Large Amplitude Whistler Waves and Electron Acceleration in the Earth's Radiation Belts: A Review of STEREO and Wind Observations

Cynthia Cattell, A. Breneman, K. Goetz, P. Kellogg, K. Kersten, J. Wygant, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN

L. B. Wilson III, Goddard Space Flight Center, Greenbelt, MD

Mark D Looper and J Bernard Blake, Aerospace Corporation, El Segundo, Ca

I. Roth, Space Science Laboratory, University of California, Berkeley, CA

ABSTRACT: One of the critical problems for understanding the dynamics of Earth's radiation belts is determining the physical processes that energize and scatter relativistic electrons. We review measurements from the Wind/Waves and STEREO S/Waves waveform capture instruments of large amplitude whistler-mode waves. These observations have provided strong evidence that large amplitude (100s mV/m) whistler-mode waves are common during magnetically active periods. The large amplitude whistlers have characteristics that are different from typical chorus. They are usually non-dispersive and obliquely propagating, with a large longitudinal electric field and significant parallel electric field. We will also review comparisons of STEREO and Wind wave observations with SAMPEX observations of electron microbursts. Simulations show that the waves can result in energization by many MeV and/or scattering by large angles during a single wave packet encounter due to coherent, nonlinear processes including trapping. The experimental observations combined with simulations suggest that quasilinear theoretical models of electron energization and scattering via small-

amplitude waves, with timescales of hours to days, may be inadequate for understanding radiation belt dynamics.

I. Introduction

The importance of whistler-mode waves for understanding the Earth's radiation belts has been a subject of continuing interest since the initial work by Kennel and Petschek (1966) that examined limits on stably trapped fluxes due interaction of resonant electrons with whistler waves. Most of the early work focused on whistler-mode waves as a loss mechanism, due to scattering into the loss cone, and dealt primarily waves with wave vectors parallel to the geomagnetic field ($k_{||}$). Later work recognized the potentially important role for whistlers in energization of electrons (Summers et al., 1998; Roth et al., 1999; Meredith et al., 2001; and references therein) and the effect of oblique propagation on the resonance conditions (Kennel, 1966; Roth et al., 1999). Because observational studies of whistler waves using spectral data, often averaged over long periods, suggested that wave amplitudes were small (the order of ~0.1 mV/m or ~.01 nT), quasi-linear approaches predominated. There were several studies (Bell, 1984; Omura and Matsumoto, 1982; Roth et al., 1999; Albert, 2002) that examined coherent acceleration via small amplitude whistlers and/or the effect of waves with wave vectors oblique to the geomagnetic field. In part motivated by the CRRES observations and renewed interest in the radiation belts, there have been numerous theoretical studies of scattering and energization of radiation belt particles via whistler waves, primarily focusing on quasi-linear approaches (see reviews by Millan and Thorne, 2007; Friedel et al, 2002; Bortnik and Thorne, 2007).

Because whistler observational studies have primarily used frequency domain data, often with low time resolution, large amplitude short-lived wave packets could be missed. Studies utilizing Cluster waveform data [Santolik et al., 2003] provided the first indication that wave amplitudes could at times be much larger (30 mV/m) than usually assumed. The four-satellite Cluster mission has also provided unique opportunities to investigate propagation effects, source locations and frequency structure of wave packets (Parrot et al., 2003; Chum et al., 2007; Santolik, 2008; Breneman et al., 2009; and references therein). Several new studies motivated by the Cluster 30 mV/m observation found nonlinear acceleration/trapping for parallel propagating waves (Omura et al., 2007). With the addition of large amplitude wave observations from STEREO (Cattell et al., 2008) and THEMIS (Cully et al., 2008), recent years have seen an explosion of studies focusing on nonlinear processes that address many aspects of whistler-mode waves in the radiation belts, including wave generation mechanisms, propagation, electron energization and wave packet structure (Bortnik et al., 2008; Yoon, 2011, Ni et al., 2011; Omura and Nun, 2011).

