

## Relativistic electron acceleration and precipitation during resonant interactions with whistler-mode chorus

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[1] Resonant interactions with whistler-mode chorus waves provide an important process for electron loss and acceleration during storm times. We demonstrate that wave propagation significantly affects the electron scattering rates. We show that stormtime chorus waves outside the plasmopause can scatter equatorial electrons  $\leq 60$  keV into the loss cone and accelerate trapped electrons up to  $\sim$  MeV energies at large pitch-angles. Using ray tracing to map the waves to higher latitudes, we show that the decrease in the ratio between the electron plasma and gyro frequencies, along with the normalized chorus frequency bandwidth, enable much higher energy electrons  $\sim 1$  MeV to be scattered into the loss cone. We suggest that off equatorial pitch-angle scattering by chorus waves is responsible for relativistic micro-burst precipitation seen on SAMPEX. Off-equatorial scattering at pitch-angles well away from the loss cone also contributes to the acceleration of higher energy  $\geq 3$  MeV electrons. **INDEX TERMS:** 7867 Space Plasma Physics: Wave/particle interactions; 2720 Magnetospheric Physics: Energetic particles, trapped; 2772 Magnetospheric Physics: Plasma waves and instabilities; 7807 Space Plasma Physics: Charged particle motion and acceleration. **Citation:** Horne, R. B., and R. M. Thorne, Relativistic electron acceleration and precipitation during resonant interactions with whistler-mode chorus, *Geophys. Res. Lett.*, 30(10), 1527, doi:10.1029/2003GL016973, 2003.

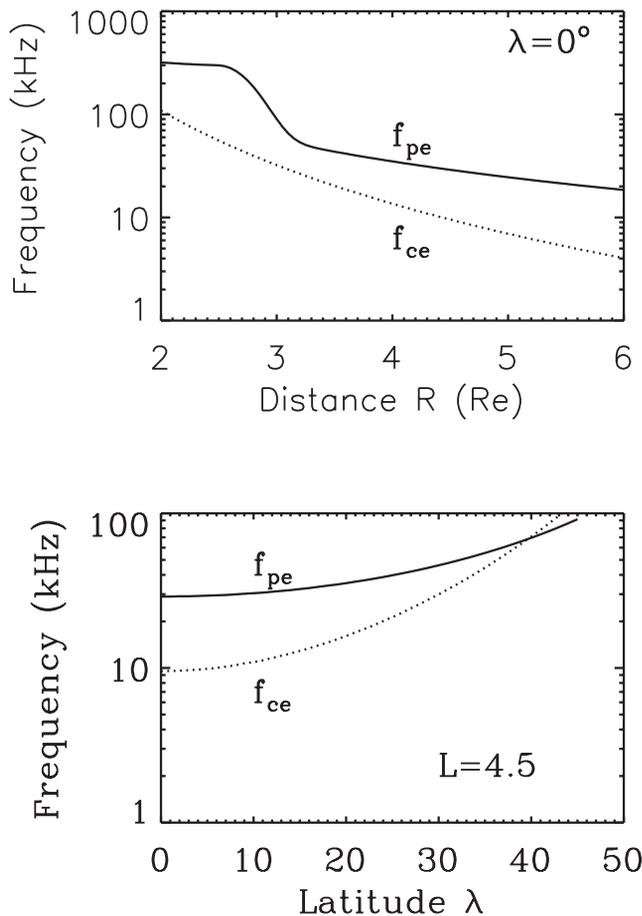
### 1. Introduction

[2] Pitch-angle scattering by electromagnetic whistler-mode waves is a dominant loss mechanism for radiation belt electrons [Lyons *et al.*, 1972; Abel and Thorne, 1998]. Under geomagnetically quiet conditions, the equilibrium radiation belt structure can be described by a balance between inward radial transport and losses to the atmosphere caused primarily by whistler-mode waves [Lyons and Thorne, 1973]. During geomagnetic storms and periods of prolonged substorm activity, the energetic outer-zone electron flux can vary by several orders of magnitude [Li *et al.*, 1997b; Meredith *et al.*, 2001, 2002a, 2000b]. Increases in flux are due to acceleration processes inside the Earth's magnetosphere [Li *et al.*, 1997a], but there is considerable debate over which is the most important mechanism [Li and Temerin, 2001; Friedel *et al.*, 2002; Horne, 2002]. In addition to causing electron scattering loss to the atmosphere [Lorentzen *et al.*, 2001], whistler-mode chorus waves can

