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Intense duskside lower band chorus waves observed by Van Allen Probes: Generation and potential acceleration effect on radiation belt electrons

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Key Points:
- A rarely-reported intense duskside chorus event recorded by Van Allen Probes
- Generation of duskside chorus by substorm-injected suprathermal electrons
- Strong acceleration effect of duskside chorus on radiation belt electrons

Abstract
Local acceleration driven by whistler mode chorus waves largely accounts for the enhancement of radiation belt relativistic electron fluxes, whose favored region is usually considered to be the plasmapause with magnetic local time approximately from midnight through dawn to noon. On 2 October 2013, the Van Allen Probes recorded a rarely reported event of intense duskside lower band chorus waves (with power spectral density up to $10^{-4}$ nT$^2$/Hz) in the low-latitude region outside of $L = 5$. Such chorus waves are found to be generated by the substorm-injected anisotropic suprathermal electrons and have a potentially strong acceleration effect on the radiation belt energetic electrons. This event study demonstrates the possibility of broader spatial regions with effective electron acceleration by chorus waves than previously expected. For such intense duskside chorus waves, the occurrence probability, the preferential excitation conditions, the time duration, and the accurate contribution to the long-term evolution of radiation belt electron fluxes may need further investigations in future.

1. Introduction
Whistler mode chorus waves have attracted considerable attentions due to their important role in the acceleration of radiation belt electrons [e.g., Horne and Thorne, 1998; Summers et al., 1998], which can significantly harm satellites in the magnetosphere [Baker, 2002]. Chorus emissions typically occur in the frequency range $0.05-0.80 f_{ce}$ ($f_{ce}$ denoting electron gyrofrequency) and split into lower and upper bands (with a gap around $0.5 f_{ce}$) [e.g., Tsurutani and Smith, 1974; Santolik et al., 2003]. These waves are generally believed to be excited near the magnetic equator [e.g., LeDuc et al., 1998] through the cyclotron resonance with anisotropic suprathermal (from a few keV to tens of keV) electrons [e.g., Kennel and Petschek, 1966; Nunn et al., 1997; Omura et al., 2008; Li et al., 2009b].

The global distribution of chorus waves has been statistically analyzed based on the observations of Combined Release and Radiation Effects Satellite (CRRES) [Meredith et al., 2001; Horne et al., 2005], Time History of Events and Macroscale Interactions during Substorms (THEMIS) [Li et al., 2009a], and other satellites [e.g., Meredith et al., 2012; Agapitov et al., 2013]. Their analyses clearly demonstrated the significant dependence of chorus wave intensity on substorm activity $AE$, magnetic shell $L$, magnetic latitude $\lambda$, and magnetic local time $\text{MLT}$. Following strong substorm activity ($AE > 300$ nT), the lower band chorus waves usually have relatively large amplitudes ($B_z = 50-100$ pT) in the nighttime ($\text{MLT}=22-06$) low latitude ($\lambda < 15^\circ$) and the
Figure 1. Overview of the intense duskside chorus event recorded by the RBSP-B satellite on 2 October 2013: (a) magnetic power spectral density $B^2$ in the frequency range of 0.1 to 5.0 kHz; (b–e) pitch angle-dependent electron differential fluxes $j$ at energies $E_k = 8.26, 26.01, 31.90, \text{ and } 54.40 \mathrm{keV}$; (f) magnetic field magnitude $B$ and $y$ component electric field $E_y$ in the modified GSE coordinate system. The wave spectral density and electron phase space density are analyzed at 05:12:18 UT (vertical dashed line) in detail.

These regions, with a small ratio (~3.5–4.0) between the electron plasma frequency $f_{pe}$ and the electron gyrofrequency $f_{ce}$, have been widely accepted as the favored regions for the chorus-driven local acceleration of radiation belt electrons [Meredith et al., 2003; Summers et al., 2007; Thorne, 2010]. Therefore, such nightside and dayside chorus waves are normally included in kinetic radiation belt models [e.g., Li et al., 2007; Varotsou et al., 2008; Albert et al., 2009; Shprits et al., 2009; Su et al., 2010]. However, the possibility of strong chorus-driven electron acceleration in other spatial regions has not been evaluated definitively. Strong chorus-driven acceleration over broader spatial regions would produce more significant and rapid enhancement in the radiation belt electron fluxes.
In this letter, we report an event of intense duskside lower band chorus waves observed by the Van Allen Radiation Belt Storm Probes (RBSP) [Mauk et al., 2013] on 2 October 2013 and further analyze their generation process and potential acceleration effect on radiation belt electrons.