In this paper, we review observations of large amplitude whistler-mode waves made by waveform capture instruments on the Wind and STEREO spacecraft in the Earth's radiation belts. Comparisons with simultaneous measurements of relativistic electrons from the SAMPEX HILT instrument are presented to address the origin of microbursts. Particle tracing simulations of the large amplitude waves provide evidence that both energization and large angle scattering can occur in a single wave encounter. Other results on wave properties are briefly summarized. We show that large amplitude whistler-waves are common (Wilson et al., 2011a, 2011b; Kellogg et al., 2011) and are correlated with microbursts (Cattell et al., 2008; Kersten et al., 2011). The electric field waveforms show evidence of electron trapping in the electric potential (Kellogg et al., 2010). The waves also have characteristics that are different from traditional 'chorus.' Note that large amplitude whistlers have also been observed in the inner belts in association with lightning and strong transmitters (Breneman et al., 2011; 2012).

II. STEREO and Wind Events

Although neither Wind nor STEREO was designed to study the earth's radiation belts, these spacecraft did have thirteen (Wind) and four (on each of the two STEREO satellites) passages through the belts. Both Wind/Waves (Bougeret et al., 1995) and S/Waves (Bougeret et al., 2008) had waveform capture instruments (called 'TDS' or time-domain sampler) designed to store and transmit the largest amplitude waves observed in a given time period, consistent with data rate allocation. S/Waves also stores the largest amplitude electric field observed in each minute (TDSMax) to provide additional diagnostics on wave amplitudes. The data sets obtained by the two missions are complementary; Wind had both search coil and electric field data, while STEREO had longer and more frequent TDS samples and the TDSMax measurement.

A. Large amplitude whistler-mode waves are common

An example of a near-equatorial (magnetic latitude ~3°) large amplitude whistler-mode waveform obtained by Wind at L~4 and MLT~2.5 is presented in Figure 1, which plots the one measured component of the magnetic field and the three components of the electric field in spacecraft coordinates. The waveform was bursty with a maximum magnetic field amplitude of >8 nT, peak to peak (to our knowledge the largest ever reported in the radiation belt), and electric field amplitude of >200 mV/m. The frequency was ~0.15 f_{ce}, the electron cyclotron frequency. These amplitudes are two to three orders of magnitude larger than those that have typically been reported in the radiation belt, based on frequency domain (filter bank) data. The estimated Poynting flux for this event was >300 $\mu W/m^2$ (Wilson et al., 2011b) roughly four orders of magnitude above estimates from previous satellite measurements (Santolik et al., 2010). Note that because Wind obtained only one component of the search coil measurement in this mode, this is a lower bound on both the magnetic perturbation and the energy flux.

That such large amplitude waves are common is demonstrated by the fact that every satellite sampling the radiation belts with an appropriate 'waveform capture' instrument observes large amplitude whistlers during intervals with substorms or other active periods. Usually if one 'event' is seen, others are seen at the maximum repetition rate allowed by the instrument electronics and satellite data rate. Illustrative examples are shown in Figures 2 and 3. Figure 2 (Wilson et al., 2011b) presents an overview of a Wind traversal of the magnetosphere on 11/13/98; the top panel shows the power in the electric field from the Waves/TNR with f_{ce} overplotted in black and the upper hybrid frequency, f_{uh}, in white; the second panel plots the magnitude and the three GSM components of the magnetic field (Lepping et al., 1995); the next two panels plot the energetic electron (labeled 'SST Foil') and ion (labeled 'SST Open') fluxes (Lin et al., 1995). During six minutes from 18:15:08- 18:21:17 UT in the post-midnight outer radiation belt, Wind obtained 14 waveform captures containing whister-mode waves (11 TDS-Fast with 3 electric field components and 3 TDS-Slow with either one or three magnetic field components), indicated by the vertical black lines. All 14 had wave electric fields >100 mV/m and all 3 TDS-Slows had dB> 4 nT. Note that there were also four large amplitude whistler waveforms seen on the evening side outer belt between ~16:24:42 and 16:44:40).