contribute to the acceleration of energetic electrons [Horne and Thorne, 1998; Summers *et al.*, 1998; Summers and Ma, 2000; Summers *et al.*, 2002]. Recent calculations of momentum diffusion rates, in the low density regime outside the plasmasphere, indicate that the timescale for energy diffusion for  $\sim$  MeV electrons is approximately a day for typical stormtime chorus wave amplitudes [Horne *et al.*, 2003b]. This is comparable to the timescale for the observed increase in electron flux during the recovery phase of geomagnetic storms. However, these diffusion calculations ignore propagation effects. Here we investigate the propagation of whistler mode chorus and point out that if propagation is taken into account, whistler-mode chorus at latitudes above  $25^\circ$  should lead to both electron scattering loss and stochastic acceleration at relativistic energies. This high latitude scattering could be responsible for the observed micro-burst precipitation and the butterfly pitch-angle distributions of trapped relativistic electrons during acceleration events.

### 2. Ray Tracing Model

[3] Electron energy diffusion rates are extremely sensitive to the frequency bandwidth and angular distribution of wave energy. Information on how these properties change during propagation can be found from ray tracing. Here we use the HOTRAY ray tracing code [Horne, 1989] to follow the rays paths from the wave source region near the magnetic equator to higher latitudes. The density model is based on a diffusive equilibrium model inside the plasmopause and a radial profile that falls as  $(R_c/R)^a$  outside. Details of the model can be found elsewhere [Inan and Bell, 1977; Horne, 1995]. The density at the base of the ionosphere ( $R_b = 7470$  km) is set to  $N_b = 1.5 \times 10^{10}$  el m $^{-3}$  with a temperature  $T_{DE} = 5000$  K and percentage ion composition of H $^+$ , He $^+$  and O $^+$  of 0.9252%, 1.224%, and 97.85%, respectively. The model includes a lower ionosphere with  $R_0 = 6460$  km and a scale height  $H = 140$  km. Other parameters in the model are  $R_c = 6400$  km,  $a = 3.0$ , and  $H_s = 2500$  km. During magnetic storms, the plasmopause location moves to lower  $L$  and often exhibits a sharper drop with  $L$ . To represent this, the plasmopause is set at  $L_p = 2.5$  with a half width of  $W = 0.3 R_e$ . Figure 1 (top) shows a radial profile of the plasma frequency  $f_{pe} = \omega_{pe}/2\pi$  in the equatorial plane. The electron gyrofrequency  $f_{ce} = \Omega_e/2\pi$  calculated for a dipole magnetic field is also shown for comparison. Note that the ratio  $f_{pe}/f_{ce}$  is a minimum just outside the plasmopause, and increases with increasing  $R$ . Electron acceleration by whistler-mode waves is more



**Figure 1.** Electron plasma and gyro-frequencies in the equatorial plane (top), and as a function of latitude for  $L = 4.5$  (bottom).

efficient for small ratios of  $f_{pe}/f_{ce}$  [Summers *et al.*, 1998; Horne *et al.*, 2003b].

[4] Whistler-mode waves can be guided along the magnetic field very effectively by one-sided density gradients [Gorney and Thorne, 1980] and plasma ducts [Inan and Bell, 1977]. Even in the absence of density gradients, whistler-mode ray paths closely follow the magnetic field. Therefore, in the bottom panel of Figure 1 we show the variation of  $f_{pe}$  and  $f_{ce}$  with latitude at  $L = 4.5$ . The ratio  $f_{pe}/f_{ce}$  falls with increasing latitude, due to the strong magnetic field gradient. This immediately raises the question whether pitch-angle and energy diffusion should be more efficient at higher latitudes.

