005; Xiao et al., 2012) into the atmosphere. EMIC waves can also heat thermal electrons and heavy ions (Thorne & Horne, 1997; Zhou et al., 2013) and contribute to the loss of central plasma sheet protons (Cao et al., 2016; Liang et al., 2014).

In the inner magnetosphere, EMIC waves can be excited by the anisotropic distribution of ring current protons with energies of ~ 10 to 100 keV (Cornwall, 1965; Gary, 1993; Wang et al., 2016; Yue et al., 2019). EMIC waves are predominately left-hand polarized (L-mode) with wave normal almost parallel to the ambient magnetic field line when they are generated near the geomagnetic equator. As they propagate to high latitudes, EMIC waves become more and more oblique (Allen et al., 2015; Hu et al., 2010; Rauch & Roux, 1982). While reaching latitude where the wave frequency equals to the crossover frequency, EMIC waves will suffer a polarization reversal and become linearly or right polarized (e.g., Chen et al., 2014; Kim & Johnson, 2016; Rauch & Roux, 1982). The polarization reversal at the crossover frequency will significantly modify the dispersive properties of EMIC waves at high latitudes and may subsequently affect the EMIC wave-driven scattering of magnetospheric particles. However, in the calculations of quasi-linear bounce-averaged particle diffusion coefficients, previous studies commonly assumed that EMIC waves are purely left-hand polarized for both strictly parallel propagating (e.g., Ni et al., 2018; Summers & Thorne, 2003; Ukhorskiy et al., 2010; Usanova et al., 2014; Xiao et al., 2012) and obliquely propagating events (e.g., Albert, 2003; Cao et al., 2016, 2019; Capannolo et al., 2019; Glauert & Horne, 2005; He et al., 2016; Ni et al., 2015; Uzbekov et al., 2016). Some recent studies also assumed that EMIC waves are confined to below the geomagnetic latitudes where the polarization reversal can occur (e.g., Ma et al., 2019).

In order to understand the effects of EMIC wave polarization reversal at crossover frequencies on particle scattering loss, in this study we perform calculations of quasi-linear bounce-averaged pitch angle diffusion coefficients of radiation belt electrons and ring current protons using both the pure L-mode and polarization reversal approaches. Our results show that inclusion of polarization reversal strongly affects the particle pitch angle scattering by H^+ band EMIC waves, while the scattering by He^+ band EMIC waves is almost unaffected. We demonstrate that the scattering of ring current protons is more likely to be affected by the polarization reversal of EMIC waves than that of radiation belt electrons.

2. Model Description

Following previous studies (e.g., Kersten et al., 2014; Li et al., 2007), we assume the EMIC wave spectral intensity I_B has a Gaussian distribution given by

$$I_B(\omega) = A \exp \left[- \left(\frac{\omega - \omega_m}{\delta\omega} \right)^2 \right] (\omega_{lc} \leq \omega \leq \omega_{uc}), \quad (1)$$

where ω is the wave frequency, ω_{lc} and ω_{uc} are the lower and upper cutoff frequencies, ω_m and $\delta\omega$ are the peak wave frequency and spectral bandwidth, and A is a normalization factor. The distribution of EMIC wave normal angle θ is also assumed to be Gaussian, given by

$$g(\theta) = \exp \left[- \left(\frac{\tan\theta - \tan\theta_m}{\tan\theta_w} \right)^2 \right] (\theta_{lc} \leq \theta \leq \theta_{uc}), \quad (2)$$

where θ_{lc} and θ_{uc} are the lower and upper cutoff normal angles, and θ_m and θ_w are the peak normal angle and angular width.

The general dispersion relation of electromagnetic waves in a cold, magnetized multi-ion (H^+ , He^+ , and O^+) plasma (Stix, 1962) is given by the following equation

$$D(\omega, k, \theta) = (S \tan^2 \theta + P) \mu^4 - (R L \tan^2 \theta + P S (2 + \tan^2 \theta)) \mu^2 + P R L (1 + \tan^2 \theta) = 0, \quad (3)$$

where k is the wave number; $\mu = k c / \omega$ is the wave refractive index; c is the speed of light; and R , L , S and P are the Stix parameters.

