



Modeling Electron Scattering and Acceleration by Whistler Mode Chorus Waves in Jupiter's Magnetosphere: Effects of Magnetic Field Model, Total Electron Density, and Electron Injections

Qianli Ma* ^(1,2), Wen Li ⁽¹⁾, and Xiao-Jia Zhang ^(2,3)

(1) Center for Space Physics, Boston University, Boston, Massachusetts, USA

(2) Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California, USA

(3) Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, California, USA

Abstract

We evaluate the energetic electron scattering and acceleration due to whistler mode chorus waves using realistic magnetic field and density models in Jupiter's magnetosphere, and study the potential effects of electron injections. The bounce-averaged diffusion coefficients are calculated using the total electron density from the diffusive equilibrium model and the magnetic field strength from the VIP4 internal magnetic field and CAN current sheet model. The electron phase space density evolution due to chorus wave is simulated at $M = 10$. The typical chorus waves could cause fast pitch angle scattering loss of electrons from tens to several hundred keV, and gradual acceleration of relativistic electrons at several MeV. The latitudinally varying density and VIP4+CAN magnetic field model leads to faster pitch angle scattering and acceleration of electrons at energies above 100 keV than the constant density and dipolar magnetic field model. The simulation is compared to the electron dynamics during an electron injection event observed by Juno on 29 October, 2018. The electron flux is enhanced at low energies during the injection event, and the Fokker Planck simulation indicates an enhanced electron acceleration due to chorus waves subsequent to the injections. The modeling indicates an electron flux increase by nearly 1 order of magnitude within 1 day, suggesting the potentially important role of chorus waves in forming Jupiter's radiation belts after injections.

1 Introduction

Jupiter's intense magnetic fields trap the energetic electrons in the radiation belts which generate strong synchrotron radiation [1]. The source of high energy electron fluxes in Jupiter's radiation belts has drawn broad and current research interests [2]. The suprathermal and energetic electrons are adiabatically transported toward Jupiter through radial diffusion and injections [3, 4], and various plasma waves can cause the loss or enhancement of electron flux through non-adiabatic pitch angle scattering and acceleration [5, 6].

Whistler mode chorus has been suggested to be capable of accelerating the relativistic electrons at several MeV in Jupiter's radiation belts [7]. Intense chorus waves are observed over most magnetic local times (MLT), M shell

range of $8 < M < 15$, magnetic latitudes from equator to 50° , at frequencies below and above half of the electron gyrofrequency ($0.5f_{ce}$) [8]. Previous quasilinear modeling works have demonstrated the potential role of chorus waves in relativistic electron acceleration using a dipole magnetic field model [9]. Jupiter's magnetic field lines are stretched by the currents in the magnetodisc, which have been described by the washer-shaped current sheet model (CAN model) [10] superimposed on the VIP4 internal magnetic field model [11]. The recently developed JRM09 magnetic field model [12] provides more accurate description of the magnetic fields near the surface, and confirms the VIP4 model fields at large distances from Jupiter. The total electron density distribution is described by the diffusive equilibrium model [13] in Jupiter's magnetosphere, which affects the resonance energy of electrons. In addition, the electron injections [4] can provide a significant amount of source electrons to be accelerated to relativistic energies, therefore affect the efficiency of the electron flux enhancement in the radiation belts. In this paper, we evaluate the electron pitch angle scattering and acceleration due to whistler mode chorus waves using the combined VIP4 internal magnetic field and CAN current sheet model (VIP4+CAN), and the total electron density model developed by [13]. We also assess the potential impacts of electron injections in the acceleration process using the electron flux observation by Juno.

2 Electron Diffusion Coefficients in Jupiter's Magnetosphere

The electron resonance energy due to whistler mode chorus wave is affected by the ratio between the plasma frequency and the electron gyrofrequency (f_{pe}/f_{ce}). We calculate the total electron density along the magnetic field lines using VIP4+CAN magnetic field model following [13]. The cold and thermal electron distribution is assumed to be in an equilibrium state determined by the pressure gradient force, centrifugal force, and ambipolar electric force for electrons and ions of 8 species. The equatorial electron flux distribution at the radial distance away from the Io's orbit is obtained from the Voyager data [13]. Figure 1a shows the total electron density distribution at 290.8° System-III longitude where the Jovigraphic, magnetic and centrifugal equators align. Using the total magnetic field strength from VIP4+CAN

model, Figure 1b shows the f_{pe}/f_{ce} ratio distribution, which is below 10 at $M \leq 10$ and increases with increasing M shell. The f_{pe}/f_{ce} ratio is also lower at higher latitudes, suggesting a higher resonance energy due to waves at higher latitudes.

