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Dependence of pitch-angle scattering rates and loss timescales on the magnetic field model

Ksenia G. Orlova[1,2] and Yuri Y. Shprits[1,3]

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[1] Radiation belt diffusion codes require, as inputs, precomputed scattering rates, which are currently bounce-averaged in the dipole magnetic field. We present the results of computations of the bounce-averaged quasi-linear pitch-angle diffusion coefficients of relativistic electrons for various distances and two MLT in the Tsyganenko 89c magnetic field model. The coefficients were computed for quiet and storm-time conditions. We compare scattering rates bounce-averaged in a non-dipole field model with those in the dipole field. We demonstrate that on the day side the effects of taking into account a realistic magnetic field are negligible at distances less than six Earth radii. On the night side diffusion coefficients may significantly depend on the assumed field model. Pitch-angle scattering rates calculated in the non-dipole field can explain the often observed night-side chorus induced precipitation. The physical explanation for the changes of pitch-angle scattering rates with the field model is presented and discussed. **Citation:** Orlova, K. G., and Y. Y. Shprits (2010), Dependence of pitch-angle scattering rates and loss timescales on the magnetic field model, *Geophys. Res. Lett.*, *37*, L05105, doi:10.1029/2009GL041639.

1. Introduction

[2] The assessment of the importance of various acceleration and loss mechanisms of relativistic electrons is crucially important for predicting and understanding the dynamics of the radiation belts. It is commonly accepted that resonant wave-particle interactions play a major role in these processes [e.g., *Shprits et al.*, 2008; *Reeves et al.*, 2009]. Bounce-averaged energy, pitch-angle, and mixed diffusion coefficients, calculated using various models of spectral properties of waves and spatial distributions of plasma waves, are used in modern radiation belt codes as inputs [e.g., *Varotsou et al.*, 2008; *Subbotin and Shprits*, 2009]. The diffusion coefficients for radiation belt models are usually computed using the quasi-linear theory [*Kennel and Engelmann*, 1966] and are bounce-averaged in the dipole magnetic field following *Lyons et al.* [1972]. During magnetic storms, however, the configuration and the value of the magnetic field are significantly changed, which may potentially influence the scattering rates. The purpose of this work is to estimate the role of a realistic magnetic field model on bounce-averaged pitch-angle scattering rates. The parameters for waves and used assumptions are presented in Section 2. In Section 4, we demonstrate the results of bounce-averaging in the Tsyganenko 89c external field [e.g., *Tsyganenko*, 1989] for quiet conditions (Kp = 2) and storm-time conditions (Kp = 6) plus internal IGRF model (further Tsyganenko or T89c). The results are compared with the calculations for the dipole field, followed by a physical explanation of how the magnetic field model can change the bounce-averaged scattering rates.

2. Parameters Used

[3] Whistler mode chorus waves are usually observed during active conditions for MLT between approximately 22 and 15 [*Meredith et al.*, 2003]. In this initial study, we considered only parallel propagating chorus waves, which simplify the interpretation of the results because electrons can only be in the first-order cyclotron resonance with such waves. The observations show that the source of chorus waves is located at the equator, and therefore we consider the wave frequencies to be dependent on the equatorial gyrofrequency. We assumed a Gaussian spread of wave power spectral density and considered that for the night-side the spectral parameters are $\omega_m = 0.35\Omega_e^{eq}$, $\delta\omega = 0.15\Omega_e^{eq}$, $\omega_{lc} = 0.05\Omega_e^{eq}$ and $\omega_{uc} = 0.65\Omega_e^{eq}$ following *Horne et al.* [2005] and for the day-side are $\omega_m = 0.2\Omega_e^{eq}$, $\delta\omega = 0.1\Omega_e^{eq}$, $\omega_{lc} = 0.1\Omega_e^{eq}$ and $\omega_{uc} = 0.3\Omega_e^{eq}$ after *Shprits et al.* [2007], where ω_m is the frequency of maximum power, $\delta\omega$ is the bandwidth, ω_{lc} and ω_{uc} are the lower and upper cutoffs outside of which the distribution is equal to zero, and Ω_e^{eq} is the electron gyrofrequency at the magnetic equator. Following *Li et al.* [2007], we assumed that the waves are confined to magnetic latitudes $\lambda_{\max} = \pm 15°$ taken from the magnetic equator on the night side and $\lambda_{\max} = \pm 35°$ on the day side. While amplitudes on the night side and day side may be different, for this study we kept the wave amplitude constant (B_w = 100 pT) and independent of latitude for all numerical experiments to separate the effects of taking into account the realistic magnetic field from other effects associated with all other input parameters.