To understand how the polarization of EMIC waves changes from predominantly left to right handed at the crossover frequencies, it is instructive to study the dispersion curves. By solving Equation 3, we show in Figure 1 the dispersion curves of EMIC waves in a multi-ion (H^+ , He^+ , and O^+) plasma at three specific latitudes $\lambda = 0^\circ$, 15° , and 20° with wave normal angles $\theta = 0^\circ$, 20° , and 30° . Here we focus on the L shell $L = 4.5$ and assume that the background magnetic field is dipolar. The electron number density is adopted from the plasmaspheric density model of Sheeley et al. (2001) and is assumed to be constant along the magnetic field line. Following previous studies (e.g., Meredith et al., 2003; Summers et al., 2007b), we choose a typical set of the ion concentration ratios, that is, $\eta_{H^+} : \eta_{He^+} : \eta_{O^+} = 0.85 : 0.1 : 0.05$. In Figure 1, the wave frequency ω is normalized to the local gyrofrequency of protons Ω_p and the wave number k is normalized to Ω_p / V_A , where V_A is the Alfvén velocity. The blue and red lines correspond to the L-mode and R-mode branches, respectively. The dashed horizontal lines correspond to the crossover frequencies ω_{cr1} and ω_{cr2} at which the L-mode and R-mode branches touch each other. The thick blue and red lines correspond to the EMIC wave spectra on the L-mode and R-mode branches, respectively. For the H^+ band spectrum, $\omega_{lc} = 0.5 \Omega_{p,eq}$, $\omega_{uc} = 0.7 \Omega_{p,eq}$, where $\Omega_{p,eq}$ is the equatorial gyrofrequency of protons. For the He^+ band spectrum, $\omega_{lc} = 2.5 \Omega_{O^+,eq}$, $\omega_{uc} = 3.5 \Omega_{O^+,eq}$, where $\Omega_{O^+,eq}$ is the equatorial gyrofrequency of oxygen ions.

Figure 1 shows that the R-mode and L-mode branches intersect at the crossover frequencies for strictly parallel propagation ($\theta = 0^\circ$) but remain uncoupled. For oblique propagation ($\theta > 0^\circ$), the L-mode branch of H^+ and He^+ bands above crossover frequency is connected to R-mode branch below. Thus, the polarization of H^+ band and He^+ band EMIC waves will change at the crossover frequency from predominantly left handed to right handed as they propagate to high latitudes, as shown in Figures 1d–1f. Additionally, it is shown that the L-mode branch of O^+ band does not touch the R-mode branch, indicating that O^+ band waves suffer no

Figure 1. Dispersion curves of EMIC waves in a cold, multi-ion (H^+ , He^+ , and O^+) plasma at three specific magnetic latitudes $\lambda = 0^\circ$, 15° , and 20° with wave normal angle $\theta = 0^\circ$, 20° , and 30° . The wave frequency ω is normalized to the local gyrofrequency of protons Ω_p , and the wave number k is normalized to Ω_p/V_A , where V_A is the Alfvén velocity. The blue and red lines denote the L-mode and R-mode branches, respectively. The dashed horizontal lines denote the crossover frequencies ω_{cr1} and ω_{cr2} at which the L-mode and R-mode branches touch each other. The thick blue and thick red lines correspond to the EMIC wave spectra on the L-mode and R-mode branches, respectively. For H^+ band spectrum, $\omega_{lc} = 0.5 \Omega_{p,eq}$, $\omega_{uc} = 0.7 \Omega_{p,eq}$, where $\Omega_{p,eq}$ is the equatorial gyrofrequency of protons. For He^+ band spectrum, $\omega_{lc} = 2.5 \Omega_{O^+,eq}$, $\omega_{uc} = 3.5 \Omega_{O^+,eq}$, where $\Omega_{O^+,eq}$ is the equatorial gyrofrequency of oxygen ions. While Figures 1a–1c show the variation of EMIC wave spectra with the increase of λ on the pure L-mode branch, Figures 1d–1f show how EMIC waves change from left-hand polarized at the equator to right-hand polarized as magnetic latitude increases.

polarization reversal during their propagation to high latitudes. For comparison, we also show in Figures 1a–1c the pure L-mode approach that was widely used to quantify the particle scattering loss by oblique EMIC waves in previous studies. In this approach, EMIC waves are assumed to be strictly left-hand polarized along the whole magnetic field line despite the fact that the L-mode branch above the crossover frequency is not connected to the L-mode branch below. It is clearly illustrated in Figure 1 that the polarization reversal will strongly modify the dispersive properties of H^+ and He^+ band EMIC waves at high latitudes.

