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Resonant scattering of plasma sheet electrons by whistler-mode chorus: Contribution to diffuse auroral precipitation

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[1] A quantitative analysis is presented of the resonant scattering of plasma sheet electrons (∼100 eV–20 keV) at L = 6 due to resonant interactions with whistler-mode chorus. Using wave parameters modeled from observations under geomagnetically disturbed conditions, it is demonstrated that the rate of pitch angle scattering can exceed the level of strong diffusion over a broad energy range (200 eV–10 keV) containing the bulk of the injected plasma sheet population. Scattering by chorus appears to be more effective than previous analyses of resonant interaction with electrostatic electron cyclotron waves. Chorus scattering is therefore a major contributor to the origin of the diffuse aurora and should also control the MLT distribution of injected plasma sheet electrons. The rates of scattering are sensitive to the distributions of wave power with respect to wave normal direction and wave frequency spectrum. Upper-band chorus ($\omega/\Omega_e > 0.5$) is the dominant scattering process for electrons below ≈5 keV while lower-band chorus ($0.1 \leq \omega/\Omega_e \leq 0.5$) is more effective at higher energies especially near the loss cone. **Citation:** Ni, B., R. M. Thorne, Y. Y. Shprits, and J. Bortnik (2008), Resonant scattering of plasma sheet electrons by whistler-mode chorus: Contribution to diffuse auroral precipitation, *Geophys. Res. Lett.*, *35*, L11106, doi:10.1029/2008GL034032.

1. Introduction

[2] Intense whistler-mode "chorus" emissions are excited in the region outside the plasmapause during the injection of anisotropic plasma sheet electrons [e.g., *Anderson and Maeda*, 1977; *Isenberg et al.*, 1982]. The waves typically occur in two distinct frequency bands, a lower band (0.1–0.5 Ω_e) and an upper band (0.5–0.8 Ω_e) [e.g., *Meredith et al.*, 2001] with respect to the equatorial electron gyrofrequency Ω_e. The observed power spectral intensity of chorus in either band depends on location and the level of geomagnetic activity. Strong upper-band chorus is observed occasionally, but only within 10° of the magnetic equator [*Bortnik et al.*, 2007]. Such high frequency chorus is able to resonate with the bulk of the plasma sheet electron population [*Inan et al.*, 1992] and has a spatial distribution (MLT, L) similar to that of the diffuse aurora [*Hardy et al.*, 1985]. Our present study is therefore mainly directed to quantifying the scattering by upper-band chorus.

[3] Although several mechanisms for diffuse auroral precipitation have previously been proposed, the dominant scattering process has not yet been clearly identified. Early studies concentrated on the role of electrostatic electron cyclotron harmonic (ECH) waves [e.g., *Lyons*, 1974]. Detailed quasi-linear scattering rates, based on observed wave spectral properties, demonstrated that ECH waves are capable of causing strong diffusion scattering of electrons (∼1 keV) near the loss cone [*Horne et al.*, 2003]. However, the main bulk of the plasma sheet is not able to resonate with such waves, since scattering is limited to small pitch angles ($\alpha_{eq} \leq 40°$). The possibility of scattering by whistler-mode chorus has also been considered [e.g., *Inan et al.*, 1992; *Villalón and Burke*, 1995]. These earlier studies demonstrated that first-order gyroresonance with upper-band chorus can efficiently scatter electrons with energy ∼1 keV or lower near the loss cone, but did not include a comprehensive evaluation of electron scattering rates based on observed wave characteristics. Diffusion codes have recently been developed, which are capable of evaluating the contribution of chorus emissions to the scattering of injected plasma sheet electrons. Here we utilize a diffusion code recently developed at UCLA based on the formulation of *Glauert and Horne* [2005], together with statistic properties of upper-band chorus observed on CRRES [*Bortnik et al.*, 2007], to evaluate quasi-linear bounce-averaged diffusion coefficients during geomagnetically disturbed conditions. We demonstrate that interactions with upper-band chorus lead to strong diffusion scattering of low-energy plasma sheet electrons (∼200 eV–2 keV), while, for higher-energy plasma sheet electrons (≥5 keV), scattering by lower-band chorus makes an important contribution to diffuse auroral precipitation.