A similar interval of large amplitude whistler-mode waves can be seen in Figure 3. The left-hand panels plot five hours of data as STEREO encountered the radiation belts; the top panel shows the energetic electron fluxes at five energies from ~250 keV to 4 MeV observed on STEREO-B, the middle panel shows the power in the electric field from 2.5 kHz to 60 kHz (the black line indicates the value of f_{ce}) on STEREO-B, and the bottom panel shows the peak electric field in one dipole channel seen in each minute by the TDS peak detector (sampled at 125 kHz) on STEREO-A (red) and STEREO-B (blue). Not that the STEREO-A data have been time-lagged by the 1.4 hour difference between the two satellite orbits. It can be seen that the large amplitude waves observed on STEREO-B occurred just after a substorm injection (lower panel right-hand side). In contrast, no large amplitude waves were observed during the STEREO-A passage through the same L-shells ~1.4 hours earlier, before the substorm onset and electron injection. During the traversal of the morning-side outer belt on STEREO-B, large amplitude waves at ~0.2 f_{ce} were observed for ~20 minutes as indicated by the electric field spectrum and the peak detector. Note that the peak detector saturated during several minutes in the region of interest on STEREO-B. During ~ 4 minutes (11:20:21-11:24:26), there were 24 0.5s duration waveform captures; 87% had electric field amplitudes >100 mV/m with maximum amplitudes >240 mV/m (Cattell et al., 2008). Two examples are shown in the upper right-hand panels.

Consistent with previous research on the association of chorus with magnetic activity (Tsurutani and Smith, 1974), the Wind and STEREO studies (Cattell et al., 2008; Wilson et al., 2011a, 2011b; and Kellogg et al., 2011) indicate that the large amplitude waves occur during intervals of geomagnetic activity. Wilson et al. (2011b) found that almost all the whistler events were associated with geosynchronous injections. Wilson et al. (2011a) showed that ~70% of the observed large whistlers occurred when AE>200 nT and that the amplitudes were weakly correlated with AE (their Figure 3). An analysis of THEMIS chorus events also shows that the wave amplitude increases with AE (Li et al., 2009).

Wilson et al. (2011a) examined the electron distributions from the Wind 3DP EESA detectors (Lin et al., 1995) observed in association with large amplitude whistler wave events. Note that the particle distributions were obtained in ~3 seconds, whereas the waveform captures typically had durations of ~0.25 s with wave packet durations on the order of ~0.1 s. Because the Wind particle detectors were not designed for radiation belt conditions, the higher energy SST detectors often saturated in the radiation belts, at least at some energies (see bottom panels of Figure 2). Essentially all the whistler wave packets that occurred within the radiation belts with associated with anisotropic electron distributions ($T_{\perp}/T_{\parallel} > 1$ for energies from ~400 eV to ≥30 keV). Using the distributions observed during several events that occurred close to the magnetic equator as input to a warm plasma dispersion solver, Kellogg et al. (2011) found that the plasma was unstable to an oblique whistler-mode wave. The regions of unstable growth did not, however, match all the observed wave characteristics. Possible explanations are that the waves were generated elsewhere or that the characteristics of the distributions changed over the measurement interval.

B. Characteristics of waves usually different from typical chorus

Whistler-mode waves observed in the radiation belts have usually been identified as chorus, lightning-associated whistlers and hiss. Chorus occurs in two bands, above and below 0.5 f_{ce}. Lower band chorus is dispersive with rising tones most commonly seen and propagation angles close to parallel to the geomagnetic field (<~10 degrees) (Goldstein and Tsurutani, 1984; Hayakawa et al., 1984). It should be noted that there are some reports of chorus propagating at larger angles (Breneman et al., 2009; Santolik et al., 2009). In contrast, most of the large amplitude whistlers observed by STEREO and Wind propagate obliquely and are usually not dispersive over the time-scale of the waveform capture. This suggests that the observed large amplitude may be a different phenomenon than chorus. The detailed data set that will be obtained from the Radiation Belt Storm Probes mission may solve this question.