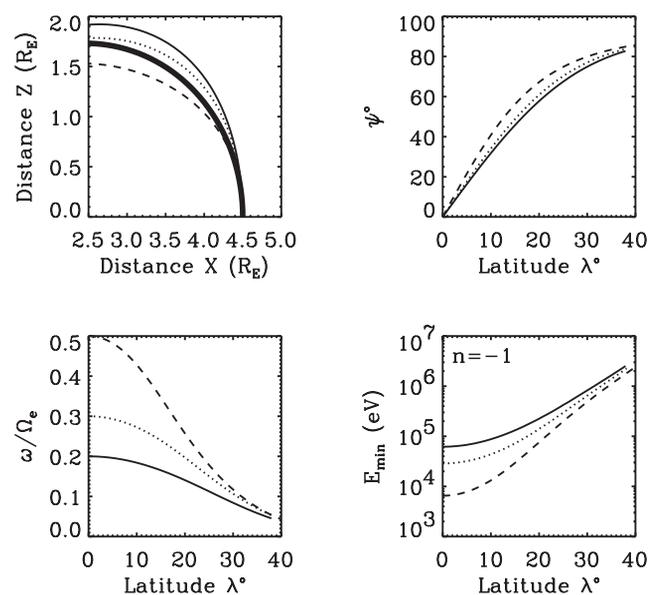
### 3. Resonant Electron Scattering

[5] We assume a wave source region near  $L = 4.5$  on the equator, which corresponds to the region where intense chorus emissions are observed during storms [Meredith *et al.*, 2002a]. Wave growth rates maximize for propagation along the ambient magnetic field [Kennel and Thorne, 1967]. We follow the ray paths of a typical band of chorus, with normalized frequencies of  $\omega/\Omega_e = 0.2, 0.3,$  and  $0.5$  from the equatorial source region and exhibit the latitudinal variation in wave properties in Figure 2. Although the rays approximately follow the same  $L$  shell ( $L = 4.5$ , illustrated by the bold solid line), lower frequency rays  $\omega/\Omega_e < 0.3$  tend

to migrate outside  $L = 4.5$  while the higher frequencies migrate to lower  $L$ . This difference in the ray paths, together with the increase in gyrofrequency, ensure that the normalized frequency of chorus falls below  $0.15 \Omega_e$  at high latitude  $\lambda \geq 25^\circ$ . Refraction by the magnetic field and plasma density gradients also cause the waves to become highly oblique  $\psi \geq 60^\circ$  at latitudes  $\geq 25^\circ$ .

[6] Also shown in Figure 2 is the minimum relativistic electron energy  $E_{min}$  along each ray path for first order cyclotron resonance with the R-mode component of the wave [e.g., Horne and Thorne, 1998]. As the waves propagate to higher latitudes, the increasing magnetic field, along with the decrease in  $f_{pe}$  and  $f_{ce}$ , enable first order cyclotron resonance with  $\sim$  MeV electrons. As the waves become more oblique, higher order resonances will also become significant, allowing scattering of even higher energy electrons.

[7] To illustrate how propagation effects change resonant diffusion, we have calculated the resonant diffusion surfaces near the equator and at  $\lambda = 25^\circ$ . We have used the formulation of Summers *et al.* [1998] which describes the diffusion of electrons caused by field-aligned whistler-mode waves spread over a finite frequency band. Figure 3 shows the results for an assumed band of whistler-mode chorus with frequencies  $0.2 \leq \omega/\Omega_e \leq 0.5$  and  $\omega_{pe}/\Omega_e = 3.0$ , corresponding to a region just outside the plasmapause. The solid black curves show the resonant ellipses calculated for the  $n = -1$  resonance at  $\omega/\Omega_e = 0.2$  and  $0.5$ . These two ellipses demarcate the boundaries in velocity space for resonant scattering by the assumed band of chorus. Also shown are the resonant diffusion curves (bold), constant energy (dotted), and the loss cone at small pitch angles (solid line). During resonant interactions, the electrons diffuse along the resonant diffusion curves [Summers *et al.*, 1998] toward regions of smaller phase space density.

