Favored regions for chorus-driven electron acceleration to relativistic energies in the Earth’s outer radiation belt

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1. Introduction

[1] Pitch angle and energy diffusion rates for scattering by whistler-mode chorus waves are proportional to the wave magnetic field intensity and are strongly dependent on the frequency distribution of the waves and to the ratio between the electron plasma frequency ($f_{pe}$) and the electron gyrofrequency ($f_{ce}$). Relativistic electrons interact most readily with lower-band chorus (0.1 < $f_{pe}$/$f_{ce}$ < 0.5) and energy diffusion leading to local acceleration to relativistic energies is most effective in regions of low $f_{pe}$/$f_{ce}$ and enhanced lower-band chorus activity occurring over a wide range of geospace during active conditions ($AE > 300$ nT). Enhanced waves in these regions could play a major role in electron acceleration to relativistic energies during periods of prolonged substorm activity.


[2] The flux of relativistic electrons ($E > 1$ MeV) in the Earth’s outer radiation belt (3 < $L$ < 7) is highly variable during enhanced magnetic activity [e.g., Meredith et al., 2003a]. Approximately 50% of all moderate and intense storms increase the relativistic electron fluxes by more than a factor of two, whereas approximately 25% decrease the fluxes by more than a factor of two [Reeves et al., 2003]. This variability is caused by an imbalance between acceleration and loss processes, both of which are enhanced during magnetically disturbed periods. Understanding this variability is important because enhanced fluxes of relativistic electrons constitute a potentially serious hazard to Earth-orbiting satellites and may pose a risk to humans in space.

[3] Studies have shown that enhancements of the relativistic electron flux are caused by acceleration processes within the magnetosphere itself [Li et al., 1997], although the exact nature of these processes remains to be determined [Li and Temerin, 2001; Horne, 2002; Friedel et al., 2002]. Radial diffusion, which violates the third adiabatic invariant, is an important inward radial transport and energization mechanism in the magnetosphere [e.g., Schulz and Lanzerotti, 1974], but local peaks in the phase space density observed near $L = 4$ during relativistic electron flux enhancements [Brautigam and Albert, 2000; Miyoshi et al., 2003] are inconsistent with mechanisms that only violate the third invariant. This suggests the need for an additional, local acceleration source that violates the first two invariants.

[4] Enhanced storm-time convection electric fields provide a seed population of outer radiation belt electrons with energies up to a few hundred keV [Obara et al., 2000]. Resonant wave-particle interactions with whistler-mode chorus can then provide a potential mechanism for accelerating this seed population to relativistic energies [e.g., Horne and Thorne, 1998; Summers et al., 1998]. Several studies have reported an association between relativistic electron flux enhancements and prolonged periods of enhanced chorus amplitudes lasting for the order of several days [Meredith et al., 2002a, 2003a; Miyoshi et al., 2003]. Further evidence in support of this mechanism has come from the energy-dependence of the spectral hardening [Meredith et al., 2002b; Summers et al., 2002] and the energy-dependent flat-topped pitch angle distributions [Horne et al., 2003a] observed during the recovery phase of the October 9, 1990 magnetic storm. O’Brien et al. [2003] have used the occurrence of MeV electron microbursts as a proxy for VLF chorus to infer that electron flux peaks observed at L ~ 4.5 may be caused by local chorus-driven acceleration whereas ULF waves could be more effective at higher L, near geosynchronous orbit and beyond.
The average lower-band chorus intensities and average values of \( f_{pel}/f_{ce} \) in the equatorial region \((-15^\circ < \lambda_m < 15^\circ)\) are shown as a function of \( L \), MLT and substorm activity in Figure 1. During quiet conditions \((AE < 100 \text{ nT})\) outside \( L = 3 \) the wave intensities are low, generally less than 100 pT\(^2\), and \( f_{pel}/f_{ce} \) is high, especially on the night side where \( f_{pel}/f_{ce} \) is typically of the order of 10. Larger wave intensities and smaller values of \( f_{pel}/f_{ce} \) occur during moderately disturbed conditions \((100 < AE < 300 \text{ nT})\), mainly in the region \( L > 4 \) between 0000 and 0800 MLT. The largest wave intensities and the smallest values of \( f_{pel}/f_{ce} \) are seen during active conditions \((AE > 300 \text{ nT})\) in the region \( L > 3 \) between 2100 and 1300 MLT. The most favorable conditions for electron acceleration to relativistic energies occur during active conditions in the region \( 4 < L < 6 \) between 0300 and 1000 MLT where \((B_w^2) = 1630 \pm 150 \text{ pT}^2\) and \( f_{pel}/f_{ce} \) lies in the range 2.8–7.3 with an average value of 3.9 ± 0.1.

Low values of \( f_{pel}/f_{ce} \) are also seen in the equatorial region over all MLT inside \( L = 3 \), irrespective of the level of substorm activity. This region tends to lie inside of the plasmapause. Substorm-independent emissions have been reported in this region and attributed to lightning and VLF transmitters [Meredith et al., 2001]. These waves could thus contribute to electron loss and acceleration in this region [Johnson et al., 1999; Roger and Clilverd, 2002], although the intensities are much smaller than the substorm-dependent intensities observed outside of the plasmapause.

### 3. Variation With L and Magnetic Local Time

#### 3.1. Equatorial Region

The average lower-band chorus intensities and average values of \( f_{pel}/f_{ce} \) in the mid-latitude region \((15 < |\lambda_m| < 30^\circ)\) are shown as a function of \( L \), MLT and substorm activity in Figure 2. Outside of the plasmapause, both the waves and \( f_{pel}/f_{ce} \) are substorm-dependent, with the highest wave intensities and the lowest values of \( f_{pel}/f_{ce} \) being seen during active conditions. The most favorable conditions for electron acceleration to relativistic energies occur during active conditions in the region \( 4 < L < 6 \) between 0600 and 1400 MLT where \((B_w^2) = 1210 \pm 80 \text{ pT}^2\) and \( f_{pel}/f_{ce} \) lies in the range 1.7–7.1 with an average value of 3.6 ± 0.1.