[4] In this study, we considered scattering of 1 MeV electrons for all calculations. We used the statistical trough plasma density model [*Sheeley et al.*, 2001] including the MLT dependence. We also assumed that plasma density is constant along the field line based on the statistical study of *Denton et al*. [2006], which showed that plasma density changes by only a small factor for latitude below approximately 30°.

[1]Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California, USA.
[2]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[3]Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California, USA.

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3. Calculation of Bounce-Averaged Pitch-Angle Scattering Rates

[5] For the general case of a non-dipole field, the bounce-averaged pitch-angle diffusion coefficient is given by *Lyons et al.* [1972]

$$\langle D_{\alpha\alpha}(\alpha_0)\rangle_{ba} = \frac{1}{\tau_B}\int_0^{\tau_B} D_{\alpha\alpha}(\alpha)\left(\frac{\partial\alpha_0}{\partial\alpha}\right)^2 dt, \qquad (1)$$

where α and α_0 are the local and equatorial pitch angles, respectively; τ_B is the electron bounce period. Subscript "ba" refers to bounce-averaged. The equation for local quasi-linear pitch-angle diffusion coefficient $D_{\alpha\alpha}$ for resonant wave-particle interaction with field-aligned whistler-mode chorus waves was derived by *Summers* [2005] and we reduced it by a factor of 2 due to *Albert* [2007].

[6] For the dipole field, bounce-averaged pitch-angle scattering rates can be calculated using the analytical expression of *Lyons et al.* [1972]. For the non-dipole field, if the field line lies in a plane perpendicular to the magnetic equator the equation (1) can be rewritten as

$$\langle D_{\alpha\alpha}(\alpha_0)\rangle_{ba} = \frac{\int_{\lambda_{m1}}^{\lambda_{m2}} \frac{D_{\alpha\alpha}(\alpha(\lambda))}{\cos\alpha(\lambda)}\left(\frac{\tan\alpha_0}{\tan\alpha(\lambda)}\right)^2\sqrt{\left(\frac{\partial r(\lambda)}{\partial\lambda}\right)^2 + r^2}\,d\lambda}{\int_{\lambda_{m1}}^{\lambda_{m2}} \sec\alpha(\lambda)\sqrt{\left(\frac{\partial r(\lambda)}{\partial\lambda}\right)^2 + r^2}\,d\lambda}, \qquad (2)$$

where λ_{m1} and λ_{m2} are the magnetic latitudes of mirror points.

4. Bounce-Averaged Pitch-Angle Diffusion Coefficients in the Tsyganenko Field Model

[7] To evaluate the effect of a more realistic field in comparison to a dipole field on scattering rates, we took a Tsyganenko field model for two cases of geomagnetic activity: Kp = 2 and Kp = 6. We performed calculations for the case when the axis of the magnetic dipole coincides with the Z-axis in GSM coordinates i.e. is perpendicular to the Earth-Sun line. The difference between the amplitude of the magnetic field along the 3D field line and the amplitude along the projection of the field line on the XZ plane is less than 1% for any given latitude. Therefore, the pitch-angle scattering rates for the Tsyganenko field model were computed in XZ plane only, using equation (2).

[8] To compare the results for different magnetic field models we computed and bounce-averaged pitch-angle scattering rates for filed lines with the same R_0, which is the distance from the Earth's center to intersection of the field line with the magnetic equator. For each considered MLT, R_0, and Kp we chose the UT for the internal IGRF field model so that in the realistic magnetic field (Tsyganenko+IGRF) the minimum **B** point of the field line lies very close to the dipole magnetic equator.

[9] Figures 1a–1c and 1d–1f show the bounce-averaged pitch-angle diffusion coefficients for the night side (MLT = 0) and the day side (MLT = 12), respectively, for three R_0 = 4, 6, and 7. The scattering rates are calculated for quiet conditions Kp = 2 (blue lines) and storm-time conditions Kp = 6 (red lines) in the Tsyganenko field model. The results are compared to the coefficients computed for the dipole field (black lines). For the night side at R_0 = 4 (Figure 1a) scattering rates at large equatorial pitch angles are only slightly higher for the dipole field model than for the Tsyganenko fields. For smaller equatorial pitch angles $\alpha_0 < 60°$, the diffusion coefficients in the Tsyganenko field for Kp = 2 and Kp = 6 increase significantly in comparison with the coefficients for the dipole field. At R_0 = 6 (Figure 1b) and R_0 = 7 (Figure 1c) electrons are scattered near the edge of the loss cone in the Tsyganenko field model during active conditions, while for the dipole and quiet T89c field models scattering near the edge of the loss cone is absent.

