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The dual role of ELF/VLF chorus waves in the acceleration and precipitation of radiation belt electrons

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Abstract

This paper provides a brief review of the role that chorus waves play in controlling the dynamics of the Earth's outer radiation belt. Three major topics are discussed: (i) the morphology, characteristics, and properties of chorus waves themselves, with special emphasis on more recent results, (ii) the role that chorus waves play in the loss of radiation belt particles, showing initial results from modeling of relativistic electron microbursts, and estimated lifetimes based on microburst occurrence rates during the main phase of storms, and (iii) the role that chorus waves play in the acceleration of electrons to relativistic energies in the recovery phase of storms, based on a new quasilinear diffusion based calculation.

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Keywords: Radiation belts; Chorus; Precipitation; Acceleration; Wave–particle interactions

1. Introduction

Dawn chorus was first reported by Storey (1953) and so-named due to its resemblance of a "rookery heard from a distance" when the signal was played through a loudspeaker. Though described only peripherally in an appendix, the key features associated with chorus (which would later be abundantly confirmed (e.g., Sazhin and Hayakawa, 1992)) were nevertheless succinctly summarized as consisting of a multitude of 'rising whistles', having a pronounced daily variation with an intensity maximum at around 6 am, as well as exhibiting a strong correlation with magnetic storms.

Using space-borne instruments it was found that the chorus emissions occurred in two distinct frequency bands (Burtis and Helliwell, 1969), as shown in the example spectrogram (Fig. 1) from the SCATHA (Spacecraft Charging AT High Altitude, or $P78-2$) satellite's very-low-frequency (VLF) receiver (reprinted from Koons and Roeder, 1990, Fig. 6b, with permission from Elsevier). These frequency bands were found to be associated with the equatorial gyrofrequency (f_{ce}, where $0.5f_{ce}$ is indicated by the arrow on the left side of the figure) along the field line passing through the satellite (Burtis and Helliwell, 1969) and peak in power near $0.34f_{ce}$ (lower band) and $0.53f_{ce}$ (upper band) (Burtis and Helliwell, 1976), exhibiting a power

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minimum near $0.5f_{\text{ce}}$ (Tsurutani and Smith, 1974), which can reach a width of $0.2f_{\text{ce}}$, or occasionally disappear entirely (Koons and Roeder, 1990).

The behavior of the individual narrowband chorus elements shown in Fig. 1 was found to be predominantly rising ($\mathrm{d}f/\mathrm{d}t>0$, occurrence probability $P=77\%$) at ~0.2–2 kHz/s (increasing with K_p and decreasing with L-shell), but could also include falling tones ($\mathrm{d}f/\mathrm{d}t<0$, $P=16\%$), some combination of the above (so-called hooks, regular and inverted, and constant tones, $P=18\%$) (Burtis and Helliwell, 1976), or structureless (Tsurutani and Smith, 1974).

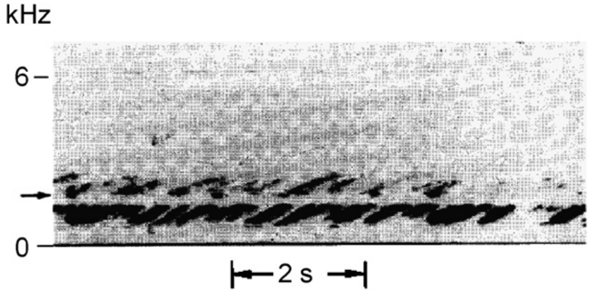

Fig. 1. An example of typical chorus waves observed on the SCATHA satellite (reprinted from Koons and Roeder, 1990, Fig. 6b with permission from Elsevier).