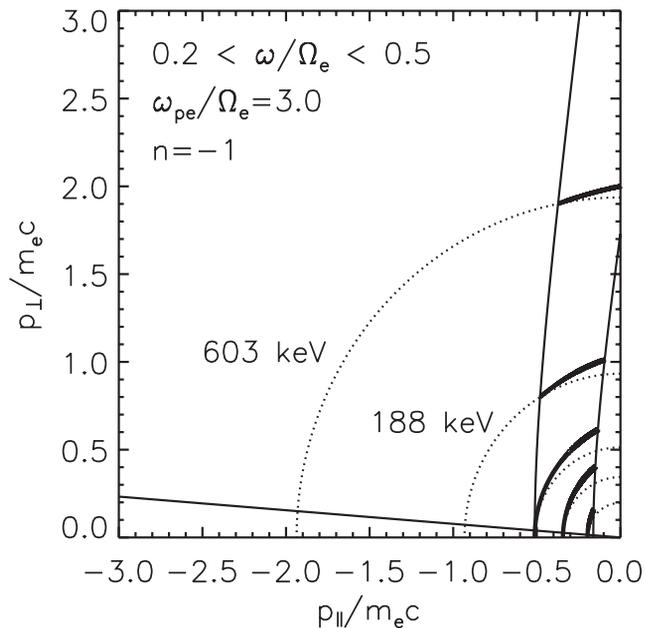


**Figure 2.** Ray paths of chorus waves (top, left) launched from the magnetic equator at  $L = 4.5$ . The field line ( $L = 4.5$ ) is shown by the bold line. Also shown are the variation in wave normal angle  $\psi$ , normalised wave frequency  $\omega/\Omega_e$ , and minimum resonant energy  $E_{min}$  for the dominant  $n = -1$  cyclotron resonance along the ray paths.

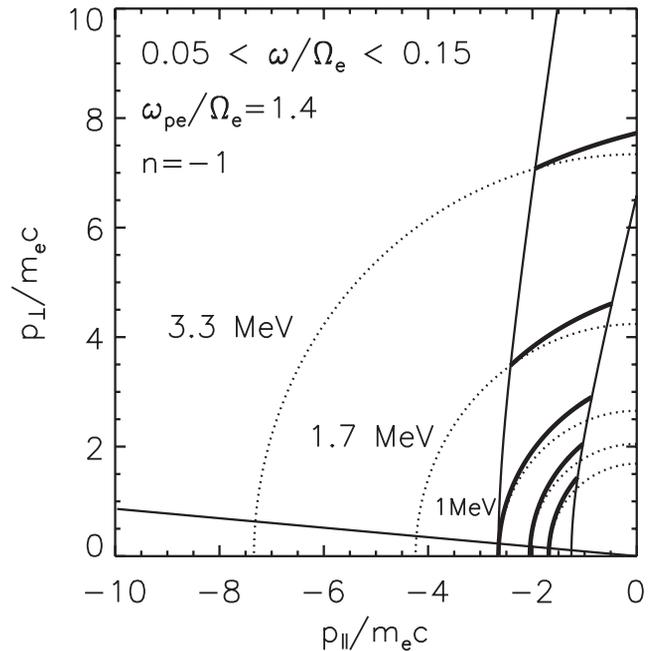
The direction of electron diffusion depends on the distribution function  $f(v)$ . For an isotropic, monotonically decreasing distribution, the contours of  $f(v)$  coincide with the dotted constant energy curves and there will be a net diffusion flux toward larger pitch-angles. The resonant electrons therefore gain energy and the waves will be damped. The energy gain is most effective for electrons above a few hundred keV and pitch-angles  $\alpha \geq 45^\circ$ . Alternatively, since the phase space density is generally depleted near the loss cone, resonant electrons will be preferentially scattered into the loss with loss of energy and associated wave growth.