[10] For the day side, the bounce-averaged pitch-angle diffusion coefficients at R_0 = 4 (Figure 1d) are very similar for all considered field models. The loss to the atmosphere timescale can be estimated as the inverse of the diffusion coefficient at the edge of the loss cone [*Shprits et al.*, 2006b], and is approximately on the scale of a few days. At R_0 = 6 (Figure 1e), there are small differences in scattering rates between all three considered models. These differences are not large in comparison with the inaccuracies of determining the latitudinal distribution of waves and the electron plasma density. Thus the scattering rates for the day side can be calculated in the dipole field model for $R_0 \leq 6$. The most noticeable difference is at R_0 = 7 (Figure 1f), where the diffusion coefficients at small equatorial pitch angles are significantly different for all the field models considered, especially at the edge of the loss cone. This difference is due to the sharp cutoff in the latitudinal distribution of waves. If waves are present at higher latitudes this difference will become much smaller. The timescale at the edge of the loss cone for T89c field model at R_0 = 7 is about two days assuming 25% MLT averaging.

5. Physical Explanation of the Results

[11] To explain the results and understand the differences in scattering rates for the Tsyganenko and dipole field models, we calculated the contribution from local scattering at R_0 = 7 at different magnetic latitudes: 0°, 5°, 10°, 15°, 20°, 25°, 30°, and 35°, shown as different colored lines in Figure 2. To illustrate the contribution of local scattering, we assumed that waves are present at all latitudes. Color-coded lines show the local pitch-angle diffusion coefficients at different latitudes. As can be seen on Figure 2, for each given latitude, only electrons within a narrow range of pitch angles can be in resonance. For the dipole field on the night side (Figure 2a), the resonant interactions at small equatorial pitch angles can occur only at latitudes of 30° and 35°, while waves on the night side are confined to approximately 10°–15° of the geomagnetic equator [*Meredith et al.*, 2003]. For a given pitch angle local scattering rates move to lower latitudes in the Tsyganenko field as compared with the dipole field. Such displacement of resonances increases scattering at small pitch angles. In particular, particles near the edge of the loss cone can be scattered at 25° and 15° latitudes in T89c Kp = 2 (Figure 2b) and T89c Kp = 6 (Figure 2c) field models, respectively. Since, in our model, waves on the night side are confined to a narrow range of magnetic latitudes $\lambda_{max} = \pm 15°$, electrons are scattered at the edge of the loss cone for T89c (Kp = 6) field and scattering is absent in the dipole and T89c (Kp = 2) field models.