More recent studies have confirmed and extended many of the features previously reported in satellite studies. For example, Fig. 2 (reproduced from Meredith et al., 2003a with permission of the American Geophysical Union) shows the lower-band chorus wave power distributed as a function of L-shell and MLT, for measurements made in the equatorial region ($|\lambda_m|<15^\circ$) and mid-latitudes ($|\lambda_m|>15^\circ$) in the top and bottom rows, respectively (where λ_m is magnetic latitude). Equatorial chorus clearly peaks in the dawn sector and increases dramatically as a function of geomagnetic activity. Mid-latitude chorus, on the other hand, peaks closer to the dayside, and also increases strongly with geomagnetic activity (Meredith et al., 2001). The fact that equatorial and mid-latitude chorus have a different spatial distribution, has implications for the regions of acceleration and loss. For example, acceleration of electrons (with typical plasmasheet energies) occurs predominantly due to equatorial chorus (Meredith et al., 2003a), whereas microbursts have been attributed to chorus at higher latitudes (e.g., Thorne et al., 2005a, b,

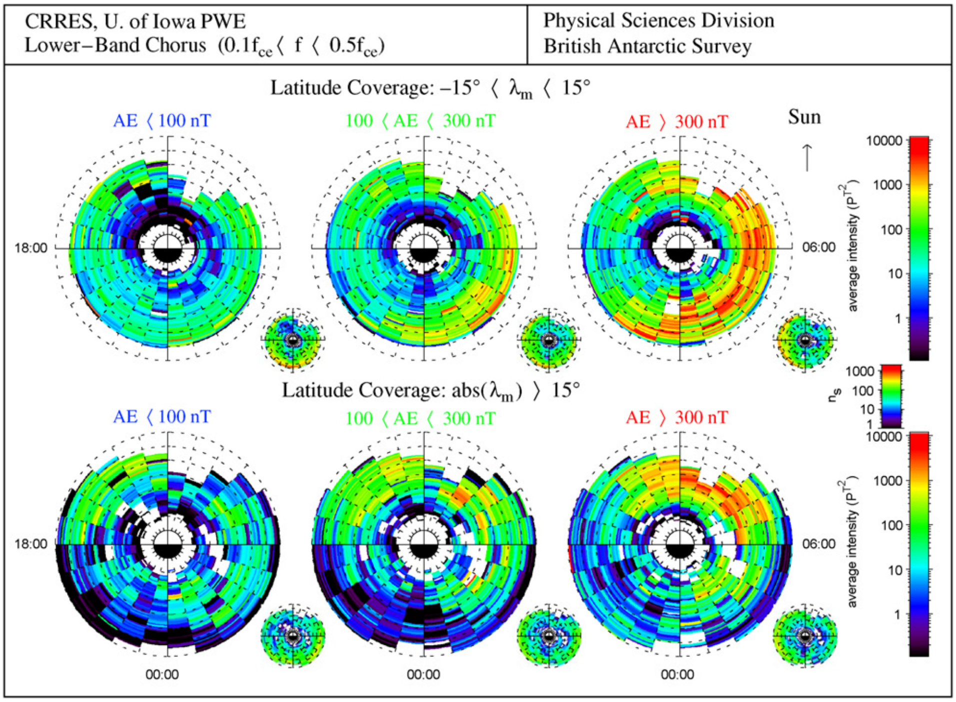

Fig. 2. Distribution of lower-band chorus power as a function of L-shell and MLT, parametrized by geomagnetic activity. The top and bottom rows show equatorial ($|\lambda_m|<15^\circ$) and mid-latitude ($|\lambda_m|>15^\circ$) chorus distributions , respectively (reproduced/modified from Meredith et al., 2003a by permission of the American Geophysical Union).

Fig. 2d) and should therefore be more closely related to the mid-latitude chorus.

Wave normal studies have also confirmed many previously known results (Burton and Holzer, 1974) namely that chorus occurs routinely at high wave normals and propagates away from the geomagnetic equator (LeDocq et al., 1998). Ray tracing combined with direction finding also indicates that chorus may be generated at the Gendrin angle (or high wave normal angles) near the source region (Lauben et al., 2002; Parrot et al., 2003) which could be related to its unidirectional propagation and two-banded structure (Bortnik et al., 2006c). This observation, however, poses a theoretical problem since growth rates calculated using quasilinear theory are expected to maximize for field aligned waves (e.g., Kennel and Thorne, 1967).

Using a new class of multipoint satellite observations, the extent of the source in the direction parallel to $\mathbf{B}_0$ was found to be ~3000–5000 km (Santolik et al., 2004), whereas perpendicular to the source, significant correlation were found to be in the range ~7–100 km (Santolik and Gurnett, 2003). The source region was also found to be 'flapping' with a timescale of minutes within 1000–2000 km of the geomagnetic equator (Santolik et al., 2004). Individual chorus elements recorded simultaneously on a number of spacecraft were observed to be offset by different frequencies, and arrived with varying time delays (Inan et al., 2004). This was interpreted as being due to the chorus source region radiating whistler waves with a broad spectrum of wave normal angles (accounting for varying propagation delays), as well as moving rapidly along the field line, causing differential Doppler shifts at each observing spacecraft (Inan et al., 2004).