2. Chorus Wave Model

[4] Following earlier studies of quasi-linear diffusion, the waves are assumed to have a Gaussian frequency distribution [*Lyons et al.*, 1971] given by

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

where $B^2(\omega)$ is the spectral intensity of the wave magnetic field, ω_m and $\delta\omega$ are the frequency of maximum wave power and bandwidth, respectively, ω_{lc} and ω_{uc} are lower and upper cutoff frequency to the wave spectrum outside which the wave power is zero, and A is a normalization factor [*Glauert and Horne*, 2005], which scales with the wave magnetic field B_W. A Gaussian wave normal distribution [*Lyons et al.*, 1971] is also assumed

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

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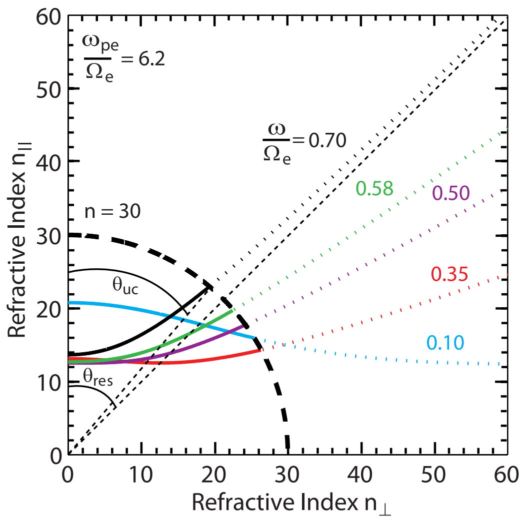

Figure 1. Refractive index surfaces for whistler-mode waves at $L = 6$ for normalized wave frequencies from 0.1 to 0.7. The dashed curve shows the circle of refractive index n = 30 above which we expect wave Landau damping to be severe. The two straight lines represent respectively the resonance cone angle θ_{res} for $\omega/|\Omega_e|$ = 0.7, and the upper limit of wave normal angle θ_{uc} used in the calculations.

where θ is the wave normal angle, θ_m the peak, θ_w the angular width, and θ_{lc} and θ_{uc} the lower and upper bounds to the wave normal distribution outside which the wave power is zero.

[5] Figure 1 shows the cold plasma whistler-mode refractive index surfaces at $L = 6$ for several normalized wave frequencies from 0.1 to 0.7. A dipole magnetic field model and the plasmatrough density model from *Sheeley et al.* [2001] are adopted to obtain the ratio of electron plasma frequency to electron gyrofrequency $\omega_{pe}/\Omega_e = 6.2$. At each wave frequency the refractive index surfaces asymptotically approach a wave resonance cone angle ($\theta \rightarrow \theta_{res}$), where $n \rightarrow \infty$. As the normalized wave frequency increases from 0.1 to 0.7, θ_{res} decreases from 84° to 45°. To simulate the anticipated Landau resonant damping in the vicinity of the resonance cone, we place an upper limit on the modeled angular distribution of waves at an angle θ_{uc} where $n = 30$. Based on the statistical properties of upper-band chorus [*Bortnik et al.*, 2007], we adopt an upper frequency $\omega_{uc} = 0.7\ \Omega_e$ for our wave distribution. From Figure 1 we obtain $\theta_{uc} = 40°$ for $\omega/\Omega_e = 0.7$, which is used as the maximum value of θ_{uc} in our subsequent calculations.

3. Electron Resonant Scattering

[6] Our calculations include contributions from the $N = -5$ to $N = 5$ cyclotron harmonic resonances and the Landau resonance $N = 0$. The following wave parameters have been adopted to model upper-band chorus at L = 6 during geomagnetically active conditions: $\omega_{lc}/(\Omega_e)_{eq} = 0.50$, $\omega_{uc}/(\Omega_e)_{eq} = 0.70$, $\omega_m/(\Omega_e)_{eq} = 0.58$, $\delta\omega/(\Omega_e)_{eq} = 0.08$; $\theta_{lc} = 0$, $\theta_{uc} = 40°$, $\theta_m = 0$, $\theta_w = 23°$; B_W = 50 pT [*Meredith et al.*, 2001]. We also assume that upper-band chorus waves are confined to latitudes $|\lambda_m| < 10°$, and that both the wave spectral intensity and electron number density remain constant along the field line, with $\omega_{pe}/\Omega_e = 6.2$ at the equator.