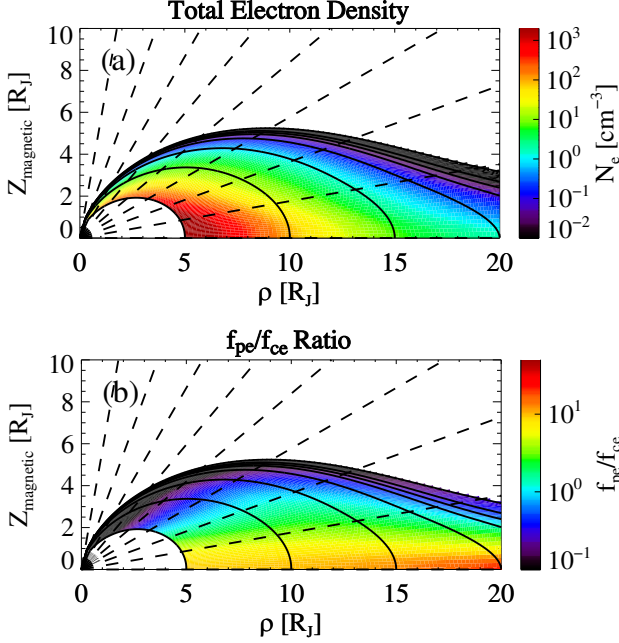


Figure 1. (a) Total electron density obtained following [13] using the VIP4+CAN magnetic field model; (b) the f_{pe}/f_{ce} ratio using the latitudinally-varying density and the VIP4+CAN magnetic field model. The solid curves are magnetic field lines at $M = 5, 10, 15, \dots, 40$, and the dashed lines are the latitude lines at $10^\circ, 20^\circ, 30^\circ, \dots, 80^\circ$.

The bounce-averaged diffusion coefficients ($\langle D_{\alpha_0 \alpha_0} \rangle$, $\langle D_{\alpha_0 p} \rangle$ and $\langle D_{pp} \rangle$) in an arbitrary magnetic field model can be calculated using the Full Diffusion Code [14]. Figure 2 shows the bounce-averaged pitch angle and momentum diffusion coefficients at $M = 10$, using the latitudinally-varying density model and VIP4+CAN model from Figure 1, in comparison with a dipolar magnetic field geometry and a constant density model. The f_{pe}/f_{ce} ratio is the same at the equator but different at higher latitudes. We consider the cyclotron resonances with harmonic numbers up to 10 and the Landau resonance. The chorus wave amplitude is assumed as 30 pT, which is a typical value from Galileo and Juno observations [8]. We assume that the chorus wave amplitude is constant from the equator to the high latitude of 50° based on the Juno statistical results [8]. The wave frequency spectrum is assumed as a Gaussian distribution, with the central frequency $f_m = 0.1f_{ce}$, wave frequency width $f_w = 0.1f_{ce}$, and frequency upper and lower cutoffs at $f_{uc} = 0.5f_{ce}$ and $f_{lc} = 0.01f_{ce}$. The wave normal angle (ψ) is assumed as a Gaussian distribution in $X = \tan \psi$ (proportional to $\exp(-(X - X_m)/X_w)^2$), with central wave normal $\psi_m = 0^\circ$, wave normal width $\psi_w = 30^\circ$, upper cutoff at $\psi_{uc} = 45^\circ$, and lower cutoff at $\psi_{lc} = 0^\circ$.

Figures 2b and 2e suggests the pitch angle scattering loss of tens of keV electrons and acceleration of MeV electrons through the first order cyclotron resonance, and the electron acceleration at several hundred eV over small pitch angles and above 10 keV over large pitch angles through Landau resonance. Higher order resonances are important for scattering and accelerating the relativistic electrons. Figure 2c shows a lower (higher) electron scattering rate at energies below (above) 100 keV when the latitudinally-varying density and VIP4+CAN magnetic field model are used compared to the constant density and dipolar field model. In addition, Figure 2f shows that the relativistic electron acceleration is overall faster using the latitudinally-varying density and VIP4+CAN magnetic field model. The difference in diffusion coefficients is up to a factor of 5 in pitch angle diffusion coefficients and about 1 order of magnitude in momentum diffusion coefficients.