3. Numerical Results

In order to quantify the effects of polarization reversal on the resonant interactions between EMIC waves and magnetospheric particles, the Full Diffusion Code (FDC) (Cao et al., 2016, 2019; Ni et al., 2008, 2015; Shprits & Ni, 2009) is implemented in the present study to calculate the bounce-averaged pitch angle diffusion coefficients by oblique EMIC waves in a multi-ion plasma. In this study, both the pure L-mode and polarization reversal approaches (as shown in Figure 1) are used, and our calculations include contributions from the $N = -10$ to 10 cyclotron harmonic resonances. We use a latitudinally varying model of wave normal angle distribution as in Ni et al. (2015), in which EMIC waves undergo parallel propagation near the geomagnetic equator and become more and more oblique at higher latitudes. Since EMIC waves undergo absorption and reflection at the bi-ion frequencies (e.g., Horne & Thorne, 1993, 1997; Hu et al., 2010), we assume that the waves are confined to below the latitudes where the wave frequency equals to the bi-ion

Figure 2. Bounce-averaged pitch angle diffusion coefficients $\langle D_{\alpha\alpha} \rangle$ of radiation belt electrons as a function of electron kinetic energy E_k and equatorial pitch angle α_{eq} corresponding to (a, b) the pure L-mode and (c, d) polarization reversal approaches. (e, f) Normalized difference in diffusion coefficients between the pure L-mode and polarization reversal approaches. From bottom to top, we show the results for H^+ and He^+ band EMIC waves, respectively.

frequencies. Following previous studies (Albert, 2003; Summers et al., 2007a), we adopt a typical wave spectrum with an amplitude of 1 nT for each emission band. For H^+ band waves, $\omega_{lc} = 0.5 \Omega_{p,eq}$, $\omega_{uc} = 0.7 \Omega_{p,eq}$, $\omega_m = 0.6 \Omega_{p,eq}$, and $\delta\omega = 0.1 \Omega_{p,eq}$. For He^+ band waves, $\omega_{lc} = 2.5 \Omega_{O^+,eq}$, $\omega_{uc} = 3.5 \Omega_{O^+,eq}$, $\omega_m = 3.0 \Omega_{O^+,eq}$, and $\delta\omega = 0.5 \Omega_{O^+,eq}$.

3.1. Bounce-Averaged Diffusion Coefficients of Radiation Belt Electrons

In Figures 2a–2d, we present the 2-D plots of quasi-linear bounce-averaged pitch angle diffusion coefficients $\langle D_{\alpha\alpha} \rangle$ of radiation belt electrons as a function of electron kinetic energy E_k and equatorial pitch angle α_{eq} for H^+ and He^+ band EMIC waves. For comparison, we also present in Figures 2e and 2f the normalized differences $2(\langle D_{\alpha\alpha} \rangle|_{PL} - \langle D_{\alpha\alpha} \rangle|_{PR}) / (\langle D_{\alpha\alpha} \rangle|_{PL} + \langle D_{\alpha\alpha} \rangle|_{PR})$, where $\langle D_{\alpha\alpha} \rangle|_{PL}$ and $\langle D_{\alpha\alpha} \rangle|_{PR}$ correspond to pitch angle diffusion coefficients for the pure L-mode (Figures 2a and 2b) and polarization reversal (Figures 2c and 2d) approaches, respectively. It is illustrated that both H^+ and He^+ band EMIC waves can efficiently pitch angle scatter electrons at a rate on the order of $>10^{-3} \text{ s}^{-1}$. Compared with He^+ band waves, H^+ band waves can scatter electrons over a broader coverage of electron energy and equatorial pitch angle. Our results show that effects of polarization reversal on EMIC-driven electron scattering have a strong dependence on the emission band. While inclusion of polarization reversal produces significant differences in electron diffusion coefficients due to H^+ band EMIC waves, He^+ band-induced diffusion coefficients are unaffected. We clearly illustrate that the pure L-mode approach underestimates the scattering efficiency of $>4 \text{ MeV}$ electrons by H^+ band EMIC waves. The largest differences in diffusion coefficients are found at 5–7 MeV near the bounce loss cone and switch to higher energies as equatorial pitch angle increases.