2. Observations and Simulations

2.1. Event Overview

Figure 1 gives an overview of this intense duskside chorus event recorded by the RBSP-B satellite on 2 October 2013. The wave magnetic power spectral distribution in the frequency range of 0.1 to 5.0 kHz was observed by the Electric and Magnetic Field Instrument and Integrated Science (EMFISIS) Waves instrument [Kletzing et al., 2013]; the suprathermal electron pitch angle distribution was collected by the Helium Oxygen Proton Electron (HOPE) [Funsten et al., 2013] and Magnetic Electron Ion Spectrometer (MagEIS) [Blake et al., 2013] instruments of the Energetic Particle, Composition, and Thermal Plasma (ECT) suite [Spence et al., 2013]; the magnetic field and electric field were detected by the EMFISIS Magnetometer and Electric Fields and Waves (EFW) [Wygant et al., 2013] instruments. During the time range from 04:50 UT to 06:00 UT, the RBSP-B satellite was located around the duskside low-latitude region outside of $L = 5$. After 05:00 UT, intense chorus waves (with power spectral density up to $10^{-3} \text{nT}^2/\text{Hz}$) can be clearly identified in the lower band ($0.1\text{–}0.5 f_{ce}$). Around 05:00 UT, the electron fluxes at different energies showed simultaneous enhancements by several orders of magnitude, accompanied by a stepped variation in magnetic field, indicating the occurrence of a substorm injection [McIlwain, 1974]. Such large fluxes of anisotropic suprathermal electrons can be expected to account for the generation of intense chorus waves in the duskside, similar to the situation in the nightside [e.g., Li et al., 2009b]. The short-timescale (several minutes) variation of electron pitch angle distribution, particularly at high energies ($E_e \geq 31 \text{ keV}$), was produced by the modulation of ULF wave-associated electric fields [e.g., Zong et al., 2009]. The long-timescale (tens minutes to hours) decay of electron differential fluxes was primarily caused by the drift of the newly injected population.

2.2. Wave Generation

The generation process of chorus waves contains two stages: initial linear growth and subsequent non-linear growth [e.g., Nunn et al., 1997; Omura et al., 2008]. Here we primarily analyze the linear growth of parallel-propagating chorus waves at a selected time 05:12:18 UT using the Waves in Homogeneous Anisotropic Magnetized Plasma (WHAMP) code [Ronnmark, 1982].

At this time (as indicated by the vertical line in Figure 1), the chorus is relatively strong. Correspondingly, the observed magnetic power spectral densities (circles) and the modeled Gauss-type frequency distribution (line) are plotted in Figure 2. The modeled distribution agrees well with the observed one, with an amplitude $B_0 = 0.552 \text{nT}$, a central frequency $f_m = 0.165 f_{ce}$, a half width $\Delta f = 0.030 f_{ce}$, a lower limit $f_1 = 0.050 f_{ce}$, and an upper limit $f_2 = 0.500 f_{ce}$.

Figure 3a shows the observed (circles) and modeled (lines) pitch angle-dependent electron phase space density (PSD) at the selected time. The modeled PSD has the form

$$F(v_\perp, v_\parallel) = \sum_{i=1}^{N} F_i$$

(1)
Figure 3. (a) Observed (circles) and modeled (lines) electron phase space densities \( F \) as functions of pitch angle \( \alpha \) at selected energies; (b) Wave linear growth rates \( \gamma \) as functions of angular frequency \( \omega \) with different \( f_{pe}/f_{ce} \) values for modeled electron phase space distribution.