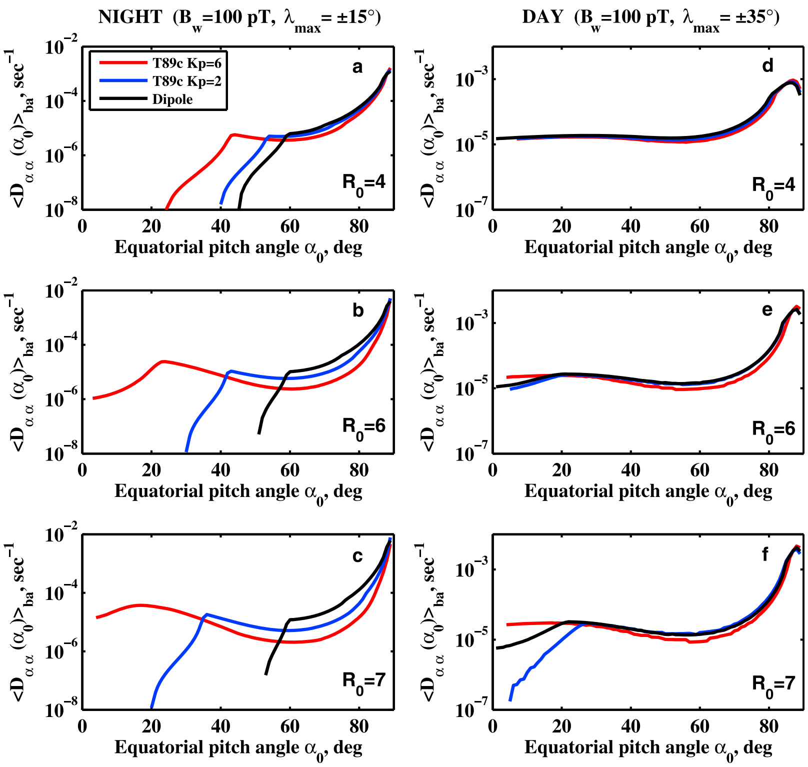

Figure 1. Bounce-averaged pitch-angle diffusion coefficients as a function of equatorial pitch angle, computed at R_0 = (a and d) 4, (b and e) 6, and (c and f) 7 in (left) T89c night-side model and (right) T89c day-side model. Black lines show the comparison with the dipole field.

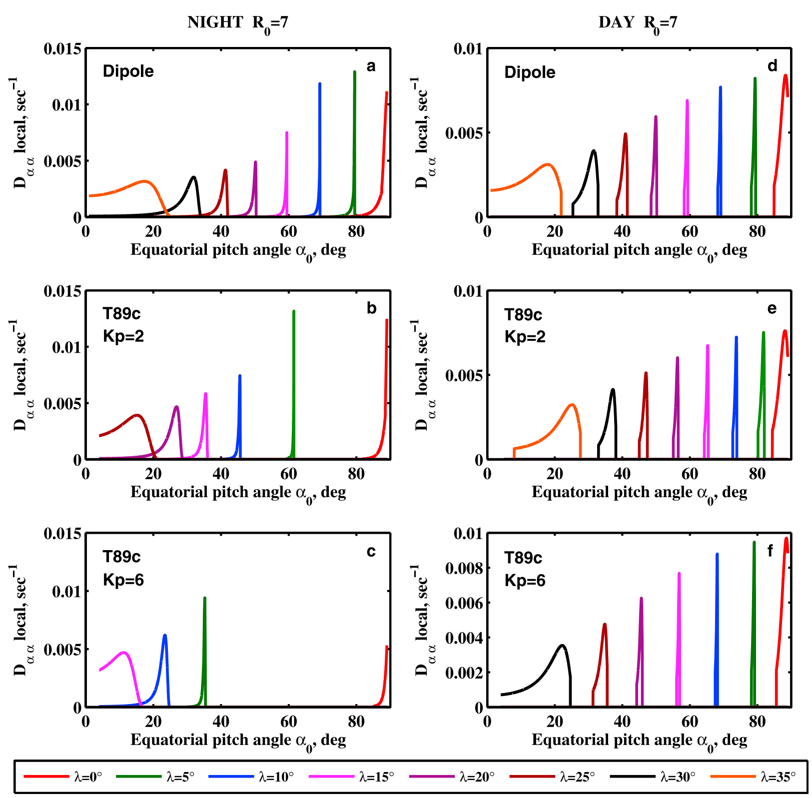

Figure 2. Variation of the local (not bounce-averaged) pitch-angle diffusion coefficients with latitude along the field line for (left) the night side and (right) the day side in (a and d) the dipole, (b and e) T89c (Kp = 2) and (c and f) T89c (Kp = 6) field models at R_0 = 7. Color-coded are local resonances at different latitudes.

