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Scattering of relativistic and ultra-relativistic electrons by obliquely propagating Electromagnetic Ion Cyclotron waves

Bogdan Uzbekov [a,*], Yuri Y. Shprits [b,c,d], Ksenia Orlova [a,b]

[a] Skolkovo Institute of Science and Technology, Moscow, Russia
[b] Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA, USA
[c] Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA
[d] Helmholtz Centre Potsdam, GFZ German Research Centre For Geosciences, Germany

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ABSTRACT

Electromagnetic Ion Cyclotron (EMIC) waves are transverse plasma waves that are generated in the Earth magnetosphere by ring current protons with temperature anisotropy in three different bands: below the H^+, He^+ and O^+ ion gyrofrequencies. EMIC events are enhanced during the main phase of a geomagnetic storm when intensifications in the electric field result in enhanced injections of ions and are usually confined to high-density regions just inside the plasmapause or within drainage plumes. EMIC waves are capable of scattering radiation belt electrons and thus provide an important link between the intensification of the electric field, ion populations, and radiation belt electrons. Bounce-averaged diffusion coefficients computed with the assumption of parallel wave propagation are compared to the results of the code that uses the full cold plasma dispersion relation taking into account oblique propagation of waves and higher-order resonances. We study the sensitivity of the scattering rates to a number of included higher-order resonances, wave spectral distribution parameters, wave normal angle distribution parameters, ambient plasma density, and ion composition. Inaccuracies associated with the neglect of higher-order resonances and oblique propagation of waves are compared to potential errors introduced by uncertainties in the model input parameters.

1. Introduction

1.1. Scattering by EMIC waves

Wave-particle interaction is an important aspect of radiation belt physics, and is responsible for the variability of particle fluxes observed. One type of plasma wave that is supported by the Earth's magnetosphere, and is able to effectively scatter radiation belt particles is the electromagnetic ion cyclotron (EMIC) wave (Thorne and Kennel, 1971; Lyons and Thorne, 1972). Recent studies have suggested that EMIC waves are most efficient at scattering ultra-relativistic electrons (e.g., Usanova et al., 2014; Shprits et al., 2015; Drozdov et al., 2015). EMIC waves are able to cause relativistic and ultra-relativistic electron loss in a matter of hours (e.g. Ni et al., 2015; He et al., 2016; Summers et al., 2007b; Usanova et al., 2014; Su et al., 2011), and thus quantification of the effect of EMIC waves on radiation belt electrons is crucial for predicting the evolution of the radiation belt electron fluxes.

While the calculations of diffusion coefficients due to very low frequency (VLF) whistlers are done for an oblique distribution of waves (e.g., Glauert and Horne, 2005; Albert, 2005; Shprits and Ni, 2009; Ni et al., 2008; Gu et al., 2012; Orlova and Shprits, 2014; Orlova et al., 2014), calculations of the scattering rates for EMIC waves usually assume parallel propagating waves (e.g., Summers and Thorne, 2003; Summers et al., 2007a; Ukhorskiy et al., 2010; Usanova et al., 2014; Shprits et al., 2014). The likely reason is a cumbersome plasma dispersion relation and related computational difficulties required to quantify effects of oblique EMIC waves in the presence of heavy ions on the radiation belt particles. In this study, we use a semi-analytical approach described in the text below. It allows us to obtain accurate and reliable solutions for diffusion coefficients, which is challenging to obtain using a purely analytical or purely numerical approach. The method and the code developed can be used to study other plasma wave modes obliquely propagating in the presence of heavy ions and their effects on radiation belt particles with high accuracy, opening opportunities for future research. The presented method guarantees that all intersections of dispersion relation and cyclotron resonance condition curves are obtained.

Albert (2003) considered all three bands of oblique EMIC waves and investigated the sensitivity of the diffusion coefficients for EMIC waves to wave normal angle distribution and resonance

* Corresponding author.
E-mail address: bogdan.uzbekov@gmail.com (B. Uzbekov).

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numbers. He also proposed a computationally efficient technique to avoid integration over ranges of latitudes, wave normal angles and resonant numbers that are not consistent with the resonance in a prescribed wave population. Yet Albert (2003) made slight approximations to the exact cold plasma theory, namely a high-density approximation, which is reasonable in the case of EMIC waves, and allows for an analytical solution as a result of simpler equations. Glauert and Horne (2005) have taken the results of the PADIE code calculated numerically the diffusion coefficients for the case of oblique EMIC waves, and compared them to the results of (Summers and Thorne, 2003), where the assumption of parallel wave propagation is made, and outlined the importance of EMIC wave obliquity. The study conducted by Glauert and Horne (2005), however, fixes ambient plasma density, ion composition and parameters of the wave spectral distribution. Ni et al. (2015) provided a useful general 14th-order polynomial equation of resonant frequencies concerning oblique EMIC wave interactions with charged particles in cold, magnetized, multi-ion plasma. The study considered multi-band EMIC waves propagating at different L-shells and having various wave normal angles. Present study fixes L-shell at $L = 4$ and only considers He band waves, but complements work of Ni et al. (2015) by conducting extensive sensitivity analysis of the diffusion coefficients for oblique EMIC to other model input parameters, including number of cyclotron resonances, wave spectral distribution, ambient plasma density and ion composition.

While Albert, (2003); Glauert and Horne, (2005); Summers et al. (2007b) considered an arbitrary ratio of plasma to gyrofrequency, in the current study we use statistical models (Carpenter and Anderson, 1992) to calculate the ratio of plasma frequency to gyrofrequency.