As the chorus waves propagate, they interact with energetic electrons when the resonance condition

$$\omega - k_{\parallel} v_{\parallel} = \frac{m\omega_{\mathrm{ce}}}{\gamma} \tag{1}$$

is satisfied, where ω is the chorus wave frequency, $k_{\parallel}$ and $v_{\parallel}$ are the components of the wave number and electron velocity parallel to $\mathbf{B}_0$, m is the resonance harmonic number, ω_{ce} is the electron cyclotron frequency, and $\gamma = (1 - v^2/c^2)^{-1/2}$ is the relativistic correction factor. Such a resonant interaction violates the first adiabatic invariant causing (in general) a change in both the energy of the electron and its pitch-angle (e.g., Kennel and Petschek, 1966; Roberts, 1969), with a corresponding large-scale behavior of either formation (acceleration) or loss of the radiation belts. The remainder of this paper examines the role of chorus as a loss mechanism (Section 2), and then as a potential mechanism for the acceleration of electrons to relativistic energies (Section 3) before summarizing our conclusions in Section 4.

2. Precipitation due to chorus

In the course of resonant wave–particle interactions, the particles undergo a non-adiabatic change in both energy and pitch-angle, and if the pitch-angles are lowered sufficiently (i.e., into the bounce loss-cone α_{lc}), they can be permanently lost to the atmosphere within one bounce period (e.g., Kennel and Petschek, 1966). Indeed, relativistic electron microbursts have been observed as sharp increases of >1 MeV fluxes above the background levels in the bounce- and drift-loss-cones (Blake et al., 1996), and have been associated with individual chorus elements both temporally and spatially (Lorentzen et al., 2001). Follow-up studies have shown that the distribution of microbursts in MLT is similar to that of chorus, peaking in the dawn sector (O'Brien et al., 2003) in association with geomagnetic storms, and further that losses are ~10–100 times greater during the main phase of the storm than during the recovery phase (O'Brien et al., 2004).

In Fig. 3 we show results from a modeling study of the precipitation driven by a single chorus element. The technique used here is that of Bortnik et al. (2006a, b) and consists of two broad steps: (i) specifying the wave properties along a given field line using numerical raytracing and interpolation (Bortnik et al., 2003), and (ii) calculating the pitch-angle changes of test-particles in the prescribed wave fields, and using these to infer the behavior of the distribution function near the edge of the loss-cone.

Fig. 3a shows a snapshot of a group of rays, injected at the geomagnetic equator. Each ray is injected with the initial wave normal angle set at the Gendrin angle (ψ_{G}) based on recent observations (Lauben et al., 2002), and amplitude weighted such that $B_{\mathrm{w}} = 10\exp([(L-5)/0.1]^2)\,\mathrm{pT}$, ensuring that the chorus element has a peak amplitude of 10 pT at $L = 5$, and rolls off over small spatial scales. The chorus element is roughly based on those reported by Lorentzen et al. (2001, Plate 3d), with lower and upper cutoffs set at 1 and 1.5 kHz, respectively, and a risetime of 2 kHz/s. A composite spectrogram is shown in Fig. 3b, where the chorus element is