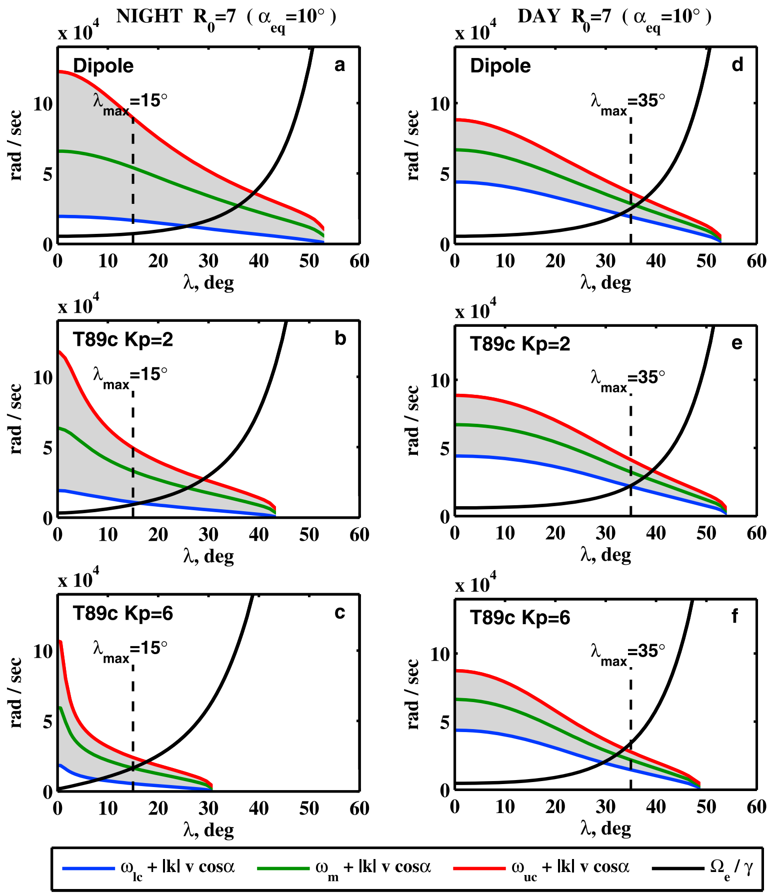

Figure 3. Comparison of the left and right parts of the resonance condition (3) for (left) the night side and (right) the day side in (a and d) the dipole, (b and e) T89c Kp = 2 and (c and f) T89c Kp = 6 field models at R_0 = 7 for α_0 = 10° at three frequencies describing Gaussian spectral distribution of waves (ω_{lc} - blue, ω_m - green, ω_{uc} - red). Intersection of black line (that show the right hand side of equation (3)) with gray region shows the latitudes at which resonance condition is satisfied. The dotted lines show the maximum latitude at which waves are present in our model.

[12] In our model, we assume that waves on the day side are present up to $\lambda_{\max} = \pm 35°$. Electrons at R_0 = 7 are scattered near the edge of the loss cone at ~35° and 30° in the dipole (Figure 2d) and T89c Kp = 6 (Figure 2f) field models, respectively. In the case of T89c Kp = 2 field (Figure 2e), however, scattering at 35° can barely affect particles near the edge of the loss cone.

[13] To understand why electrons have resonance with the waves for the same equatorial pitch angle at lower latitudes at the night side for the Tsyganenko field model than in the dipole field, it is instructive to look at the resonance condition

$$\omega + |\mathbf{k}|\upsilon \cos\alpha = \Omega_e/\gamma, \quad (3)$$

where γ is relativistic parameter, υ is the electron velocity, **k** is the wave vector, and Ω_e is assumed to be a positive. Figures 3a–3c show the dependence of the left and right sides of equation (3) on latitude for three wave frequencies: ω_{lc}, ω_m, ω_{uc} (blue, green, and red lines respectively) at R_0 = 7 for α_0 = 10° at the night side. Figures 3a–3c show the resonance condition curves for the dipole, T89c Kp = 2, and T89c Kp = 6 field models, respectively. The filled gray region corresponds to the area between the lower and upper cutoff lines of the left part in the resonance condition (3), plotted up to the electrons' mirror latitudes. The intersection of the black line (right part of (3)) with the gray region shows the latitudes at which the resonance condition is satisfied. The dotted lines correspond to the maximum latitude where the waves are considered to be present in our model. The Tsyganenko magnetic field for Kp = 2 and Kp = 6 on the night side increases stronger with latitude than it does the dipole field. Also, T89c field, during active conditions, grows stronger with latitude than it does during quiet conditions. This can be clearly seen by comparing the relativistic gyrofrequency dependences ($\Omega_e/\gamma \sim B$) for these fields in Figures 3a–3c. There is also a difference in characteristic spectral frequencies of waves (ω_{lc}, ω_m, ω_{uc} and $\delta\omega$) for different field models, which are scaled as an equatorial gyrofrequency. Stronger increases in magnetic field with latitude and the changes in equatorial values of magnetic field in T89c field model for Kp = 2 and Kp = 6 result in weaker growth of vector **k** with latitude due to the dispersion relation and stronger growth of the local pitch angle α along the field line due to the conservation of the first adiabatic invariant. All these differences for the dipole and Tsyganenko field models contribute to the left and right parts of the resonance condition (3). As a result, there are no resonant wave-particle interactions in the chosen range of night chorus waves for the dipole and T89c Kp = 2 fields, but in T89c Kp = 6 field model electrons have resonance with waves approximately at frequencies from ω_{lc} to ω_m.