[7] Bounce-averaged quasi-linear diffusion coefficients for electrons interacting with modeled upper-band whistler-mode chorus at $L = 6$ are shown in Figure 2, for energies ranging from 100 eV to 20 keV. Near the loss cone (~1.8° at $L = 6$), 200 eV–2 keV electrons undergo rapid pitch angle diffusion, comparable to or above the strong diffusion limit D_{sd} [*Schulz*, 1974]. Under such rapid scattering, the electron distribution should become essentially isotropic, and injected plasma sheet electrons should be precipitated into the atmosphere on time scales comparable to an hour. We note that pitch angle diffusion near the loss cone of 500 eV–2 keV electrons due to upper-band chorus is also more rapid by at least one order of magnitude than previous

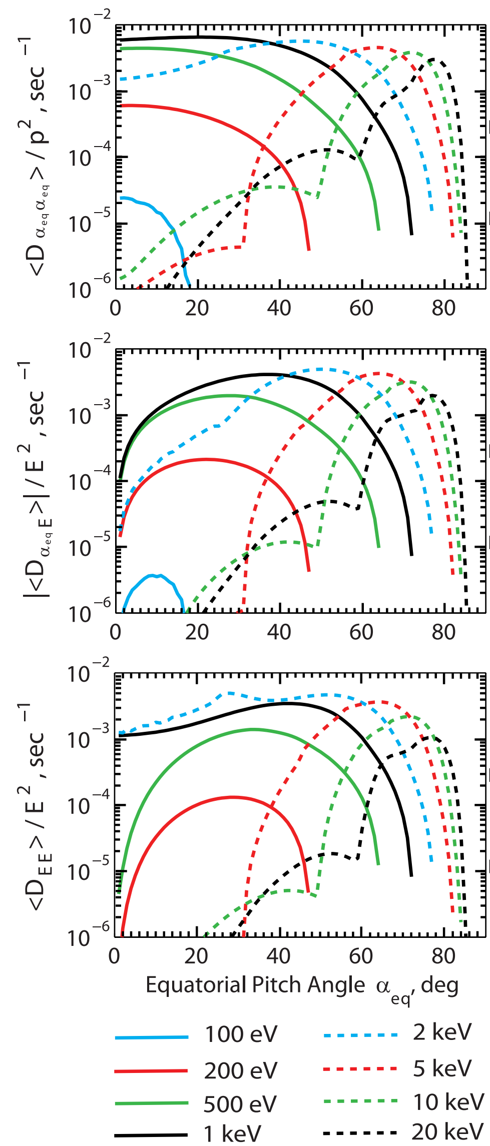

Figure 2. Bounce-averaged (top) pitch angle, (middle) mixed, and (bottom) energy diffusion coefficients for the indicated plasma sheet electron energies ranging from 100 eV to 20 keV due to storm-time upper-band whistler-mode chorus at $L = 6$.