#### 3.2. Mid-Latitude Region

The average lower-band chorus intensities and average values of \( f_{pel}/f_{ce} \) in the mid-latitude region \((15 < |\lambda_m| < 30^\circ)\) are shown as a function of \( L \), MLT and substorm activity in Figure 2. Outside of the plasmapause, both the waves and \( f_{pel}/f_{ce} \) are substorm-dependent, with the highest wave intensities and the lowest values of \( f_{pel}/f_{ce} \) being seen during active conditions. The most favorable conditions for electron acceleration to relativistic energies occur during active conditions in the region \( 4 < L < 6 \) between 0600 and 1400 MLT where \((B_w^2) = 1210 \pm 80 \text{ pT}^2\) and \( f_{pel}/f_{ce} \) lies in the range 1.7–7.1 with an average value of 3.6 ± 0.1.

### 4. Variation With L and Magnetic Latitude

The average lower-band chorus intensities and average values of \( f_{pel}/f_{ce} \) for active conditions are plotted as a function of the radial distance from the center of the Earth projected onto the plane of the magnetic equator, \( x \), and GSM \( z \), for three different local time sectors in Figure 3. Dipole field lines and lines of constant magnetic latitude are included on the plot to help visualise the behaviour of these parameters as a function of \( L \) and \( \lambda_m \). The left hand panels...
5. Discussion

[11] Electron acceleration to relativistic energies driven by whistler-mode chorus is likely to be most effective in regions where enhanced lower-band chorus coincides with regions of low $f_{pe}/f_{ce}$. These two conditions are best satisfied outside of the plasmapause during active conditions from 2100 MLT through dawn to 1500 MLT. In the equatorial region high wave intensities and low values of $f_{pe}/f_{ce}$ are seen predominantly in the region from 2100 to 1300 MLT, with the most favored region being from $4 < L < 6$ between 0300 and 1000 MLT.

[12] The enhancement of lower-band chorus waves in regions of relatively low $f_{pe}/f_{ce}$ require cyclotron resonant energies in the range of 10–100 keV near the loss cone [e.g., Meredith et al., 2002b; Horne and Thorne, 2003]. The source of free energy for wave growth can be provided by the energy loss of such particles during diffusion into the loss cone. But, for a quasi-isotropic electron pitch angle distribution, the same frequency waves can also interact with higher energy electrons (hundreds of keV to several MeV) at larger pitch angles and cause acceleration [e.g., Albert, 2002; Meredith et al., 2002b]. Indeed, diffusion calculations suggest that significant acceleration to relativistic energies by whistler-mode chorus could occur in these regions on a timescale of $\sim$1 day [Horne et al., 2003b].

[13] Electromagnetic ion cyclotron (EMIC) waves also interact with relativistic electrons resulting in pitch angle scattering and subsequent electron loss at MeV energies [Thorne and Kennel, 1971; Summers and Thorne, 2003; Albert, 2003]. Electron minimum resonant energies may fall below 2 MeV during magnetic storms for wave frequencies just below the hydrogen or helium ion gyrofrequencies in localised regions where $f_{pe}/f_{ce}$ is greater than 10. During active conditions the equatorial ratio of $f_{pe}/f_{ce}$ is greater than 10 on the dusk-side, primarily in the region $L > 4.5$ between 1400 and 1900 MLT comparable with the region where these lower energy ($E < 2$ MeV) events have been observed [Meredith et al., 2003b]. Any relativistic electron acceleration signatures must also overcome any losses caused by these EMIC waves.

6. Conclusions

[14] We have used CRRES wave data to study the combined behaviour of the lower-band chorus magnetic field intensities together with the ratio $f_{pe}/f_{ce}$ to quantify the behaviour of these parameters as a function of spatial

![Figure 2](image-url)  
**Figure 2.** Substorm-dependence of the average value of the mid-latitude ratio $f_{pe}/f_{ce}$ (lower panels) and the average mid-latitude lower-band chorus magnetic field intensities (upper panels) as a function of $L$, MLT. The color scale bars are as shown in Figure 1.

![Figure 3](image-url)  
**Figure 3.** The ratio $f_{pe}/f_{ce}$ (lower panels) and the lower-band chorus magnetic field intensities (upper panels) for three different local time sectors during active conditions as a function of $x$ and $z$ (see text). The color scale bars are again as shown in Figure 1.
location and substorm activity and to determine the most important regions for electron acceleration to relativistic energies. The key results of our statistical survey are:

1. In the equatorial region the most favorable conditions occur during active conditions in the region $4 < L < 6$ between 0300 and 1000 MLT where $f_{pe}/f_{ce}$ lies in the range 2.8–7.3 with an average value of 3.9 ± 0.1.

2. In the mid-latitude region the most favorable conditions occur during active conditions in the region $4 < L < 6$ between 0600 and 1400 MLT where $f_{pe}/f_{ce}$ lies in the range 1.7–7.1 with an average value of 3.6 ± 0.1.

17. Resonant wave-particle interactions involving enhanced lower-band chorus waves in these regions may contribute significantly to the energization of a seed population of electrons with energies of a few hundred keV to relativistic energies during enhanced magnetic activity. Such interactions are likely to contribute to the reformation of the relativistic outer zone population following prolonged substorm activity lasting for the order of several days.

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**References**


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