\[
F_i = \frac{n_i}{\sqrt{\pi} V_{thi}} \exp \left[ -\left( \frac{v_{\perp i}}{V_{thi}} - V_{dr_i} \right)^2 \right] \\
\times \left\{ \frac{\Delta_i}{\alpha_{\perp i}} \exp \left( -\frac{v_{\perp i}^2}{\alpha_{\perp i} V_{thi}^2} \right) + \frac{1 - \Delta_i}{\alpha_{\parallel i} - \alpha_{\perp i}} \right\} \left[ \exp \left( -\frac{v_{\perp i}^2}{\alpha_{\perp i} V_{thi}^2} \right) - \exp \left( -\frac{v_{\perp i}^2}{\alpha_{\parallel i} V_{thi}^2} \right) \right],
\]

(2)

where \( N \) is the number of plasma components; \( n_i, V_{thi} = \sqrt{2T_i/m_i} \), and \( V_{dr_i} \) are the density, thermal velocity, and field-aligned normalized drift velocity for \( i \)th plasma component, respectively; \( \alpha_{\perp i}, \alpha_{\parallel i}, \) and \( \Delta_i \) control the temperature anisotropy as well as the size and depth of loss-cone for \( i \)th plasma component. Adopting those parameters listed in Table 1 leads to reasonable agreement between the modeled and observed distributions over a wide energy range 0.015–101.6 keV.

Figure 3b presents the obtained linear growth rate \( \gamma \) for the modeled PSD with five different values of \( f_{pe}/f_{ce} \). The black line corresponds to \( f_{pe}/f_{ce} = 7.1 \) (comparable to the previous statistical results [Meredith et al., 2003; Li et al., 2009a]), with the total electron density \( n = \sum_{i=1}^{6} n_i = 9.55 \times 10^6 \) m\(^{-3}\) determined through the PSD-fitting process and the background magnetic field \( B = 140 \) nT observed by the EMFISIS instrument (see Figure 1f). Note that the real-time measurement of upper hybrid frequency [Kletzing et al., 2013] gives the generally consistent value of \( f_{pe}/f_{ce} \). The other colored lines correspond to four decreased or increased values of \( f_{pe}/f_{ce} \) (with respect to the reference value 7.1). The peak growth rate is found to increase rapidly with \( f_{pe}/f_{ce} \) increasing. For all values of \( f_{pe}/f_{ce} \), the peak frequency and frequency coverage of positive growth rates are roughly consistent with those of observed chorus spectra (see Figure 2), suggesting that the substorm-injected anisotropic suprathermal electrons can produce intense chorus waves in the duskside region via cyclotron resonance.

<table>
<thead>
<tr>
<th>Component</th>
<th>( n_i(\text{m}^{-3}) )</th>
<th>( T_i(\text{keV}) )</th>
<th>( \Delta_i )</th>
<th>( \alpha_{\perp i} )</th>
<th>( \alpha_{\parallel i} )</th>
<th>( V_{dr_i} )</th>
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<tr>
<td>1</td>
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<td>1.00</td>
<td>1.00</td>
<td>0.50</td>
<td>0</td>
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<td>0.0239</td>
<td>0.70</td>
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<td>0</td>
</tr>
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<td>0.0682</td>
<td>0.90</td>
<td>1.04</td>
<td>0.94</td>
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</tr>
<tr>
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<td>0.7278</td>
<td>0.90</td>
<td>1.13</td>
<td>0.11</td>
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<tr>
<td>5</td>
<td>( 5.0 \times 10^5 )</td>
<td>1.9219</td>
<td>0.65</td>
<td>1.33</td>
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<tr>
<td>6</td>
<td>( 5.5 \times 10^5 )</td>
<td>5.2812</td>
<td>0.90</td>
<td>1.25</td>
<td>0.12</td>
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</table>
2.3. Wave Acceleration Effect

In order to objectively evaluate the chorus-driven acceleration effect, we display the duskside chorus wave observations of both RBSP twin satellites in Figure 4. Obviously, these duskside chorus waves can be detected over a relatively wide spatiotemporal region. Note that the RBSP-A satellite was located in the plasmasphere during 0500–0525 UT, forbidding the occurrence of chorus waves. The wave spectral distributions averaged over half an hour are further modeled by two Gauss-type functions for the calculation of quasi-linear bounce-averaged diffusion coefficients. The detailed calculations are implemented by the storm-time evolution of electron radiation belt (STEERB) code [Xiao et al., 2009; Su et al., 2010] at $L = 5.6$ in a dipole-like background magnetic field with the equatorial magnetic field $B = 140$ nT (see Figure 1).