In this study we focus on the He band left-hand polarized EMIC waves (L-mode), due to its typically higher amplitude and subsequent comparison to H and O bands (Saikin et al., 2015). At the same time, right-hand polarized (r-mode) EMIC waves are rarely observed experimentally (e.g. Meredith et al., 2003, 2014; Allen et al., 2015). In addition, the R-mode waves are not as efficient at scattering ultra-relativistic electrons as the L-mode waves.

1.2. Code description

We have performed calculations of the bounce-averaged diffusion coefficients for oblique EMIC waves using Full Diffusion Code (FDC) (e.g. Ni et al., 2008; Shprits and Ni, 2009; Gu et al., 2012), following the theoretical approach presented in Glauert and Horne (2005). The details of the calculations are presented in the supporting information. The code is capable of computing resonant scattering rates, including first-order, Landau, and higher-order resonances and uses the methodology of Orlova and Shprits (2011) to integrate bounce period and momentum diffusion coefficients, avoiding uncertainty at the mirror point.

Substituting resonance conditions for wave-particle interactions into the cold plasma dispersion relation yields a fourteenth order polynomial with respect to the wave frequency ω. For the version of the code developed for this study, the coefficients are derived semi-analytically using the Matlab Symbolic Toolbox and then incorporated into the code explicitly. Coefficients of the polynomial are not presented in this work, as they are very cumbersome. The roots of the polynomial, satisfying both cold plasma dispersion relation and resonance conditions, are computed using a standard polynomial root finder. Only roots that lie between the lower and upper cut-off frequencies of the wave are considered. The roots are then checked on their R-mode or L-mode origin, and filtered according to the mode under consideration (e.g. R-mode roots are not considered, when studying the effects of the L-mode waves only). The dispersion relation derivative, $(\partial\omega/\partial k)|_{\mathcal{D}=0}$, which is required to compute local diffusion coefficients, is also calculated semi-analytically with the help of the Matlab Symbolic Toolbox. The resulting derivative formula is very cumbersome and therefore not presented here.

From the mathematical standpoint, the dispersion relation derivative $(\partial\omega/\partial k)|_{\mathcal{D}=0}$, as well as coefficients of the polynomial derived substituting resonance conditions into the dispersion relation $\mathcal{D}(k, \omega, X)$=0, are functions of local magnetic field value, ambient plasma density n_e, plasma ion composition (parameters $\zeta_{H^+} = n_{H^+}/n_e$, $\zeta_{He^+} = n_{He^+}/n_e$, and $\zeta_{O^+} = =n_{O^+}/n_e$), particle energy, local pitch angle α, wave normal angle θ and resonant number n. The choice of these variables makes the code relatively easy to adapt to studies of other plasma wave modes and their effects on the trapped radiation at various magnetospheres.

We assume distributions of wave normal angle $g(\theta)$ and wave spectral density $B^2(\omega)$ to be Gaussian:

$$B^2(\omega) = \begin{cases} A^2\exp\left(-\left(\frac{\omega-\omega_m}{\delta\omega}\right)^2\right), & \omega_{lc} \le \omega \le \omega_{uc} \\ 0, & otherwise \end{cases}$$

where ω_m and $\delta\omega$ are distribution maximum and bandwidth respectively, ω_{lc} and ω_{uc} are lower and upper cut-off frequencies, and A is a normalisation factor. And for the wave angular spread:

$$g(X) = \begin{cases} \exp\left(-\left(\frac{X-X_m}{X_w}\right)^2\right), & X_{min} \le X \le X_{max} \\ 0, & otherwise \end{cases}$$

where $X = tan(\theta)$, X_w is the angular distribution bandwidth, X_m is the peak value, and X_{min} and X_{max} are the cut-off values.

We set MLT presence of the waves to 100%. In order to obtain more realistic scattering rates, our diffusion coefficients need to be scaled by the width of the MLT sector where waves are present. The scaling is performed by simple multiplication of the coefficients by realistic MLT presence. Maximum latitude of the wave propagation is set to 20° following statistical study of Meredith et al. (2003).

We have validated the code by comparing our results with those from Glauert and Horne (2005).

2. Sensitivity simulations

In this section, we first study contribution of the Landau, first-order and higher-order resonances to the bounce-averaged pitch angle diffusion coefficients for oblique EMIC waves. This analysis allows us to estimate the number of resonances that needs to be included into calculations to give sufficiently accurate results. We then move to comparison of the scattering rates calculated for EMIC waves propagating parallel to the magnetic field and for the case of oblique propagation of waves. Finally, we study sensitivity of the diffusion coefficients for oblique EMIC waves to the key model input parameters – wave spectral distribution, wave normal angle distribution, ambient plasma density, and ion composition.

2.1. Contribution of various resonances

Fig. 1 shows the contribution of various resonances to the bounce-averaged pitch angle diffusion coefficients for electron energies of 3, 5, 7, and 10 MeV. The scattering rates were computed at $L = 4$ with the input parameters summarized in Table 1.

From Fig. 1 we see that the principal resonance ($n = 1$) can give a fairly good estimate of the diffusion coefficients at energies of up to 7 MeV, while at $E = 10$ MeV, the resonance represented by $n = -1$ number overtakes the principal resonance at pitch angles below 20°, which should be taken into account. It is interesting to note resonances appearing in pairs corresponding to $|n|$, and how