We illustrate in Figure 3 the line plots of electron bounce-averaged pitch angle diffusion coefficients $\langle D_{\alpha\alpha} \rangle$ as a function of proton equatorial pitch angle at five indicated energies for H^+ and He^+ band EMIC waves. The solid and dashed lines correspond to the pure L-mode and polarization reversal approaches, respectively. It is clearly shown that inclusion of polarization reversal at the crossover frequencies does not influence the pitch angle scattering of electrons by He^+ band EMIC waves, while H^+ band-induced pitch angle diffusion coefficients of ultrarelativistic electrons are strongly affected. It is shown that polarization reversal can cause an obvious increase of pitch angle diffusion coefficients of $>4 \text{ MeV}$ electrons at low pitch angles. Especially for 6 MeV electrons, the increase of diffusion coefficients can be up to a factor of ~ 4 . Thus, it is expected that the loss timescales of $>4 \text{ MeV}$ electrons will decrease since the loss timescales are mainly controlled by the

Figure 3. Bounce-averaged pitch angle diffusion coefficients $\langle D_{\alpha\alpha} \rangle$ of radiation belt electrons as a function of electron equatorial pitch angle α_{eq} for five indicated electron energies corresponding to H^+ and He^+ band EMIC waves. The solid and dashed lines correspond to the pure L-mode and polarization reversal approaches, respectively.

pitch angle scattering rate near the loss cone (Albert & Shprits, 2008; Shprits et al., 2006). Figure 3 also shows that as electron energy increases, the changes of diffusion coefficients caused by the polarization reversal become weaker but occur over a broader coverage of electron pitch angle. The results demonstrate that the polarization reversal plays an important role in the scattering loss of radiation belt electrons by H^+ band EMIC waves.

3.2. Bounce-Averaged Diffusion Coefficients of Ring Current Protons

To investigate the role of polarization reversal at crossover frequencies in the resonant scattering of ring current protons by EMIC waves, we present in Figure 4 the 2-D plots of proton bounce-averaged pitch angle

Figure 4. Same as Figure 2, except for ring current protons.

Figure 5. Same as Figure 3, except for ring current protons.

diffusion coefficients $\langle D_{\alpha\alpha} \rangle$ (Figures 4a–4d) and normalized differences (Figures 4e and 4f) as a function of proton kinetic energy and equatorial pitch angle. From top to bottom, we show the results for H^+ and He^+ band EMIC waves, respectively. Figure 4 shows that He^+ band-induced scattering of protons is slightly affected by the polarization reversal. Near the bounce loss cone, inclusion of polarization reversal enhances the scattering efficiency of 100–200 keV protons and weakens the scattering efficiency of 80–100 keV protons. The largest normalized differences in diffusion coefficients are found to be smaller than $\sim 50\%$ and shift to higher energies as proton equatorial pitch angle increases. However, inclusion of polarization reversal significantly affects the pitch angle scattering of ring current protons by H^+ band EMIC waves, showing a strong dependence on proton energy and equatorial pitch angle. Pronounced decrease of pitch angle diffusion coefficients are found for 10–50 keV protons at $\alpha_{eq} < 30^\circ$ and 100 keV to 1 MeV protons at $\alpha_{eq} < 50^\circ$, and the corresponding normalized differences are larger than 100%. Therefore, the pure L-mode approach tends to seriously overestimate the scattering loss of these protons by H^+ band EMIC waves. Compared with 10–50 keV protons, the decrease of diffusion coefficients of >100 keV protons is more significant and occurs over a narrower coverage of proton pitch angle.

Figure 5 shows the line plots of proton bounce-averaged pitch angle diffusion coefficients $\langle D_{\alpha\alpha} \rangle$ as a function of proton equatorial pitch angle for the five indicated energies, for both H^+ and He^+ band EMIC waves. The solid and dashed lines correspond to the pure L-mode and polarization reversal approaches, respectively. It is shown that inclusion of polarization reversal results in significant decrease of pitch angle diffusion coefficients of 10, 30, and 300 keV protons at low pitch angles; however, there is almost no change for electron population with other energies or pitch angles. Especially for 300 keV protons, the decrease of diffusion coefficients at $\alpha_{eq} < 10^\circ$ can be larger than an order of magnitude. Such remarkable decreases of pitch angle diffusion coefficients near the bounce loss cone will obviously increase the loss timescales of these protons due to H^+ band EMIC waves. For He^+ band EMIC waves, inclusion of polarization reversal only produces slight changes in pitch angle diffusion coefficients of 100 and 300 keV protons. At pitch angles close to the loss cone, the differences in diffusion coefficients are even smaller than a factor of 1.5, suggesting that the polarization reversal will not have an important impact on the He^+ band wave-driven loss of ring current protons.