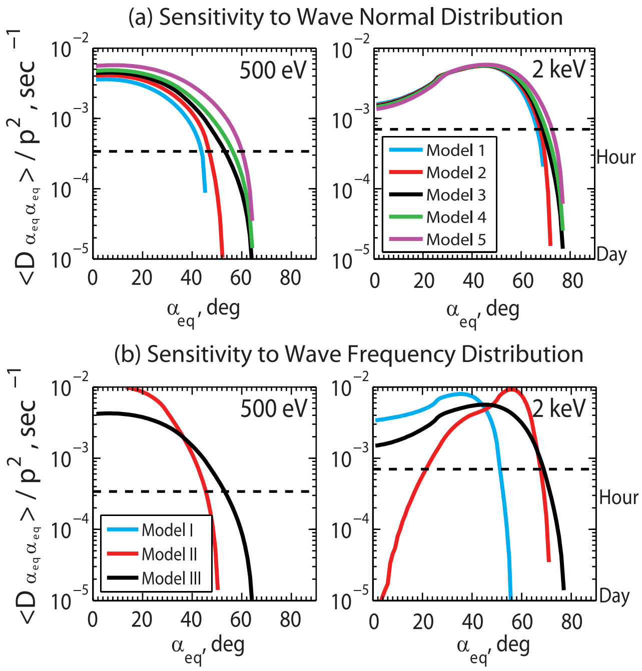

Figure 3. Sensitivity of upper-band chorus pitch angle diffusion coefficients to (a) wave normal distribution and (b) wave frequency distribution at L = 6, for electrons at 500 eV and 2 keV. The details of chosen distributions of wave normal and wave frequency are specified in Table 1. The horizontal dashed line in each plot represents the strong diffusion rate D_{sd}.

estimates of ECH wave scattering $\langle D_{\alpha_{eq}\alpha_{eq}}\rangle/p^2 \sim 2.0\text{–}0.4 \times 10^{-4}$ sec^{-1} for $E \sim 0.5\text{–}2$ keV [*Horne and Thorne*, 2000]. This suggests that resonant interactions with upper-band chorus should be an important, if not dominant, mechanism for rapid removal of injected plasma sheet electrons, leading to diffuse auroral precipitation. At higher electron energies the resonant diffusion coefficient due to upper-band chorus extends to higher equatorial pitch angle close to 90° while pitch angle diffusion rates for lower-energy electrons (<1 keV) typically peak at small equatorial pitch angle near the loss cone. Pitch angle scattering by first-order cyclotron resonance is the dominant contribution to the exhibited results, but Landau resonance also becomes important near the loss cone for higher-energy electrons (>1 keV), leading to rapid energy diffusion of 1–2 keV electrons.

4. Sensitivity of Results to Adopted Wave Model

[8] Previous studies of the spectral properties and wave normal distribution of upper-band chorus indicate considerable variability. The sensitivity of our model calculation to such variations are explored in Figure 3 for a range of model parameters specified in Table 1. Although the pitch angle diffusion coefficients are somewhat dependent on the adopted wave parameters, the results can be summarized as follows. At 500 eV the diffusion rate both increases and extends to higher equatorial pitch angles as the wave normal distribution changes from more field aligned to larger wave normals close to the resonance cone angle. For 2 keV, there is negligible variation with angular distribution. The adopted wave frequency distribution has a larger effect on the pitch angle diffusion rates. Inclusion of more wave power at higher frequencies enhances the pitch angle scattering rate of low-energy electrons, and restriction of wave power to lower frequencies can result in the absence of scattering at 500 eV. Note also that pitch angle diffusion extends to high equatorial pitch angles closer to 90° for larger upper cutoff frequencies, suggesting the importance of the upper bound of upper-band chorus spectrum in affecting the pitch angle distribution of these plasma sheet electrons.

[9] Since lower-band chorus and upper-band chorus are frequently observed to occur simultaneously within the nightside MLT sector, it is important to compare the role of scattering by each wave band on diffuse auroral precipitation. Our adopted parameters for the upper-band chorus are the same as those used for Figure 2. We use the following typical parameters for nightside lower-band chorus within the outer zone during geomagnetically disturbed periods [e.g., *Li et al.*, 2007]: $\omega_{lc}/(\Omega_e)_{eq} = 0.10$, $\omega_{uc}/(\Omega_e)_{eq} = 0.50$, $\omega_m/(\Omega_e)_{eq} = 0.35$, $\delta\omega/(\Omega_e)_{eq} = 0.10$; $\theta_{lc} = 0$, $\theta_{uc} = 45°$, $\theta_m = 0$, $\theta_w = 30°$; $B_W = 50$ pT, and $|\lambda_m| < 15°$. Figure 4 compares bounce-averaged pitch angle diffusion rates due to either wave band at L = 6 for the specified electron energies. Lower-band chorus is unable to resonate with low-energy electrons (<1 keV) whereas upper-band chorus can induce strong diffusion scattering below several keV. For electrons above 5 keV, both lower-band and upper-band chorus contribute to pitch angle scattering: lower-band chorus is most effective at lower equatorial pitch angles and upper-band chorus more important at high equatorial pitch angles closer to 90°.