For ease of comparison, Figure 5 illustrates the diffusion coefficients for three wave models: (1) duskside chorus observed by RBSP-B (see Figure 4c) with equatorial $f_{pe}/f_{ce} = 7.1$, $B_t = 0.195$ nT, $f_m = 0.205$ $f_{ce}$.
Figure 5. Quasi-linear bounce-averaged (a, c) pitch angle and (b, d) momentum diffusion rates of radiation belt electrons at different energies for duskside (solid lines, Figures 5a and 5b for RBSP-B and Figures 5c and 5d for RBSP-A) and nightside (dashed lines) chorus waves.

Δf = 0.059 f_ce, f_1 = 0.050 f_ce and f_2 = 0.500 f_ce; (2) duskside chorus observed by RBSP-A (see Figure 4d) with equatorial f_pe/f_ce = 7.1, B_t = 0.064 nT, f_m = 0.393 f_ce, Δf = 0.061 f_ce, f_1 = 0.050 f_ce, and f_2 = 0.500 f_ce; (3) typical nightside chorus [Horne et al., 2005] with equatorial f_pe/f_ce = 3.8, B_t = 50 pT, f_m = 0.350 f_ce, Δf = 0.150 f_ce, f_1 = 0.050 f_ce, and f_2 = 0.650 f_ce. All the three types of waves are assumed to spread in the low-latitude region |λ| < 15° with the same Gauss-type normal-angle distribution [Horne et al., 2005].

Although the three models have quite different f_pe/f_ce and/or spectral distribution, the corresponding diffusion coefficients indeed show similar behaviors. All the diffusion coefficients maximize for equatorial pitch angles α_eq > 60°, indicating that the energetic electrons would be trapped in the magnetosphere and undergo significant momentum diffusion. According to the quasi-linear theory, the diffusion coefficients are proportional to the square of wave amplitude B_t. Compared to the nightside chorus waves, the duskside chorus waves observed by RBSP-B, with about 4 times larger amplitude, have approximately 15 times larger pitch angle diffusion coefficients but 4 times larger momentum diffusion coefficients in the range α_eq > 60°. Such relatively limited enhancement in momentum diffusion can be explained by the increase of f_pe/f_ce (unconducive to the acceleration of energetic electrons [Summers et al., 1998; Horne et al., 2005]). In contrast, the duskside chorus waves observed by RBSP-A with a relatively small amplitude possess the much smaller diffusion coefficients in both pitch angle and momentum. These results suggest that the duskside lower band chorus waves with large amplitudes would contribute significantly to the acceleration of radiation belt electrons even in the high f_pe/f_ce region.

3. Conclusions and Discussions

Favored regions for chorus-driven acceleration of radiation belt electrons are usually considered to be the plasmatrough regions with magnetic local time approximately from midnight through dawn to noon. Here we analyze a rarely reported event of intense duskside lower band chorus waves (with power spectral density up to 10^{-3}nT^2/Hz) observed by the twin RBSP satellites on 2 October 2013 and clearly demonstrate the possibility of broader spatial regions with effective acceleration by chorus waves than previously expected.

During this event, the substorm injection caused several orders of magnitude enhancement in the suprathermal electron fluxes near the equatorial regions (λ < 15°) outside of L = 5. We develop a data-based analytical model for the distribution of newly injected suprathermal electrons over a wide energy range 0.015–101.6 keV and then calculate the linear growth rate of parallel-propagating chorus waves.
waves using the WHAMP code. The obtained peak frequency and frequency range of positive growth rate are found to agree well with those of observed chorus spectra, suggesting that the intense duskside chorus waves can be excited by the substorm-injected anisotropic suprathermal electrons through cyclotron resonance. Future statistical works are required to systematically identify the preferential conditions for the excitation of such strong duskside chorus waves.