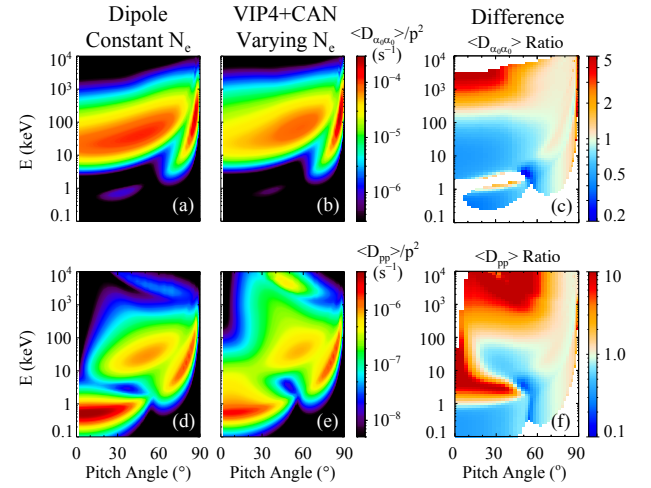


Figure 2. The bounce-averaged pitch angle diffusion coefficients as a function of equatorial pitch angle and energy using (a) the dipolar magnetic field and latitudinally-constant density model; (b) the VIP4+CAN magnetic field model and latitudinally-varying density model; (c) The difference calculated by $\langle D_{\alpha_0 \alpha_0} \rangle_{\text{VIP4+CAN, Varying } N_e} / \langle D_{\alpha_0 \alpha_0} \rangle_{\text{Dipole, Constant } N_e}$. (d)-(f) The same as (a)-(c) except for momentum diffusion coefficients. The adopted wave amplitude of chorus is 30 pT. The white area in Figure 2c is the region where the pitch angle diffusion coefficients are smaller than 10⁻⁷ s⁻¹, and the white area in Figure 2f is the region where the momentum diffusion coefficients are smaller than 10⁻⁹ s⁻¹.

3 Fokker Planck Simulation

We simulate the electron phase space density evolution due to whistler mode chorus waves using the diffusion coefficients computed in Figure 2 for the two density and magnetic field models. The modified Fokker Planck equation is numerically solved using the arbitrary magnetic field model geometry [15] with a time step of 1 s. The initial phase space density of electron is assumed as a Kappa distribution using the parameters in Jupiter's radiation belts [16].

At low energies (~ 20 keV, Figure 3a), the chorus waves cause the decay of electrons to gradually form the ‘top-hat’ shaped pitch angle distribution, and the electron loss is faster using the constant density and dipolar magnetic model. At 500 keV energy (Figure 3b), the chorus waves cause the decay of electrons to form the pancake-shaped distribution, and the loss is faster using the latitudinally-varying density and VIP4+CAN magnetic field model. The electron loss and acceleration are roughly balanced within 3 days at 3 MeV energy (Figure 3c). At 5.6 MeV energy (Figure 3d), the chorus waves cause electron acceleration to form the flat-top pitch angle distribution using the latitudinally-varying density and VIP4+CAN magnetic field model, while the acceleration is not evident using the constant density and dipolar magnetic field model.

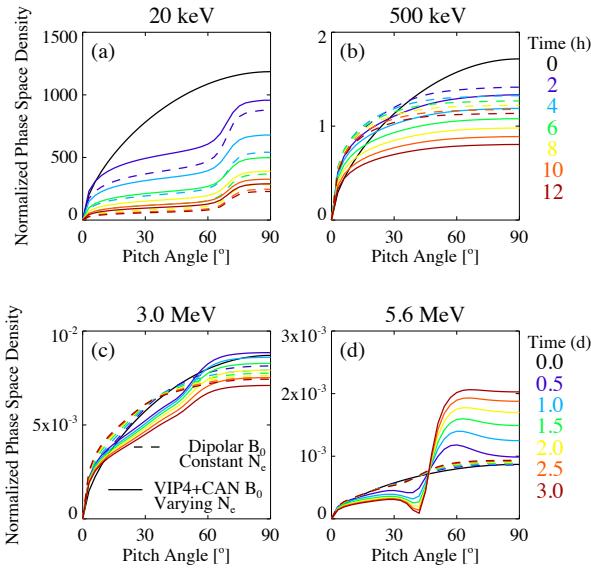


Figure 3. Evolution of electron phase space density as a function of equatorial pitch angle for different energies, using the dipolar magnetic field and latitudinally-constant density model (dashed line) and the VIP4+CAN field and latitudinally-varying density model (solid line). Due to the different time scales at lower and higher energies, the evolution is shown for 12 h at energies below 1 MeV, and for 3 days at energies above 1 MeV.