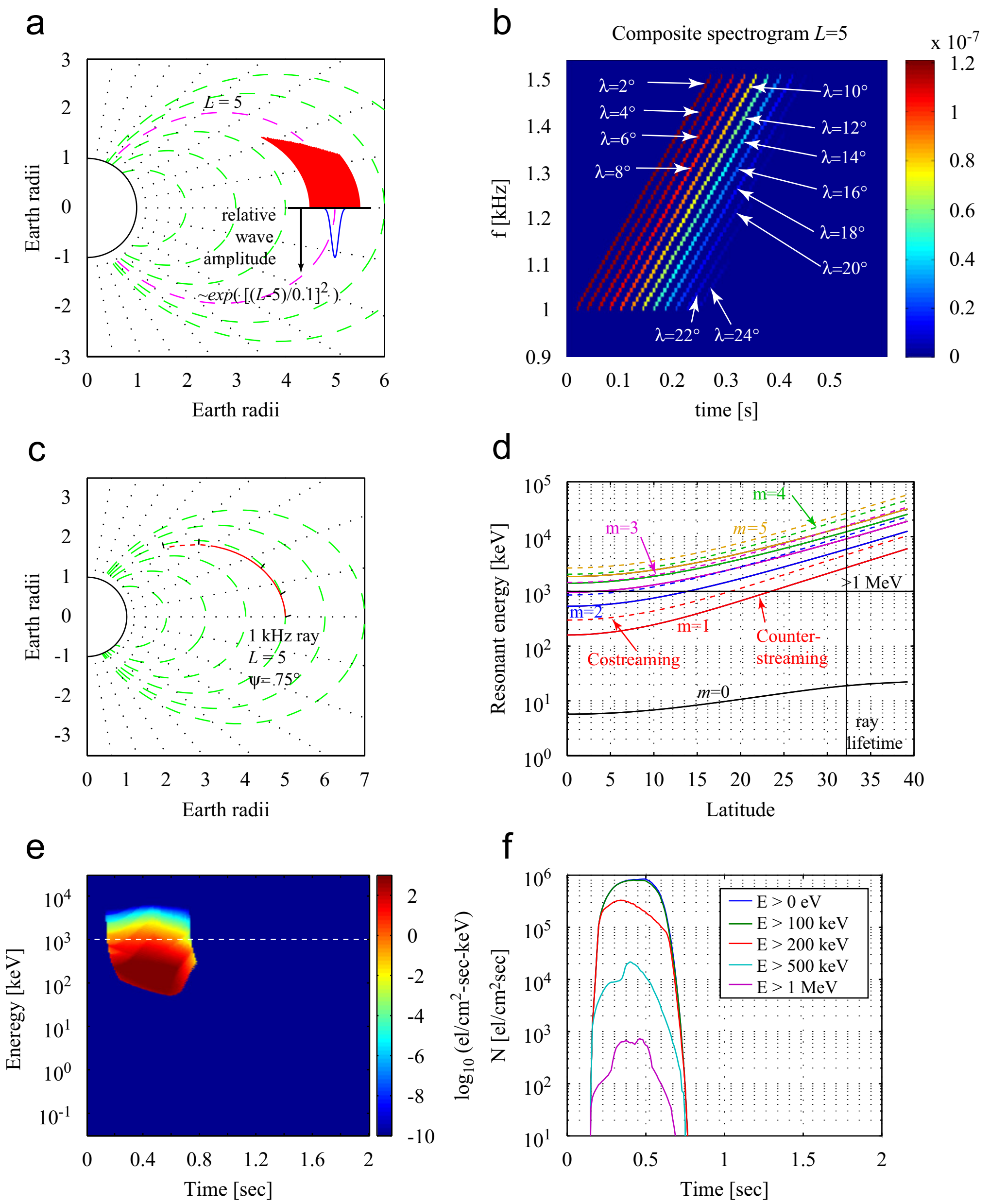

Fig. 3. Modeling of chorus driven electron precipitation: (a) chorus element rays; (b) composite spectrogram at $L = 5$; (c) central ray of chorus packet; (d) resonant energies of interacting electrons; (e) precipitated differential number flux, and (f) integrated precipitated flux above various energies.

plotted at a set of latitudes successively incremented by 2°. The time delays clearly increase with increasing observation latitude, and the wave power is diminished due to Landau damping, such that by $\lambda = 24°$ the wave is extinguished.

The energies of resonant electrons are investigated by examining only the central ray of the chorus wave packet at 1 kHz, shown in Fig. 3c. The ray is shown as a solid line for the duration of its lifetime (i.e., before power is reduced by 10 dB), and dashed line thereafter, indicating that it propagates to ~32°. We then evaluate (1) using the wave parameters of this central ray as an example (Fig. 3c) for various resonance modes m, and show the results as a function of latitude in Fig. 3d. The ray lifetime is shown as a vertical line at $\lambda \sim 32°$

indicating that beyond this latitude the wave is too weak to produce any substantial scattering. The 1 MeV threshold is shown as a horizontal line, indicating that the scattering of relativistic electrons >1 MeV in the dominant $m=1$ mode is expected to take place in a narrow latitudinal window between $\lambda{\sim}24^\circ$ when these particles are able to resonate with the wave, and $\lambda{\sim}32^\circ$ when the wave power is extinguished, consistent with past work (Thorne et al., 2005a).