Statistical studies of the observed large amplitude whistler-mode waves observed by Wind inside 15 Re have been described by Wilson et al. (2011a, 2011b) and Kellogg et al. (2011). Wilson et al. found that ~90% of the large whistlers occurred in the radiation belts and ~70% during active times. Almost all are in the lower band, i.e. have frequencies at peak power below 0.5 f_{ce}. Only a few (~20%) of the observed wave packets show the frequency changes with time that are typical of chorus (Wilson et al., 2011b). Kellogg et al. (2011) shows one example of a waveform that does have a rise in frequency with time (their Figure 2). No dispersion was seen in any of the twenty-four 12/12/2006 STEREO waveforms. An example is shown in Figure 4; the waveforms are on the left-hand side and the Fourier transforms are on the right. It can be seen that the frequency is constant throughout the packet. Note that the second harmonic is a signature of electron trapping to be discussed below.

The Wind waveform samples had durations of ~17 ms to ~1000 ms (typically ~250 ms) and the STEREO ones had durations of ~520 ms. Although dispersion could have occurred over longer intervals, this is unlikely given that the durations of individual whistler packets were usually the order of tenths of a second. In addition, studies of chorus risers (Santolik et al., 2003; Breneman et al., 2009) have indicated that the frequency changes occur on time-scales that would be observable in the Wind and STEREO TDS.

Figure 5 shows a Wind waveform in minimum variance coordinates for one event when vector wave magnetic field was transmitted; the panels on the left plot the time series of the three components and the panels on the right present the hodograms. The expected right-hand polarization is clear in the upper hodogram, and the wavevector, **k**, was 44° to the geomagnetic field. Of the 46 events for which three components of the wave magnetic field were obtained, 35% had a propagation angle greater than 20°. Note that most of the waveform samples on both Wind and STEREO were close to the equator and that Wilson et al. (2011a) found no correlation between the propagation angle and magnetic latitude. It is therefore unlikely that the oblique propagation is due only to propagation effects.

Kellogg et al. (2010) described an alternative approach to determining the direction of wave vector for waveforms that show the distortion that is consistent with electron trapping in the electrostatic potential. The electric field of the trapped layer of electrons must be parallel to **k**. For the 24 STEREO TDS in the outer belt on 12/12/2006, the average angle between **k** and **B** varied from ~ 46 to 51 deg, consistent with angles determined from the electric field polarization and the cold plasma dispersion relation.

C. Waves are associated with microbursts

For more than twenty years, observations of 'microbursts,' short bursts of relativistic electrons, have been seen by balloon detectors or low altitude satellites imaging the loss cone [Blake et al., 1996; Millan and Thorne, 2007, Millan et al., 2011 for review]. Although electromagnetic ion cyclotron waves [Thorne and Kennel, 1971; Alpert and Bortnik, 2009] are often proposed to provide the scattering, no good explanation has yet been presented that can account for all the observed phenomenology. Lorentzen et al. (2001) provided evidence that suggested that oblique chorus could provide the needed scattering.

There was a fortuitous conjunction between SAMPEX and STEREO during the intervals when both STEREO-A and STEREO-B encountered the radiation belts on December 12, 2006 (Cattell et al., 2008). Figure 6 (Kersten et al., 2011) summarizes the wave and microburst observations; the top plot in both panels A and B shows the counts in the SAMPEX HILT detector (Blake et al., 1996) with the L-shells of both satellites overplotted and the bottom plot (TDSMax) shows the value of the maximum wave electric field in each minute; panel C shows an expanded interval of the relativistic electron counts in HILT; and panel D shows one of the STEREO-B waveform captures. As described above, no large amplitude waves occurred during the STEREO-A passage, which occurred when the magnetic activity was low. Panel A shows that there was no microburst activity observed by SAMPEX during the STEREO-A traversal of the radiation belt. During the STEREO-B encounter, intense microbursts occurred (top plot in panel B) in conjunction with large amplitude waves. The time variations in the microbursts (panel C) are similar to those seen in the waves (panel D).

Near conjunctions between SAMPEX and Wind have been studied (Kersten et al., 2011) to further explore the relationship between relativistic electron loss and waves. Figure 7 presents an example that occurred on November 13, 1998. Intense microbursts are visible in the four minutes of relativistic electron count rates plotted in the upper panel. During this time period, Wind Waves observed large amplitude whistler mode waves; one example waveform is plotted in the bottom panel.