Wave-particle interactions strongly depend on the background ratio $f_{pe}/f_{ce}$, wave intensity, and frequency distribution. The chorus-driven acceleration effect at high energies may be reduced by the high $f_{pe}/f_{ce}$ but promoted by the low central frequency and large wave amplitude. We construct two data-based duskside chorus wave models and compute the corresponding quasi-linear bounce-averaged diffusion coefficients of radiation belt energetic electrons using the STEERB code. The obtained diffusion coefficients of the two models maximize for large equatorial pitch angles $\alpha_{eq} > 60^\circ$, similar to those of typical nightside chorus waves. The duskside chorus waves observed by RBSP-B have a large amplitude ($\beta_e = 0.195$ nT), and their peak momentum diffusion rates are ~4 times larger than those of typical nightside chorus. In contrast, the duskside chorus waves observed by RBSP-A have a small amplitude ($\beta_e = 0.064$ nT), and their peak momentum diffusion rates are nearly one fifth of those of typical nightside chorus waves. These results indicate that the lower band chorus waves with a relatively large amplitude may yield a potentially strong acceleration effect on the radiation belt energetic electrons, even in the duskside high $f_{pe}/f_{ce}$ region. It should be mentioned that the wave amplitudes here are obtained through the averaging process over a relatively short timescale (half an hour) for a specific event. Future research should be targeted at determining the occurrence probability of such intense duskside chorus waves and their accurate contribution to the long-term evolution of radiation belt electron fluxes.

In this study, the adopted duskside value of $f_{pe}/f_{ce} = 7.1$ is generally consistent with that derived from the real-time measurements of upper hybrid frequency [Kletzing et al., 2013] and magnetic field. A smaller value of $f_{pe}/f_{ce} = 5.8$ can be obtained at $L = 5.6$ based on a dipole magnetic field model and the density model of Sheeley et al. [2001], leading to the larger diffusion coefficients of the duskside chorus. The diffusion coefficients of “typical” nightside chorus waves provide a reference standard to qualitatively evaluate the acceleration effect of duskside chorus waves. The adopted spectral parameters for the nightside chorus waves are simply extracted from the previous statistical model of Horne et al. [2005] (rather than the real-time observations). Recently, some new chorus wave models depending on the geomagnetic activities have been developed [e.g., Li et al., 2011; Meredith et al., 2012; Agapitov et al., 2013; Spasojevic and Shraper, 2014]. These models could give the nightside chorus waves with larger amplitude than that of Horne et al. [2005], and consequently the corresponding diffusion coefficients would exceed those of the duskside chorus observed by RBSP-B in this event.

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The data for this paper are available at the following RBSP websites: EMFISIS, http://emfisis.physics.uwu.edu/Flight/, http://rspb-b.WFR-spectral-matrix_emfisis-L2_20131002_v1.3.5.cdf, http://rspb-a.WFR-spectral-matrix_emfisis-L2_20131002_v1.3.6.cdf, http://rspb-b.magnetometer_uvw_emfisis-L2_20131002_v1.3.1.cdf, and http://rspb-a.magnetometer_uvw_emfisis-L2_20131002_v1.3.1.cdf, ECT, http://www.rbsp-ect.lanl.gov/data_pub/, http://rspb_a_relo2_ect-hope-PA-L3_20131002_v4.0.0cdf, and http://rspb_b_relo2_ect-mageis-merged-L3_20131002_v3.0.0.cdf; EFW, http://rspb.space.umn.edu/data/rbsp/, http://rspb_b-efw-l2.esyv_despun_20131002_v01.cdf. We acknowledge K. Ronnmark for the using of WHAMP code. This work was supported by the Natural National Science Foundation of China grants 41274169, 41274174, 41174125, 41131065, 41210103, 41074120, 41230166, and 4130434, the Chinese Academy of Sciences grants KZCX2-EW-QN510 and KZDD-EW-01-04, the National Key Basic Research Special Foundation of China grant 2011CB111403, the Strategic Priority Research Program on Space Science of the Chinese Academy of Sciences grant XDA04060201, and the Fundamental Research Funds for the Central Universities WK2080000301. This work was also supported from JHU/APL contracts 921647 and 967399 under NASA Prime contract NAS5-01072.

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