The precipitated differential number flux driven by the wave distribution of Fig. 3b is shown in Fig. 3e, where the 1 MeV threshold is indicated with a white dashed line. As indicated, the bulk of the pitch-angle scattering occurs near the equator, where the wave–particle interaction is most efficient (e.g., Bell, 1984) and the waves are most intense. Peak precipitation fluxes (for 100–300 keV electrons), are $\sim$100 electrons/cm^2 s keV (integrated over the loss-cone solid angle), and last a few tenths of a second.

To compare more readily with the microburst fluxes observed on SAMPEX, the precipitated differential number flux is integrated with respect to energy (e.g., Eq. (19a) in Bortnik et al., 2006a) above various energy thresholds as shown in Fig. 3f. Multiplying the peak flux of the >1 MeV (magenta curve in Fig. 3f) by the geometric factor (60 cm^2 ster) and collection time (20 ms), results in peak count rates of a several hundred per 20 ms, very similar to observed values (Lorentzen et al., 2001, Plate 3b). Thus we believe there is strong theoretical and observational evidence to associate individual chorus elements with microbursts of relativistic electrons.

As mentioned above, microburst occurrence frequency and intensity tends to maximize in the main phase of storms (O'Brien et al., 2004) which can act as an effective loss mechanism for the radiation belts. Using microburst intensity and occurrence rates from SAMPEX during the October 1998 storm, and comparing to trapped flux levels from POLAR, Thorne et al. (2005a) were able to make lifetime estimates for electrons >1 MeV as shown in Fig. 4 (reproduced from Thorne et al., 2005a, Fig. 1, with permission of the American Geophysical Union). The gray dots in this figure represent instantaneous (and local) lifetime estimates, and the circles indicate 0.25L averages. The instantaneous values were then adjusted for microburst occurrence rates and oversampling (due to atmospheric backscatter), to produce the solid curve in Fig. 4, which are comparable to $\sim$1 day. Thus, chorus is believed to play an important role as a loss process during the main phase of storms, comparable to other loss processes which also act on the timescale of a day, such as combined scattering by plasmaspheric hiss and EMIC waves (Albert, 2003; Summers and Thorne, 2003) as well as radial diffusion due to ULF waves (Shprits and Thorne, 2004).

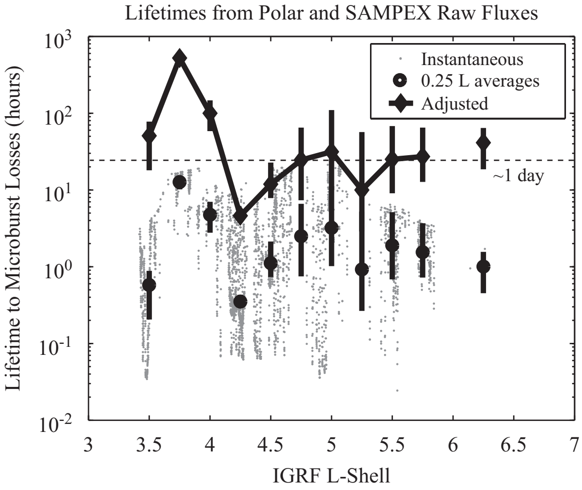

Fig. 4. Calculated lifetimes due to microburst losses (reproduced/modified from Thorne et al., 2005a, Fig. 1, by permission of the American Geophysical Union).

3. Acceleration due to chorus

The long-held view that the radiation belts are formed as a result of inward radial diffusion from a source population at higher L-shells (e.g., Falthammer, 1965; Schultz and Lanzerotti, 1974; Elkington et al., 1999), is undergoing some modification in light of recent findings (e.g., Horne et al., 2005a).