The observed correlation between large amplitude whistler-mode waves and microbursts is consistent with results of a particle-tracing code that traces electrons in a dipole magnetic field with whistler wave with characteristics based on the observations. Results show that resonant electrons can be scattered by very large angles in a single wave encounter (Cattell et al., 2008; Kersten et al., 2011).

III. Discussion and Conclusions

We have briefly reviewed a set of studies using Wind and STEREO data to characterize the occurrence and properties of whistler-mode waves in the outer radiation belt and the association with relativistic electron microbursts as seen on SAMPEX. The results of particle tracing codes modeling the interaction of electrons with waves similar to those observed show that these large amplitude, oblique waves can energize resonant electrons by the order of MeV during single wave packet encounter and/or scatter electrons by large angles. Energization and scattering are not due to slow quasi-linear, stochastic processes. The process is non-linear, associated with either or both cyclotron wave trapping and Landau resonance, resulting in rapid changes in pitch angle and energy. This suggests that usual theoretical models of electron energization and scattering via small-amplitude waves, with timescales of hours to days, cannot provide a complete understanding of radiation belt dynamics.

Both STEREO and Wind have measured whistler-mode waves in the Earth's radiation belt with amplitudes of greater than 240 mV/m in the electric field and 8 nT in the magnetic field, 2 to 3 orders of magnitude larger than previously reported. Wave properties distinctly different from usual lower band chorus, including large amplitudes, oblique propagation, non-dispersive, large longitudinal electric fields and significant electric field components parallel to the geomagnetic field. Similar large amplitude whistler-mode waves have been reported using THEMIS data (Cully et al., 2008). The Wind and STEREO data indicate that these coherent large amplitude oblique whistler mode waves are common in the outer radiation belt during magnetically active periods. During a STEREO B encounter with the outer belt after a substorm, large amplitude waves occurred for ~20 minutes, the time taken for the passage through the belt.

STEREO observations provide evidence that the large amplitude whistlers are associated with rapid enhancement (timescale of ~10 minutes) in fluxes of relativistic electrons in outer radiation belt (Cattell et al., 2008). These observations were made during a high speed stream and after a small substorm injection, but were not associated with a magnetic storm. The waves may be larger during major storms or after stronger injections. Waves can scatter electrons by large angles, consistent with the SAMPEX microbursts seen during large amplitude wave events when near conjunctive measurements were available (Kersten et al., 2011).

The interaction of the waves with electrons can be highly nonlinear; both electrostatic (Kumagai et al., 1980) and cyclotron trapping of electrons can occur. Kellogg et al. (2010, 2011) described the modifications in the whistler electric field associated with trapping of electrons in the electric potential of the oblique whistler. This mechanism can only occur in obliquely propagating waves, consistent with the fact that the waveform distortion is not seen in large-amplitude parallel or near-parallel propagating waves. The density of trapped electrons can be large enough to significantly modify the whistler wave electric field. Note that this trapping is distinctly different from cyclotron resonance trapping, which can also occur and is associated with the rapid energization and scattering seen in both the observations and particle tracing results.

The STEREO and Wind waveform capture data, in conjunction with SAMPEX particle data and simulations, have provided unique measurements that indicate the potentially critical role of large amplitude whistler waves. A complete description of radiation belt dynamics will involve use of nonlinear mechanisms. Because neither mission was designed for radiation belt studies, their coverage of the region is limited. A detailed and more complete picture of the waves and their roles in radiation belt dynamics will be provided by the Radiation Storm Belt Probes (Ukhorskiy et al., 2011) and the BARREL mission (Millan et al., 2011).

Acknowledgements: This research was supported by NASA grant NNX07AI05G, NNX07AF23G, NNX08AT81G and a contract from APL for the development of RBSP/EFW. L. B. Wilson III was supported by NESSF grant NNX07AU72H and a Dr. Leonard Burlaga/Arctowski Medal Fellowship, and K. Kersten was partially supported by a Dr. Leonard Burlaga/Arctowski Medal Fellowship.