4. Discussion and Conclusions

In this study, we find significant discrepancies between the contributions of polarization reversal to the particle scattering by H^+ and He^+ band EMIC waves. While the polarization reversal strongly affects the H^+

band-induced pitch angle scattering rates of particles, it has almost no influence on the particle diffusion caused by He^+ band. We suggest that this is mainly due to the larger wave number at the crossover frequency ω_{cr1} than at the crossover frequency ω_{cr2} , as shown in Figure 1. Since particle minimum resonant energy decreases with increasing EMIC wave number (e.g., Silin et al., 2011), it is expected that the minimum resonant energy at ω_{cr1} is lower than that at ω_{cr2} . For the two EMIC wave bands, the corresponding minimum resonant energies of electrons at ω_{cr1} and ω_{cr2} are ~ 4.2 and >10 MeV, respectively, while the minimum resonant energies are ~ 4 and 55 keV for protons (see supporting information Figure S1). Compared with the He^+ band, the polarization reversal of H^+ band can affect the pitch angle scattering of particles over a much broader coverage of energy. This is in agreement with Figures 2 and 4, which show that scattering rates of particles with energy lower than the minimum resonant energies at the crossover frequencies are unaffected by the polarization reversal.

Our results clearly show that the most significant differences in particle diffusion coefficients between the pure L-mode and polarization reversal approaches are found at high energies and low equatorial pitch angles. We suggest that this is mainly associated with high latitudes where the polarization reversal of EMIC waves occurs. As the magnetic latitude increases, the particle resonant region tends to shift to high energy and low equatorial pitch angle due to the stronger background magnetic field intensity. Meanwhile, it should be noted that in our calculations of bounce-averaged diffusion coefficients of both electrons and protons, we ignored the contribution from Landau resonance ($N = 0$). Even though EMIC waves can efficiently scatter near-equatorially mirroring electrons (e.g., Fu et al., 2018), the polarization reversal of EMIC waves occurs at high latitudes. This indicates that the polarization reversal will not affect the scattering of radiation belt electrons due to Landau resonance. For ring current protons, although the polarization reversal can cause changes in scattering rates due to Landau resonance (as shown in Figure S2), their scattering rates are several orders of magnitude smaller than those due to cyclotron resonances. Thus, the contribution of Landau resonance to the net proton diffusion coefficients can be negligible.

In the present study, we have investigated the contribution of polarization reversal at the crossover frequencies to the pitch angle scattering of radiation belt electrons and ring current protons by both H^+ and He^+ band EMIC waves. By calculating the quasi-linear bounce-averaged pitch angle diffusion coefficients using both the pure L-mode and polarization reversal approaches, we find that the effects of polarization reversal on EMIC wave-induced particle scattering are strongly dependent on the emission band, particle kinetic energy, and equatorial pitch angle.

Our major conclusions are summarized as follows:

- (1) While inclusion of polarization reversal produces significant changes in H^+ band EMIC wave-induced pitch angle scattering rates of both radiation belt electrons and ring current protons, pitch angle scattering by He^+ band EMIC waves is almost unaffected. We find that this is mainly due to the much higher minimum resonant energy at the crossover frequency ω_{cr2} than that at crossover frequency ω_{cr1} .
- (2) Our results show that the polarization reversal of H^+ band EMIC waves tends to enhance the scattering efficiency of ultrarelativistic (>4 MeV) electrons at $\alpha_{eq} < 40^\circ$. The most pronounced increase of electron scattering rates occurs at the energies of 5–7 MeV by a factor of up to ~ 4 .
- (3) Compared with the scattering rates of radiation belt electrons, the scattering rates of ring current protons are more sensitive to the polarization reversal of H^+ band EMIC waves. It is demonstrated that the pure L-mode approach, which has been commonly adopted in previous studies, tends to overestimate the scattering rates of 10–50 keV protons for $\alpha_{eq} < 50^\circ$ and >100 keV protons for $\alpha_{eq} < 30^\circ$. Especially for >100 keV protons, inclusion of the wave polarization reversal produces differences of over an order of magnitude in the scattering rates near the bounce loss cone, suggesting that the pure L-mode approach significantly underestimates the loss timescales of these protons due to H^+ band waves.

Data Availability Statement

The numerical results can be obtained online (from <https://doi.org/10.6084/m9.figshare.12624149>).

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