During the October–November 2003 Halloween storm (Baker et al., 2004) it was shown that the intense ULF fluctuations necessary to drive inward radial diffusion through drift resonance with energetic electrons decay during the period when the radiation belts are reformed (Horne et al., 2005a). At the same time, chorus waves observed on the ground become very intense, emerge from low L-shells, and persist throughout the period of particle acceleration (Horne et al., 2005a; Spasojevic and Inan, 2005). Similar association of acceleration periods with chorus have been observed from space (Meredith et al., 2002a, b; Miyoshi et al., 2003; Meredith et al., 2003b). In addition, a number of studies combining storm-time observations with modeling have shown that recovery phase acceleration rates are inconsistent with the radial diffusion model and support energization due to chorus (Brautigam and Albert, 2000; Shprits et al., 2006a).

Finally, peaks in the electron phase space density (*f*) have been observed at intermediate values of L during active periods, consistent with local acceleration mechanisms, but inconsistent with inward radial diffusion which would require a positive gradient of f with L ($\partial f/\partial L > 0$) (Selesnick and

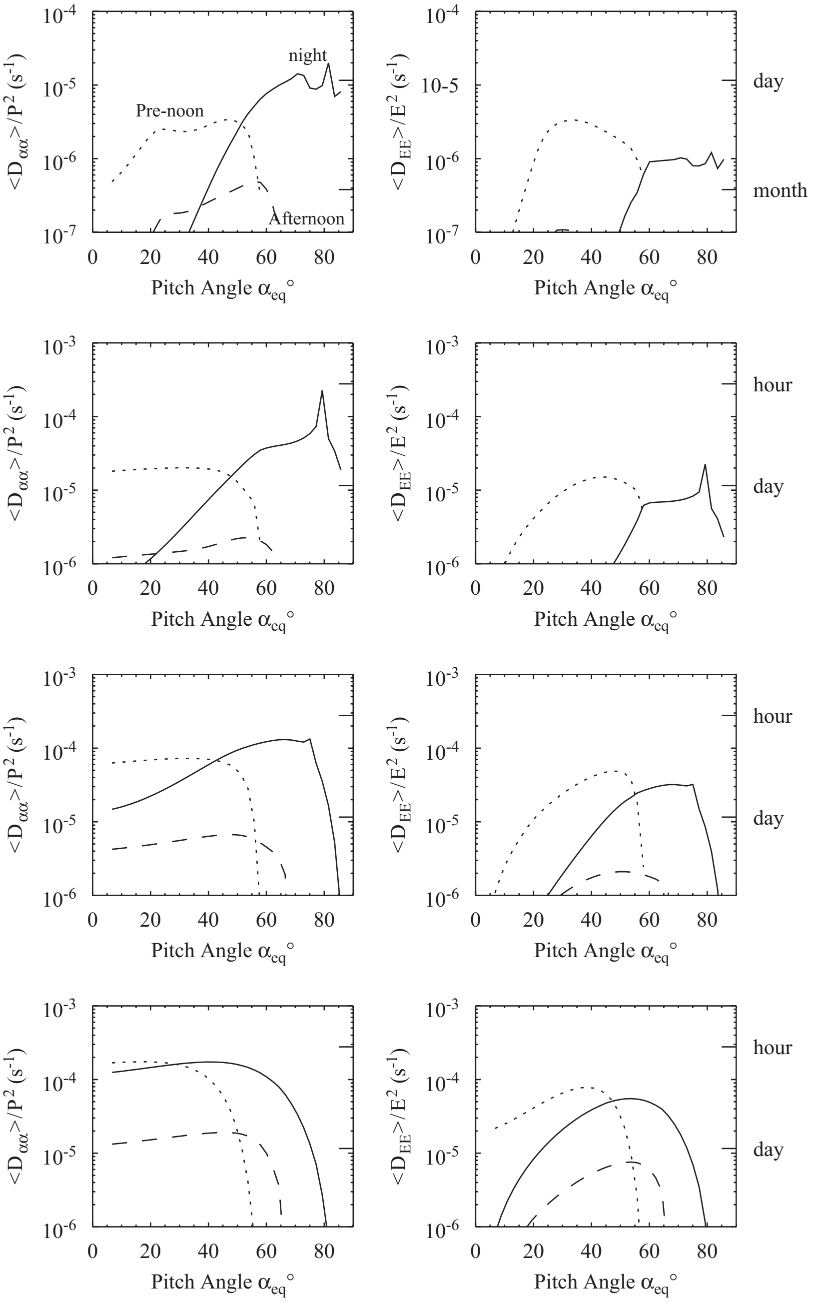

Fig. 5. Pitch-angle and energy diffusion coefficients (left and right columns, respectively) driven by chorus in the night (solid), pre-noon (dotted), and afternoon (dashed lines) sectors, respectively. From top to bottom, rows correspond to 1 MeV, 300, 100, and 30 keV energies, respectively (reproduced/modified from Horne et al., 2005b, Fig. 6, by permission of the American Geophysical Union).