REFERENCES

Albert, J. M. (2002), Nonlinear interaction of outer zone electrons with VLF waves, Geophys. Res. Lett., 29(8), 1275, doi:10.1029/2001GL013941

Albert, J. M. (2008), Efficient approximations of quasi-linear diffusion coefficients in the radiation belts, J. Geophys. Res. , 113, A06208, doi:10.1029/2007JA012936.

Albert, J.M., and J. Bortnik, (2009) Nonlinear interaction of radiation belt electrons with electromagnetic ion cyclotron waves. Geophys. Res. Lett. 36, L12110.

Bell, T. F. (1984), The nonlinear gyroresonance interaction between energetic electrons and coherent VLF waves propagating at an arbitrary angle with respect to the earth's magnetic field, J. Geophys. Res., 89, 905 – 918.

Bell, T. F. (1986), The wave magnetic field amplitude threshold for non-linear trapping of energetic gyroresonant and Landau resonant electrons by nonducted VLF waves in the magnetosphere, J. Geophys. Res., 91, 4365 – 4379. 2007JA012886.

Blake, J.B., Looper, M.D., Baker, D.N., Nakamura, R., Klecker, B., Hovestadt, D., (1996) New high temporal and spatial resolution measurements by SAMPEX of the precipitation of relativistic electrons. Adv. Space Res. 18 (8), 171–186.

J. Bortnik, R.M. Thorne, The dual role of ELF/VLF chorus waves in the acceleration and precipitation of radiation belt electrons, Journal of Atmospheric and Solar-Terrestrial Physics, Volume 69, Issue 3, March 2007, Pages 378-386, 10.1016/j.jastp.2006.05.030.

Bortnik, J., R. M. Thorne, and U. S. Inan (2008), Nonlinear interaction of energetic electrons with large amplitude chorus, Geophys. Res. Lett., 35, 21,102, doi:10.1029/2008GL035500.

Bougeret, J.-L., M. L. Kaiser, P. J. Kellogg, R. Manning, K. Goetz, S. J. Monson, N. Monge, L. Friel, C. A. Meetre, C. Perche, L. Sitruk, and S. Hoang (1995), Waves: The Radio and Plasma Wave Investigation on the Wind Spacecraft, Space Science Reviews, 71, 231–263, doi: 10.1007/BF00751331.

Bougeret, J. L. et al., S/Waves: The Radio and Plasma Wave Investigation on the STEREO Mission, Space Sci. Rev. , DOI 10.1007/s11214-007-9298-8, 2008.

Breneman, A. W., C. A. Kletzing, J. Pickett, J. Chum, and O. Santolik (2009), Statistics of multispacecraft observations of chorus dispersion and source location, J. Geophys. Res., 114, A06202, doi:10.1029/2008JA013549.

Breneman, A., C. Cattell, J. Wygant, K. Kersten, L. B. Wilson III, S. Schreiner, P. J. Kellogg, and K. Goetz (2011), Large-amplitude transmitter-associated and lightning-associated whistler waves in the Earth's inner plasmasphere at L < 2, J. Geophys. Res., 116, A06310, doi:10.1029/2010JA016288.

Cattell, C., J. R. Wygant, K. Goetz, K. Kersten, P. J. Kellogg, T. von Rosenvinge, S. D. Bale, I. Roth, M. Temerin, M. K. Hudson, R. A. Mewaldt, M. Wiedenbeck, M. Maksimovic, R. Ergun, M. Acuna, and C. T. Russell (2008), Discovery of very large amplitude whistler-mode waves in Earth’s radiation belts, Geophys. Res. Lett., 35, 1105, doi:10.1029/2007GL032009.

Chum, J., Santolik, O., Breneman, A. W., Kletzing, C. A., Gurnett, D. A., and Pickett, J. S.: Chorus source properties that produce time shifts and frequency range differences observed on different Cluster spacecraft, J. Geophys. Res., 112, A06206, doi:10.1029/2006JA012061, 2007.