4 Effects of Electron Flux Injections

The energy spectrum of empirical electron flux distribution is relatively hard in Jupiter’s radiation belts compared to the spectrum at Earth or Saturn [16]. However, the electron injections in Jupiter’s magnetosphere could cause the significant electron flux enhancements at tens to several hundred keV, providing a significant amount of source electrons to be accelerated to relativistic energies. An electron injection event is observed by Juno on 29 October 2018 (Figure 4a). The electron flux enhancements are mostly observed at 30 – 300 keV energies, and the lower energy electrons are observed earlier than higher energy electrons.

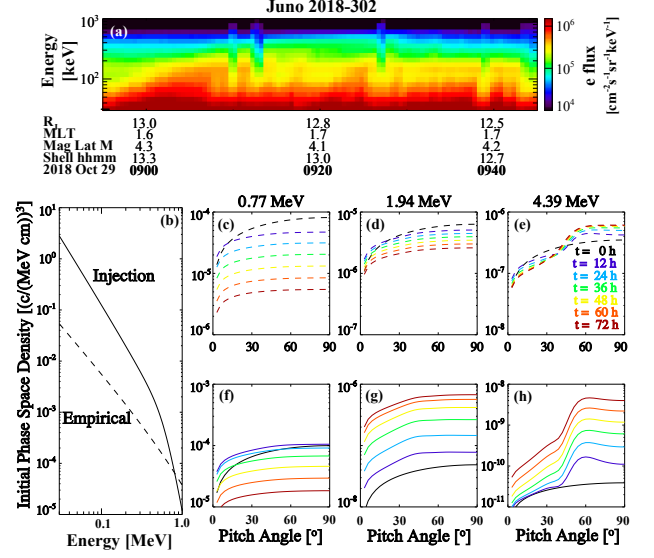


Figure 4. Comparison of electron phase space density evolutions using different initial phase space density profiles in Fokker Planck simulation. (a) Energy spectrogram of spin-averaged electron fluxes at the energies of 30 keV – 1 MeV observed by Juno, showing dispersive electron injection features. (b) The initial electron phase space density profiles from the empirical model (dashed) [16] and Juno observation during injections at $\sim 09:05$ UT on DOY 302 in 2018 (solid). (c–e) The evolution of electron phase space density as a function of equatorial pitch angle for the energies of 770 keV, 1.94 MeV and 4.39 MeV, using the initial condition from the empirical model. (e–g) The evolution of electron phase space density using the initial condition during injections. The chorus wave model and electron diffusion coefficients are the same as Figure 2.

Using the observed energy spectrum of electron phase space density during the injection event as the initial condition (Figure 4b), we simulate the electron phase space density evolution due to chorus waves and compare the results using the empirical spectrum as the initial condition. The other simulation inputs are the same. Figures 4c–4h show a robust electron acceleration at 1.94 MeV and 4.39 MeV during the electron injection event, while the electron distribution using the empirical initial distribution shows a decay at 1.94 MeV and a slow increase at 4.39 MeV. The electron flux increases by nearly 1 order of magnitude in 1 day at the energy of 4.39 MeV during the injections, suggesting the important contribution of chorus waves to the source of relativistic electrons and the formation of Jupiter’s radiation belts.

5 Conclusions

We evaluated the electron diffusion coefficients due to whistler mode chorus waves using the diffusive equilibrium total electron density model and VIP4+CAN magnetic field model in Jupiter’s magnetosphere. The lower electron density at higher latitudes and the stretched magnetic field line geometry cause the enhanced electron

scattering rates at energies above 100 keV, reduced electron scattering loss at lower energies, and overall enhanced electron acceleration. Our Fokker Planck simulation suggests the decay of electron fluxes at energies below several hundred keV, and flux enhancement at energies above several MeV. The pitch angle scattering loss and acceleration of relativistic electrons are both faster using the latitudinally-varying density and VIP4+CAN magnetic field model than the latitudinally-constant density and dipolar field model. Since the equatorial density and magnetic field are scaled to be the same between the two models, their different simulation results indicate that the latitudinally-varying density and the more realistic magnetic field geometry are important to quantify the electron flux variations.

We used the empirical distribution of electron fluxes as the initial condition of the radiation belt simulation. Juno observed the dispersive electron injections on 29 October 2018, providing enhanced electron fluxes at energies below 300 keV. Our Fokker Planck simulation indicates that the relativistic electron acceleration is much faster if the initial electron distribution during the injection is considered. The whistler mode chorus waves are potentially capable to cause flux enhancement by nearly 1 order of magnitude within the timescale of 1 day. The detailed study of electron acceleration due to an intense chorus wave event following electron injections observed by Juno is left as our future investigation.