[10] During geomagnetically disturbed conditions upper-band chorus wave amplitudes can vary over a large range from ∼10 pT to above 100 pT [e.g., *Meredith et al.*, 2001; *Santolik et al.*, 2003], in the present study we have chosen a slightly high but reasonably intermediate wave amplitude. Quasi-linear diffusion coefficients for different wave power can be easily obtained by scaling the results shown to the square of wave amplitude. While the characteristic energy for cyclotron resonance increases as the cold plasma density

Table 1. Wave Normal Distributions and Wave Frequency Distributions Adopted to Investigate the Sensitivity of Diffusion Coefficients to the Adopted Spectral Property and Angular Distribution of Upper-Band Whistler-Mode Chorus Wave Power

	Wave Normal Distributions[a]			
	θ_{lc}	θ_{uc}	θ_m	θ_w
Model 1	0	10°	0	10°
Model 2	0	30°	0	23°
Model 3	0	40°	0	23°
Model 4	0	40°	10°	23°
Model 5	0	40°	30°	23°
	Wave Frequency Distributions[b]			
	$\omega_{lc}/(\Omega_e)_{eq}$	$\omega_{uc}/(\Omega_e)_{eq}$	$\omega_m/(\Omega_e)_{eq}$	$\delta\omega/(\Omega_e)_{eq}$
Model I	0.50	0.58	0.54	0.04
Model II	0.58	0.66	0.62	0.04
Model III	0.50	0.70	0.58	0.08

[a]For fixed wave frequency distribution $\omega_{lc}/(\Omega_e)_{eq} = 0.50$, $\omega_{uc}/(\Omega_e)_{eq} = 0.70$, $\omega_m/(\Omega_e)_{eq} = 0.58$, $\delta\omega/(\Omega_e)_{eq} = 0.08$.
[b]For fixed wave normal distribution $\theta_{lc} = 0$, $\theta_{uc} = 40°$, $\theta_m = 0$, $\theta_w = 23°$.

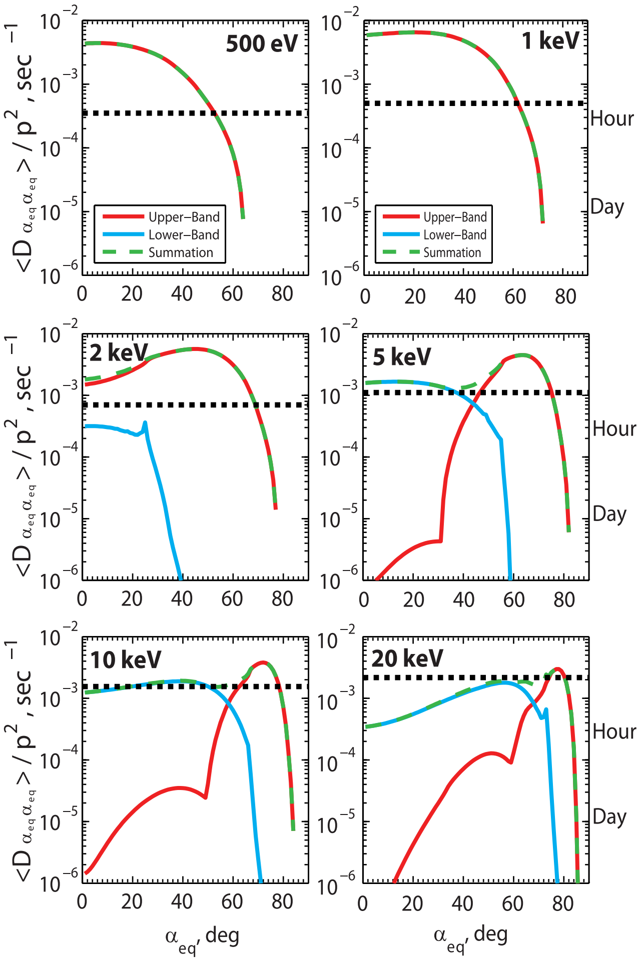

Figure 4. Comparison of bounce-averaged pitch angle diffusion rates due to typical nightside lower-band (solid curve in blue) and upper-band chorus (solid curve in red) at L = 6 for representative electron energies. The combined scattering of lower-band and upper-band chorus is shown as green dashed curve in each plot. The horizontal dashed line in each plot represents the strong diffusion rate D_{sd}.