[8] Near the loss cone, first order cyclotron is restricted to electrons with energies between  $\sim 10$ – $60$  keV. Higher energy electrons can also be scattered by equatorial chorus, but only at larger pitch-angles well away from the loss cone. Based on equatorial interactions alone, such high energy electrons would remain trapped in the magnetosphere. The net effect of the resonant interactions with equatorial chorus is that lower energy electrons ( $\leq 60$  keV), which have a high flux, provide the free energy for wave gain, while higher energy trapped electrons, where the flux is much lower, can be accelerated.

[9] Observations indicate that chorus emissions are able to propagate to high latitude without substantial damping [Meredith *et al.*, 2001]. Consequently, based on our ray tracing results we also consider electron resonant scattering near  $\lambda \approx 25^\circ$  (Figure 4). We adopt a normalized frequency band  $0.05 \leq \omega/\Omega_e \leq 0.15$  and  $\omega_{pe}/\Omega_e = 1.4$ . Although the waves at higher latitude are expected to be oblique, our formulation for the resonant diffusion surfaces is based on the analysis of Summers *et al.* [1998], which was restricted to parallel propagation. Even for oblique waves the  $n = -1$



**Figure 3.** Cyclotron resonant ellipses (solid) and resonant diffusion surfaces (bold) for a band of whistler-mode waves at the equator at  $L = 4.5$ . The frequency band is  $0.2 \leq \omega/\Omega_e \leq 0.5$ , and  $\omega_{pe}/\Omega_e = 3.0$ . Also shown are constant energy surfaces (dotted) at 10, 29, 63, 188, and 603 keV. The loss-cone for  $L = 4.5$  is shown as a straight line.



**Figure 4.** Cyclotron resonant ellipses (solid) and resonant diffusion surfaces (bold) at a latitude of  $\lambda = 25^\circ$  for  $L = 4.5$ . The frequency band is  $0.15 \leq \omega/\Omega_e \leq 0.05$ , and  $\omega_{pe}/\Omega_e = 1.4$ . Also shown are constant energy surfaces (dotted) at 497, 655, 938, 1715, and 3274 keV. The loss-cone for  $L = 4.5$  is shown as a straight line.

resonance will still dominate but there will also be important contributions from the higher order resonances. The off-equatorial scattering should therefore occur over an even broader range of pitch-angles and energies than those indicated in Figure 4, but this would only enhance our main result. It is immediately apparent that resonant diffusion at higher latitudes occurs for much higher resonant energies than at the equator. For the adopted wave parameters, electrons up to 1 MeV can be scattered into the loss cone by first-order cyclotron resonant interactions compared to  $E \leq 60$  keV at the equator. Higher harmonic scattering (not considered here) will allow even higher energy electron precipitation. Scattering of trapped electrons well away from the loss cone will occur at much higher energies ( $\geq 3$  MeV), and will contribute to further electron acceleration.

#### 4. Discussion

[10] During magnetic storms, short duration micro-bursts of precipitating relativistic electrons have been observed on SAMPEX in association with enhanced whistler-mode chorus [Lorentzen *et al.*, 2001]. Our calculations suggest that equatorial scattering is unlikely to be responsible, since the dominant first-order cyclotron resonant energies near the loss cone are typically of the order of a few tens of keV. Higher order cyclotron resonances and very low values of  $\omega_{pe}/\Omega_e$  are required for equatorial  $\sim$  MeV electron scattering near the loss cone, but the efficiency of such scattering remains low [Horne *et al.*, 2003b]. However, wave propagation to higher latitudes enables resonant scattering near the loss cone at much higher (relativistic) energies, consistent with typical energies required to account for the

SAMPEX micro-bursts. This suggests that off-equatorial pitch-angle scattering is more likely to be responsible for the relativistic precipitation. The fact that the duration of micro-burst precipitation is much less than 1s is also consistent with the short duration rising frequency elements often observed in chorus [Tsurutani and Smith, 1974].