6 Acknowledgements

This work was supported by subcontract 699046X to UCLA under prime contract ZZM06AA75C. QM would like to acknowledge the NASA grant 80NSSC20K0196. WL would like to acknowledge the NASA grant 80NSSC20K0557, NSF grant AGS-1847818, and the Alfred P. Sloan Research Fellowship FG-2018-10936.

7 References

1. D. Santos-Costa, and S. J. Bolton, “Discussing the processes constraining the Jovian synchrotron radio emission's features”, *Planetary and Space Science*, **56**, 3–4, 2008, pp. 326–345, doi:10.1016/j.pss.2007.09.008.
2. P. Kollmann, et al., “Electron acceleration to MeV energies at Jupiter and Saturn”, *Journal of Geophysical Research: Space Physics*, **123**, 2018, pp. 9110–9129, doi:10.1029/2018JA025665.
3. D. Santos-Costa, and S. A. Bourdarie, “Modeling the inner Jovian electron radiation belt including non-equatorial particles”, *Planetary and Space Science*, **49**, 3–4, 2001, pp. 303–312, doi:10.1016/S0032-0633(00)00151-3.
4. B. H. Mauk, et al., “Transient aurora on Jupiter from injections of magnetospheric electrons”, *Nature*, **415**, 2002, pp. 1003–1005, doi:10.1038/4151003a.

5. R. M. Thorne, “Microscopic plasma processes in the Jovian magnetosphere”, *Physics of the Jovian Magnetosphere*, 1983, pp. 454–488, Cambridge Univ. Press, doi:10.1017/CBO9780511564574.014.
6. R. B. Horne, et al. (2008), “Gyro-resonant electron acceleration at Jupiter”, *Nature Physics*, **4**, 2008, pp. 301–304, doi:10.1038/nphys897.
7. E. E. Woodfield, et al., “The origin of Jupiter's outer radiation belt”, *Journal of Geophysical Research: Space Physics*, **119**, 2014, pp. 3490–3502, doi:10.1002/2014JA019891.
8. W. Li, et al., “Global Distribution of Whistler Mode Waves in Jovian Inner Magnetosphere”, *Geophysical Research Letters*, **47**, e2020GL088198, 2020, doi:10.1029/2020GL088198.
9. B. Ni, et al., “Radiation belt electron scattering by whistler-mode chorus in the Jovian magnetosphere: Importance of ambient and wave parameters”, *Earth and Planetary Physics*, **2**, 2018, pp. 1–14, doi:10.26464/epp2018001.
10. J. E. P. Connerney, et al., “Modeling the Jovian current sheet and inner magnetosphere”, *Journal of Geophysical Research*, **86**, A10, 1981, pp. 8370–8384, doi:10.1029/JA086iA10p08370.
11. J. E. P. Connerney, et al., “New models of Jupiter's magnetic field constrained by the Io flux tube footprint”, *Journal of Geophysical Research*, **103**, A6, 1998, pp. 11929–11939, doi:10.1029/97JA03726.
12. J. E. P. Connerney, et al., “A new model of Jupiter's magnetic field from Juno's first nine orbits”, *Geophysical Research Letters*, **45**, 2018, pp. 2590–2596, doi:10.1002/2018GL077312.
13. L. P. Dougherty, et al., “Survey of Voyager plasma science ions at Jupiter: 2. Heavy ions”, *Journal of Geophysical Research: Space Physics*, **122**, 2017, pp. 8257–8276, doi:10.1002/2017JA024053.
14. Q. Ma, et al., “Energetic Electron Scattering due to Whistler Mode Chorus Waves Using Realistic Magnetic Field and Density Models in Jupiter's Magnetosphere”, *Journal of Geophysical Research: Space Physics*, **125**, e2020JA027968, 2020, doi:10.1029/2020JA027968.
15. Q. Ma, et al., “Evolution of the plasma sheet electron pitch angle distribution by whistler-mode chorus waves in non-dipole magnetic fields”, *Annales Geophysicae*, **30**, 2012, pp. 751–760, doi:10.5194/angeo-30-751-2012.
16. B. H. Mauk, and N. J. Fox, “Electron radiation belts of the solar system”, *Journal of Geophysical Research*, **115**, A12220, 2010, doi:10.1029/2010JA015660.