[14] Figures 3d–3f show the right and left parts of resonance condition (3) on the day side for the dipole and Tsyganenko Kp = 2 and Kp = 6 field models respectively. While on the night side, the magnetic field in the dipole model grows weaker than in T89c Kp = 2 model, on the day side the dipole field (black line on Figure 3d) grows stronger than during quiet conditions in the Tsyganenko field model (black line on Figure 3e). Therefore, electrons have resonance with waves for a larger range of wave frequencies in the dipole field than during the quiet conditions in the Tsyganenko model. Consequently, the local scattering rates at the same latitudes at $R_0 = 7$ move to the higher equatorial pitch angles on the day side in T89c Kp = 2 field model in comparison with the dipole (Figures 2d and 2e). During active conditions, the Tsyganenko field (Figure 3f) on the day side grows stronger than the dipole field and T89c Kp = 2 field models, which makes the black line, showing the relativistic gyrofrequency, to become steeper. Electrons have resonance with chorus waves at all frequencies for T89c Kp = 6 field model (intersection of the gray region and black lines in Figure 3f lies at latitudes $\lambda < \lambda_{\max}$).

6. Summary and Discussion

[15] The differences between scattering rates computed in a dipole field and those computed in a non-dipole field may be significant. The change of bounce-averaged pitch-angle diffusion coefficients in the non-dipole field is due to the changes in the electron gyrofrequency, change of how wave vector and pitch angle vary with latitude and also change in the magnetic field at the equator which changes the spectral distribution of chorus waves. All these factors contribute to moving the resonance condition to lower latitudes. The calculations presented in this paper show that, during active conditions, the pitch-angle scattering by chorus waves in a realistic magnetic field can diffuse relativistic electrons to the loss cone not only on the day side, as was previously shown [e.g., *Thorne et al.*, 2005; *Shprits at et al.*, 2006a], but also on the night side. This explains the often observed night-side chorus induced precipitation [*O'Brien et al.*, 2003]. The differences in the scattering rates bounce-averaged in the dipole and Tsyganenko fields can be seen even at $R_0 = 4$ on the night side. At $R_0 = 7$, the differences can reach orders of magnitude. We also demonstrate that on the day side the scattering rates for field-aligned chorus waves can be computed in the approximation of the dipole field for $R_0 \leq 6$.

[16] While in this study we assumed a constant wave amplitude of 100 pT, for quiet conditions (Kp = 2), amplitudes can be an order of magnitude smaller than assumed. In such cases the bounce-averaged pitch-angle diffusion coefficients will be two orders of magnitude smaller. Also the wave spectrum in our model is scaled as equatorial gyrofrequency, which is dependent on the magnetic field model. To check the role of frequency distribution we calculated the pitch-angle scattering rates for three field models using the same wave spectrum proportional to the equatorial gyrofrequency of T89c for Kp = 2. The results are only slightly different from that of presented on Figure 1, which indicates that the change in spectrum does play some role, but it is not the only factor which determines scattering rates. The main conclusions of our work are robust without regards to assumed wave frequency spectrum.

[17] In this initial study, we calculated pitch-angle scattering rates for field-aligned chorus waves for relativistic MeV electrons. The computations of energy, pitch-angle and mixed diffusion coefficients for different energies and other parameters will be the subject of future research. In this paper, we also considered only first order wave-particle resonance and two MLT: 0 and 12. In the future, we will also consider diffusion by other types of waves, scattering by high order resonances, and latitudinal distribution of plasma density, and use more recent versions of Tsyganenko field models. Our sensitivity simulations show that similar results are obtained when more advanced magnetic field models such as T01 are used. In this study we only presented the results for T89c model for clarity of the presentation.

[18] This study shows that while there are still a number of unknown parameters that determine scattering rates, use of a realistic magnetic field model for computing and bounce-averaging of scattering rates in a non-dipole field will be crucially important for future radiation belt modeling. Computation of scattering rates in the non-dipole field will be particularly important for computation of scattering rates for Jupiter where magnetic field is highly scratched.

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K. G. Orlova and Y. Y. Shprits, Department of Atmospheric and Oceanic Sciences, University of California, 405 Hilgard Ave., 7127 Math Sciences Bldg., Los Angeles, CA 90095, USA. (ks13orl@gmail.com)