[11] Our wave propagation study indicates that the wide bandwidth of waves excited at the equator maps to a narrow bandwidth at higher latitudes with much lower normalized frequencies. The ratio of  $\omega_{pe}/\Omega_e$  also decreases at high latitude (Figure 1, bottom) leading to much higher resonant electron energies ( $\sim$  MeV) over a considerably wider range of pitch-angles ( $30^\circ \leq \alpha \leq 90^\circ$ ) than at the equator ( $85^\circ \leq \alpha \leq 90^\circ$ ). For an isotropic pitch-angle distribution, the resonant scattering at high latitude will result in substantial relativistic electron acceleration. Thus, the resulting pitch-angle distributions at high energies should become much broader than the equatorial calculations suggest. Broad flat top pitch-angle distributions have been observed during the recovery phase of a magnetic storm during relativistic electron acceleration events, together with distributions peaked near  $\alpha \approx 45^\circ$  known as butterfly distributions [Horne et al., 2003a; Selesnick and Blake, 2002]. For  $L \geq 6$ , butterfly distributions exhibit a local time dependence that is consistent with drift shell splitting [Selesnick and Blake, 2002]. However, near  $L = 4$  there is no clear local time dependence. Since the magnetic field is more dipolar, and since the timescale for inward radial transport to  $L \approx 4$  becomes very long, flat top distributions could also be due to diffusion by whistler-mode chorus, and a substantial part of this diffusion could be occurring at higher latitudes. Furthermore, if scattering at higher latitudes is sufficiently strong, and localized, then the particle distribution function may even become peaked at intermediate pitch-angles  $\sim 45^\circ$ . Examination of the particle distribution functions as a function of latitude would be able to confirm the importance of wave diffusion.

[12] The final shape of the electron distributions will depend on an integration of the scattering rates at all latitudes along the bounce path of the particles. Existing bounce-average scattering codes [e.g., Lyons, 1974; Albert, 1999] are not able to treat resonant interactions between electrons and chorus emission in the low density limit, although local diffusion rates have recently been evaluated [Horne et al., 2003b]. In future, we intend to incorporate wave propagation effects, such as the change in distribution of wave energy with wave normal angle with increasing latitude, into a realistic bounce-averaged description of electron scattering, in order to model the local evolution of the relativistic electrons due to VLF wave scattering during storms.