Cully, C. M., J. W. Bonnell, and R. E. Ergun (2008), THEMIS observations of long-lived regions of large-amplitude whistler waves in the inner magnetosphere, Geophys. Res. Lett., 35, L17S16, doi:10.1029/2008GL033643.

Cully, C. M., V. Angelopoulos, U. Auster, J. Bonnell, and O. Le Contel (2011), Observational evidence of the generation mechanism for rising-tone chorus, Geophys. Res. Lett., 38, L01106, doi:10.1029/2010GL045793.

Friedel, R.H.W , G.D Reeves, T Obara, Relativistic electron dynamics in the inner magnetosphere — a review, Journal of Atmospheric and Solar-Terrestrial Physics, Volume 64, Issue 2, January 2002, Pages 265-282, 10.1016/S1364-6826(01)00088-8.

Goldstein, B. E., and B. T. Tsurutani (1984), Wave Normal Directions of Chorus Near the Equatorial Source Region, *J. Geophys. Res.*, 89(A5), 2789–2810, doi:10.1029/JA089iA05p02789.

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, doi:10.1029/JA089iA05p02811.

Horne, R. B., R. M. Thorne, S. A. Glauert, J. M. Albert, N. P. Meredith, and R. R. Anderson (2005), Timescale for radiation belt electron acceleration by whistler mode chorus waves, J. Geophys. Res., 110, 3225, doi:10.1029/2004JA010811.

Kellogg, P. J., C. A. Cattell, K. Goetz, S. J. Monson, and L. B. Wilson III (2010), Electron trapping and charge transport by large amplitude whistlers, Geophys. Res. Lett., 37, L20106, doi:10.1029/2010GL044845.

Kellogg, P. J., C. A. Cattell, K. Goetz, S. J. Monson, and L. B. Wilson III (2011), Large amplitude whistlers in the magnetosphere observed with Wind-Waves, *J. Geophys. Res.*, 116, A09224, doi:10.1029/2010JA015919.

Kennel, C. F., and H. E. Petschek (1966), Limit on stably trapped particle fluxes, J. Geophys. Res., 71, 1–28, doi:10.1029/JZ071i001p00001.

Kennel, C. F., Low frequency whistler mode, *Phys. Fluids* **9**, 2190 (1966).

Kersten, K., C. A. Cattell, A. Breneman, K. Goetz, P. J. Kellogg, J. R. Wygant, L. B. Wilson III, J. B. Blake, M. D. Looper, and I. Roth (2011), Observation of relativistic electron microbursts in conjunction with intense radiation belt whistler-mode waves, Geophys. Res. Lett., 38, L08107, doi:10.1029/2011GL046810.

Kumagai, H., K. Hashimoto, I. Kimura, and H. Matsumoto (1980), Computer simulation of a Cerenkov Interaction between obliquely propagating whistler mode waves and an electron beam, Phys. Fluids, 23, 184, doi:10.1063/1.862837.

Lepping, R. P., et al. (1995), The Wind magnetic field investigation, Space Sci. Rev., 71, 207–229, doi:10.1007/BF00751330.

Li, W., R. M. Thorne, V. Angelopoulos, J. Bortnik, C. M. Cully, B. Ni, O. LeContel, A. Roux, U. Auster, and W. Magnes (2009), Global distribution of whistler-mode chorus waves observed on the THEMIS spacecraft, Geophys. Res. Lett., 36, L09104, doi:10.1029/2009GL037595

Lin, R. P., et al. (1995), A three-dimensional plasma and energetic particle investigation for the Wind spacecraft, Space Sci. Rev., 71, 125–153, doi:10.1007/BF00751328.

Lyons, L. R., R. M. Thorne, and C. F. Kennel (1972), Pitch-angle diffusion of radiation belt electrons within the plasmasphere, J. Geophys. Res., 77, 3455–3474, doi:10.1029/JA077i019p03455.