Blake, 1997; Green and Kivelson , 2004; Chen et al., 2005; Iles et al., 2006).

The idea that newly injected plasmasheet electrons (with energies above a few hundred keV) (Baker et al., 1998; Obara et al., 2000) could be accelerated to relativistic energies on appropriate timescales is well supported theoretically (Horne and Thorne, 1998, 2003; Summers et al., 1998, Horne et al., 2005b). Fig. 5 (reproduced from Horne et al., 2005b, Fig. 6, with permission of the American Geophysical Union) shows the bounce and drift averaged pitch-angle diffusion coefficient ($D_{\alpha\alpha}$, left column) and energy diffusion coefficient (D_{EE}, right column), calculated at a number of energies (from top to bottom: 1 MeV, 300, 100, and 30 keV), with explicit contributions from night, pre-noon, and afternoon chorus characteristics (solid, dotted, and dashed lines, respectively). The time-scale for electron loss due to pitch-angle diffusion can be roughly approximated as the inverse of the diffusion coefficient value near the loss-cone (Shprits et al., 2006b), while that for acceleration is roughly estimated as the inverse of the maximum value of the energy diffusion coefficient.

As shown in Fig. 5, the key factor is that there is a competition between acceleration and loss due to chorus. At 30 keV the loss timescale is ~2 h (acceleration ~3.5 h) indicating that particles are lost faster than they are energized. At 300 keV, the loss and acceleration timescales are roughly comparable at ~14 h, but at 1 MeV the acceleration timescale becomes much shorter (~3.9 days) than the loss timescale (~23 days), indicating that particles are energized faster than they are lost (Horne et al., 2005b). Since lower energy (30 keV) particles lose energy to the chorus wave as they diffuse to lower pitch-angles (resulting in wave growth), and higher energy particles (1 MeV) are preferentially accelerated by the wave, the above analysis suggests an energy transfer from the lower energy particles which give up energy, and are responsible for wave generation, through the chorus wave, and to the higher energy particles which are ultimately accelerated by the wave (Horne et al., 2005b). Recent observations tend to confirm that there is an "anchor point" in evolving flux measurements during active periods, above which fluxes increase and below which they decrease (Summers et al., 2002). This anchor point is at ~460 keV, in agreement with theoretical estimates (Summers et al., 2002; Horne et al., 2005b).

4. Summary and conclusions

This paper presented a brief review of the major characteristics of whistler-mode chorus waves together with a selection of recent findings about chorus propagation, and source characteristics. The dual role of chorus as a loss and source mechanism was then discussed, showing how in the main phase of intense storms, chorus can act as a very effective loss process for radiation belt electrons, giving timescales which are on the order of a day and are comparable to loss rates expected from other leading loss mechanisms such as plasmaspheric hiss and EMIC waves. We have presented a detailed calculation showing the expected precipitation signature of energetic electrons due to a single chorus element, which was in close agreement with signatures of >1 MeV relativistic electron microbursts observed on SAMPEX.

During the recovery phase of storms, chorus waves tend to act as a source mechanism, energizing a seed population of electrons with energies of a few hundred keV to relativistic energies on timescales of a few days. In fact, an "anchor point" has been found (both theoretically and experimentally) at a few 100 keV above which chorus tends to preferentially accelerate electrons, and below which chorus tends to precipitate electrons. Since electrons that are precipitated tend to lose energy (which is absorbed by the wave and results in wave growth), chorus may act as a mediating agent—absorbing a small fraction of power from the low-energy electrons (30 keV), resulting in wave growth and propagation, and ultimately being transferred to the acceleration of high energy electrons. This process is especially effective when a relatively continuous source of ~30 keV electrons can be maintained to produce chorus for the several-day period required to accelerate electrons to relativistic energies. This suggests that prolonged periods of enhanced convection are a requirement for effective acceleration.

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