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## References

- Abel, R. W., and R. M. Thorne, Electron scattering loss in Earth's inner magnetosphere: 1. Dominant physical processes, *J. Geophys. Res.*, **103**, 2385, 1998.
- Albert, J. M., Analysis of quasi-linear diffusion coefficients, *J. Geophys. Res.*, **104**, 2429, 1999.
- Friedel, R. H. W., G. D. Reeves, and T. Obara, Relativistic electron dynamics in the inner magnetosphere—A review, *J. Atmos. Sol. Terr. Phys.*, **64**, 265, 2002.
- Gorney, D. J., and R. M. Thorne, A comparative ray-trace study of whistler ducting in the Earth's plasmasphere, *Geophys. Res. Lett.*, **7**, 133, 1980.
- Horne, R. B., Path-integrated growth of electrostatic waves: The generation of terrestrial myriametric radiation, *J. Geophys. Res.*, **94**, 8895, 1989.
- Horne, R. B., Propagation to the ground at high latitudes of auroral radio noise below the electron gyrofrequency, *J. Geophys. Res.*, **100**, 14,637, 1995.
- Horne, R. B., The contribution of wave particle interactions to electron loss and acceleration in the Earth's radiation belts during geomagnetic storms, in *Review of Radio Science 1999–2002*, edited by W. R. Stone, pp. 801–828, chap. 33, John Wiley, New York, 2002.
- Horne, R. B., and R. M. Thorne, Potential waves for relativistic electron scattering and stochastic acceleration during magnetic storms, *Geophys. Res. Lett.*, **25**, 3011, 1998.
- Horne, R. B., N. P. Meredith, R. M. Thorne, D. Heynderickx, R. H. A. Iles, and R. R. Anderson, Evolution of energetic electron pitch angle distributions during storm time electron acceleration to megaelectronvolt energies, *J. Geophys. Res.*, **108**(A1), 1016, doi:10.1029/2001JA009165, 2003a.
- Horne, R. B., S. A. Glauert, and R. M. Thorne, Resonant diffusion of radiation belt electrons by whistler-mode chorus, *Geophys. Res. Lett.*, **30**, doi:10.1029/2003GL016963, in press, 2003b.
- Inan, U. S., and T. F. Bell, The plasmapause as a VLF wave guide, *J. Geophys. Res.*, **82**, 2819, 1977.
- Kennel, C. F., and R. M. Thorne, Unstable growth of unducted whistlers propagating at an angle to the geomagnetic field, *J. Geophys. Res.*, **72**, 871, 1967.
- Li, X., and M. A. Temerin, The electron radiation belt, *Space Sci. Rev.*, **95**, 569, 2001.
- Li, X., D. N. Baker, M. Temerin, D. Larson, R. P. Lin, G. D. Reeves, M. Looper, S. G. Kanekal, and R. A. Mewaldt, Are energetic electrons in the solar wind the source of the outer radiation belt?, *Geophys. Res. Lett.*, **24**, 923, 1997a.
- Li, X., D. N. Baker, M. Temerin, T. E. Cayton, E. G. D. Reeves, R. A. Christensen, J. B. Blake, M. D. Looper, R. Nakamura, and S. G. Kanekal, Multisatellite observations of the outer zone electron variation during the November 3–4, 1993, magnetic storm, *J. Geophys. Res.*, **102**, 14,123, 1997b.
- Lorentzen, K. R., J. B. Blake, U. S. Inan, and J. Bortnik, Observations of relativistic electron microbursts in association with VLF chorus, *J. Geophys. Res.*, **106**, 6017, 2001.
- Lyons, L. R., Pitch angle and energy diffusion coefficients from resonant interactions with ion-cyclotron and whistler waves, *J. Plasma Phys.*, **12**, 417, 1974.
- Lyons, L. R., and R. M. Thorne, Equilibrium structure of radiation belt electrons, *J. Geophys. Res.*, **78**, 2142, 1973.
- Lyons, L. R., R. M. Thorne, and C. F. Kennel, Pitch-angle diffusion of radiation belt electrons within the plasmasphere, *J. Geophys. Res.*, **77**, 3455, 1972.
- Meredith, N. P., R. B. Horne, and R. R. Anderson, Substorm dependence of chorus amplitudes: Implications for the acceleration of electrons to relativistic energies, *J. Geophys. Res.*, **106**, 13,165, 2001.
- Meredith, N. P., R. B. Horne, R. H. A. Iles, R. M. Thorne, D. Heynderickx, and R. R. Anderson, Outer zone relativistic electron acceleration associated with substorm-enhanced whistler mode chorus, *J. Geophys. Res.*, **107**(A7), 1144, doi:10.1029/2001JA900146, 2002a.
- Meredith, N. P., R. B. Horne, D. Summers, R. M. Thorne, R. H. A. Iles, D. Heynderickx, and R. R. Anderson, Evidence for acceleration of outer zone electrons to relativistic energies by whistler mode chorus, *Ann. Geophys.*, **20**, 967, 2002b.
- Selesnick, R. S., and J. B. Blake, Relativistic electron drift shell splitting, *J. Geophys. Res.*, **107**(A9), 1265, doi:10.1029/2001JA009179, 2002.
- Summers, D., and C. Ma, A model for generating relativistic electrons in the Earth's inner magnetosphere based on gyroresonant wave-particle interactions, *J. Geophys. Res.*, **105**, 2625, 2000.
- Summers, D., R. M. Thorne, and F. Xiao, Relativistic theory of wave-particle resonant diffusion with application to electron acceleration in the magnetosphere, *J. Geophys. Res.*, **103**, 20,487, 1998.
- Summers, D., C. Ma, N. P. Meredith, R. B. Horne, R. M. Thorne, D. Heynderickx, and R. R. Anderson, Model of the energization of outer-zone electrons by whistler-mode chorus during the October 9, 1990 geomagnetic storm, *Geophys. Res. Lett.*, **29**(24), 2174, doi:10.1029/2002GL016039, 2002.
- Tsurutani, B. T., and E. J. Smith, Postmidnight chorus: A substorm phenomenon, *J. Geophys. Res.*, **79**, 118, 1974.

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