decreases, upper-band chorus can still scatter ≥1 keV electrons on strong diffusion when the electron density at $L = 6$ decreases from 7.8 cm^{-3} used in this study to ~1 cm^{-3}, the lower density values according to the *Sheeley et al.* [2001] trough density model.

5. Discussion

[11] The importance of lower-band whistler-mode chorus to radiation belt electron dynamics has recently been recognized due to its dual role in both the precipitation and acceleration of relativistic radiation belt electrons [e.g., *Thorne et al.*, 2005; *Bortnik and Thorne*, 2007; *Li et al.*, 2007]. The analysis presented here demonstrates that upper-band chorus also plays a major role in the precipitation loss of injected plasma sheet electrons. For observed upper-band chorus wave amplitudes during disturbed conditions, quasi-linear pitch angle diffusion rates near the loss cone are substantially larger than previous estimates for ECH waves [*Horne and Thorne*, 2000], leading to strong diffusion precipitation over a broad range of energies between 200 eV to 10 keV. Scattering by a combination of lower-band and upper-band chorus also occurs over a wide range of equatorial pitch angles, leading to rapid removal of the bulk of plasma sheet electrons injected into the inner magnetosphere on time scales faster than the electron transport rates due to electric and magnetic gradient drifts. The range of electron energies and pitch angles, which are subject to rapid scattering, is sensitive to the angular distribution of oblique upper-band chorus emissions, which is currently poorly understood. If such waves propagate close to the whistler resonance cone, as suggested by *Hayakawa et al.* [1984] and *Muto et al.* [1987], resonant scattering could extent to even lower energies and higher pitch angles than shown in Figure 2. However, hot plasma modifications of the wave refractive index would have to be carefully included for waves near the resonance cone.

[12] Future improvements in our understandings of the role of chorus on plasma sheet scattering will require much better observational information on the angular distribution and the frequency spectrum of upper-band chorus, and its spatial distribution during different levels of geomagnetic activity. Under less disturbed conditions, the rates of scattering may fall below the strong diffusion level, causing substantial variation in auroral precipitation and allowing more effective electron transport to the dayside. Questions can also be raised on the validity of quasi-linear theory to treat scattering by the large amplitude discrete chorus emissions: a test particle approach should be pursued to test these results. Neither chorus nor ECH waves are able to resonate with plasma sheet electrons near $\alpha_{eq} = 90°$. However, observations indicate that the fluxes of injected electrons near 0000 MLT are an order of magnitude larger than at 1200 MLT [e.g., *Bortnik et al.*, 2007], indicating substantial loss during convective drift to the dayside. The absence of scattering over a range of pitch angles near 90° might be related to the formation of pancake distributions [*Meredith et al.*, 1999], but a complete 3-D modeling of transport and loss will be required to answer this question.

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References

Anderson, R. R., and K. Maeda (1977), VLF emissions associated with enhanced magnetospheric electrons, *J. Geophys. Res.*, *82*(1), 135–146.

Bortnik, J., and R. M. Thorne (2007), The dual role of ELF/VLF chorus waves in the acceleration and precipitation of radiation belt electrons, *J. Atmos. Sol. Terr. Phys.*, *69*, 378–386.

Bortnik, J., R. M. Thorne, and N. P. Meredith (2007), Modeling the propagation characteristics of chorus using CRRES suprathermal electron fluxes, *J. Geophys. Res.*, *112*, A08204, doi:10.1029/2006JA012237.

Glauert, S. A., and R. B. Horne (2005), Calculation of pitch angle and energy diffusion coefficients with the PADIE code, *J. Geophys. Res.*, *110*, A04206, doi:10.1029/2004JA010851.