Millan, R.M. et al., Understanding relativistic electron losses with BARREL. Journal of Atmospheric and Solar- Terrestrial Physics (2011), doi:10.1016/j.jastp.2011.01.006

Millan, R. and R. M. Thorne, Review of radiation belt relativistic electron losses, J. Atmos. Solar-Terr. Physics 69, 362, 2007.

Ni, B., R. M. Thorne, Y. Y. Shprits, K. G. Orlova, and N. P. Meredith (2011), Chorus-driven resonant scattering of diffuse auroral electrons in nondipolar magnetic fields, *J. Geophys. Res.*, 116, A06225, doi:10.1029/2011JA016453.

Omura, Y., and H. Matsumoto (1982), Computer simulations of basic processes of coherent whistler wave-particle interactions in the magnetosphere, J. Geophys. Res., 87, 4435, doi:10.1029/JA087iA06p04435.

Omura, Y., N. Furuya, and D. Summers (2007), Relativistic turning acceleration of resonant electrons by coherent whistler mode waves in a dipole magnetic field, *J. Geophys. Res.*, 112, A06236, doi:10.1029/2006JA012243.

Omura, Y., and D. Nunn (2011), Triggering process of whistler mode chorus emissions in the magnetosphere, *J. Geophys. Res.*, 116, A05205, doi:10.1029/2010JA016280.

Parrot, M., O. Santolik, N. Cornilleau-Wehrlin, M. Maksimovic, and C. C. Harvey (2003), Source location of chorus emissions observed by Cluster, Ann. Geophys., 21, 473–480.

Roth, I., M. Temerin, M. K. Hudson, Resonant enhancement of relativistic electrons during geomagnetically active periods, Ann. Geophysicae 17, 631-638,1999.

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

Santolık, O., J. S. Pickett, D. A. Gurnett, J. D. Menietti, B. T. Tsurutani, and O. Verkhoglyadova (2010), Survey of Poynting flux of whistler mode chorus in the outer zone, J. Geophys. Res., 115, doi:10.1029/2009JA014925.

Sauer, K., and R. D. Sydora (2010), Beam-excited whistler waves at oblique propagation with relation to STEREO radiation belt observations, Ann. Geophys., 28, 1317–1325.

Schriver, D., M. Ashour-Abdalla, F. V. Coroniti, J. N. LeBoeuf, V. Decyk, P. Travnicek, O. Santol´ık, D. Winningham, J. S. Pickett, M. L. Goldstein, and A. N. Fazakerley (2010), Generation of whistler mode emissions in the inner magnetosphere: An event study, J. Geophys. Res., 115, A00F17, doi:10.1029/2009JA014932.

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.

Thorne, R.M., Kennel, C.F., 1971. Relativistic electron precipitation during magnetic storm main phase. J. Geophys. Res. 76, 4446.

Tsurutani, B. T., and E. J. Smith (1974), Postmidnight Chorus: A Substorm Phenomenon, *J. Geophys. Res.*, 79(1), 118–127, doi:10.1029/JA079i001p00118.

Ukhorskiy, A. , B. Mauk, N. Fox, D. Sibeck and J. Grebowsky, Radiation belt storm probes: Resolving fundamental physics with practical consequences, Journal of Atmospheric and Solar-Terrestrial Physics 73 (2011) 1417–1424

Wilson, Lynn, III, Cynthia Cattell, Paul Kellogg , Keith Goetz , John Wygant , Aaron Breneman , Kris Kersten, , A statistical study of large amplitude whistler wave and few eV to 30 keV electron distributions observed in the magnetosphere by Wind, arXiv:1101.3303v1, 2011.

Wilson, L. B., III, C. A. Cattell, P. J. Kellogg, J. R. Wygant, K. Goetz, A. Breneman, and K. Kersten (2011), The properties of large amplitude whistler mode waves in the magnetosphere: Propagation and relationship with geomagnetic activity, Geophys. Res. Lett., 38, L17107, doi:10.1029/2011GL048671.

Yoon, P. H. (2011), Large-amplitude whistler waves and electron acceleration, *Geophys. Res. Lett.*, 38, L12105, doi:10.1029/2011GL047893.

$$\omega - k_{||} v_{||} = m\Omega_e/\gamma$$