Hardy, D. A., M. S. Gussenhoven, and E. Holeman (1985), A statistical model of auroral electron precipitation, *J. Geophys. Res.*, *90*(A5), 4229–4248.

Hayakawa, M., Y. Yamanaka, M. Parrot, and F. Lefeuvre (1984), The wave normals of magnetospheric chorus emissions observed on board GEOS 2, *J. Geophys. Res.*, *89*(A5), 2811–2821.

Horne, R. B., and R. M. Thorne (2000), Electron pitch angle diffusion by electrostatic electron cyclotron harmonic waves: The origin of pancake distributions, *J. Geophys. Res.*, *105*(A3), 5391–5402.

Horne, R. B., R. M. Thorne, N. P. Meredith, and R. R. Anderson (2003), Diffuse auroral electron scattering by electron cyclotron harmonic and whistler mode waves during an isolated substorm, *J. Geophys. Res.*, *108*(A7), 1290, doi:10.1029/2002JA009736.

Inan, U. S., Y. T. Chiu, and G. T. Davidson (1992), Whistler-mode waves and morningside aurorae, *Geophys. Res. Lett.*, *19*(7), 653–656.

Isenberg, P. A., H. C. Koons, and J. F. Fennel (1982), Simultaneous observations of energetic electrons and dawnside chorus in geosynchronous orbit, *J. Geophys. Res.*, *87*(A3), 1495–1503.

Li, W., Y. Y. Shprits, and R. M. Thorne (2007), Dynamic evolution of energetic outer zone electrons due to wave-particle interactions during storms, *J. Geophys. Res.*, *112*, A10220, doi:10.1029/2007JA012368.

Lyons, L. R. (1974), Electron diffusion driven by magnetospheric electrostatic waves, *J. Geophys. Res.*, *79*(4), 575–580.

Lyons, L. R., R. M. Thorne, and C. F. Kennel (1971), Electron pitch-angle diffusion driven by oblique whistler-mode turbulence, *J. Plasma Phys.*, *6*, 589–606.

Meredith, N. P., A. D. Johnstone, S. Szita, R. B. Horne, and R. R. Anderson (1999), Pancake electron distributions in the outer radiation belts, *J. Geophys. Res.*, *104*(A6), 12,431–12,444.

Meredith, N. P., R. B. Horne, and R. R. Anderson (2001), Substorm dependence of chorus amplitudes: Implications for the acceleration of electrons to relativistic energies, *J. Geophys. Res.*, *106*(A7), 13,165–13,178.

Muto, H., M. Hayakawa, M. Parrot, and F. Lefeuvre (1987), Direction finding of half-gyrofrequency VLF emissions in the off-equatorial region of the magnetosphere and their generation and propagation, *J. Geophys. Res.*, *92*(A7), 7538–7550.

Santolk, O., D. A. Gurnett, J. S. Pickett, M. Parrot, and N. Cornilleau-Wehrlin (2003), Spatio-temporal structure of storm-time chorus, *J. Geophys. Res.*, *108*(A7), 1278, doi:10.1029/2002JA009791.

Schulz, L. (1974), Particle lifetimes in strong diffusion, *Astrophys. Space Sci.*, *31*, 37–42.

Sheeley, B. W., M. B. Moldwin, H. K. Rassoul, and R. R. Anderson (2001), An empirical plasmasphere and trough density model: CRRES observations, *J. Geophys. Res.*, *106*(A11), 25,631–25,641.

Thorne, R. M., R. B. Horne, S. A. Glauert, N. P. Meredith, Y. Shprits, D. Summers, and R. R. Anderson (2005), The influence of wave-particle interactions on relativistic electron dynamics during storms, in *Inner Magnetosphere Interactions: New Perspectives From Imaging*, *Geophys. Monogr. Ser.*, vol. 159, edited by J. Burch, M. Schulz, and H. Spence, pp. 101–112, AGU, Washington, D. C.

Villalón, E., and W. J. Burke (1995), Pitch angle scattering of diffuse auroral electrons by whistler mode waves, *J. Geophys. Res.*, *100*(A10), 19,361–19,369.

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