

The principal role of chorus ducting for night-side relativistic electron precipitation

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Key Points:

- We present observations of night-side relativistic electron precipitation induced by whistler-mode waves
- We perform a comparison of observations with simulation results for different wave propagation regimes
- We show that only ducted whistler-mode waves can effectively scatter relativistic electrons on the night-side

Abstract

Night-side chorus waves are often observed during plasma sheet injections, typically confined around the equator and thus potentially responsible for precipitation of $\lesssim 100\text{keV}$ electrons. However, recent low-altitude observations have revealed the critical role of chorus waves in scattering relativistic electrons on the night-side. This study presents a night-side relativistic electron precipitation event induced by chorus waves at the strong diffusion regime, as observed by the ELFIN CubeSats. Through event-based modeling of wave propagation under ducted or unducted regimes, we show that a density duct is essential for guiding chorus waves to high latitudes with minimal damping, thus enabling the strong night-side relativistic electron precipitation. These findings underline both the existence and the important role of density ducts in facilitating night-side relativistic electron precipitation.

Plain Language Summary

Chorus waves, an important mode of electromagnetic waves in Earth's magnetosphere, play a vital role in scattering energetic electrons (electron precipitation) in the radiation belts. It has been shown in observations that night-side chorus waves usually remain confined near their equatorial source and thus do not significantly affect relativistic electron precipitation. However, recent observations challenge this notion, suggesting a viable connection between the night-side relativistic electron precipitation and chorus waves. In this work, we present an event observed on the ELFIN CubeSats that reveals intense relativistic electron precipitation on the night-side, where the ratio between precipitation and trapped fluxes reaches the theoretical maximum of 1. To investigate the physical mechanism responsible for this event, we used numerical modeling to simulate scenarios with and without a density-enhancement duct along magnetic field lines. Our results show that such ducts can efficiently trap chorus waves and guide them to high latitudes without significant damping where they can efficiently interact with the relativistic electrons. By comparing the precipitation intensity in ducted and unducted cases, we affirm the crucial role of density ducts in driving strong night-side relativistic electron precipitation.

44 1 Introduction

45 Electromagnetic whistler-mode waves, specifically the most intense population – chorus waves, play a
 46 dual role in radiation belt dynamics, where their resonant interaction with energetic electrons are
 47 responsible for both electron acceleration and losses to the Earth’s atmosphere (e.g., Bortnik & Thorne,
 48 2007; Thorne et al., 2021, and references therein). One of the main drivers of chorus wave generation is
 49 plasma sheet electron injections in the night-side magnetosphere (e.g., Tao et al., 2011; Fu et al., 2014).
 50 These injections bring in transversely anisotropic electrons, which then drift dawnward to the dayside.
 51 Along this drift path, electrons can generate chorus waves, but the exact wave properties depend on the
 52 local plasma conditions and magnetic field configuration (see reviews by Katoh & Omura, 2016; Tao et
 53 al., 2020; Omura, 2021; Kong et al., 2023, and references therein). It has been shown in observations via
 54 many spacecraft (e.g. THEMIS, CRRES, Cluster, Dynamic Explorer 1, Double Star TC1 etc.) that night-
 55 side chorus waves are usually confined around the equatorial plane, whereas dayside waves can propagate
 56 to middle or even high latitudes (Meredith et al., 2012; Agapitov et al., 2013; Santolík et al., 2014). For
 57 the most intense field-aligned chorus waves, this difference in the wave latitudinal extent directly leads to
 58 their different contributions to electron losses and acceleration (Meredith et al., 2003): night-side, near-
 59 equatorial waves are mostly responsible for the precipitation of $< 100\text{keV}$ electrons and effective in
 60 electron acceleration up to relativistic energies (Allison et al., 2021), whereas dayside waves are
 61 responsible for relativistic electron losses (Thorne et al., 2005). Indeed, the distribution of the most
 62 intense precipitation events, microbursts, have confirmed the prevalence of electron losses on the dayside
 63 (Douma et al., 2017; Shumko et al., 2021; H. Chen et al., 2023; Shekhar et al., 2017). However, the
 64 statistical studies mentioned above also indicate the presence of relativistic electron precipitation on the
 65 night side. Recent observations from the low-Earth-orbit (LEO) ELFIN CubeSats have further confirmed
 66 the occurrence of these intense relativistic electron precipitation signatures on the night side (Artemyev et
 67 al., 2024). These findings of frequent, strong relativistic precipitation on the night side contrast with the
 68 existing theoretical understanding previously discussed, as there is currently no satisfactory theoretical
 69 explanation for this phenomenon. Given that the significant contributions of such precipitation events to
 70 relativistic electron losses have been confirmed (Tsai et al., 2024), it is crucial to explore the mechanisms
 71 driving night-side relativistic precipitation to enhance our understanding of radiation belt dynamics.

72 Two potential mechanisms can lead to relativistic electron losses in the night-side inner magnetosphere.
 73 First, after being generated around the equator, whistler waves may propagate along curved magnetic
 74 field lines, become very oblique and resonate with relativistic electrons through high-order resonances
 75 (see discussions in Lorentzen et al., 2001). Indeed, this mechanism for relativistic electron precipitation
 76 has been confirmed in the dawn-flank magnetosphere (Gan et al., 2023), but it is unclear whether the
 77 same mechanism can work on the night-side, where enhanced suprathermal electrons damp oblique waves
 78 much more effectively (e.g., L. Chen et al., 2013). Second, these equatorially generated waves can be
 79 trapped into local density ducts (e.g., Hanzelka & Santolík, 2019; R. Chen et al., 2021) and propagate to
 80 middle latitudes or all the way to the ionosphere without damping (Shen et al., 2021). At middle latitude,
 81 these intense field-aligned chorus waves may provide effective scattering and precipitation of relativistic
 82 electrons. This mechanism was proposed to explain relativistic electron losses on the dusk-side and
 83 dayside (e.g., Artemyev et al., 2021; L. Chen et al., 2022), but has not been verified for the night-side.

84 In this study we examine ELFIN (Angelopoulos et al., 2020) observations of very intense, relativistic (up
 85 to $1 - 2\text{MeV}$) electron precipitation in the night-side inner magnetosphere. Using ELFIN electron
 86 measurements with high energy resolution, we separate the chorus-driven precipitation from the plasma
 87 sheet precipitation due to electron scattering by the magnetic field line curvature (see discussions of this

mechanism in Yahnin et al., 2016; Capannolo et al., 2022). Then we simulate electron resonant interactions with chorus waves traced in a realistic magnetosphere configuration (see the model details in Kang et al., 2022a), in order to evaluate the relative importance of unducted (oblique) and ducted (field-aligned) wave scattering. As shown in simulations, the observed relativistic electron precipitation at the strong diffusion limit (completely filled loss cone; see Kennel, 1969) can only be explained by the scattering of ducted waves. These results imply the importance of incorporating realistic plasma density structures and wave distributions into global radiation belt models.

2 ELFIN observations of relativistic electron losses

We analyze in detail ELFIN CubeSat observations recorded during the two-day interval 11-12 June 2021. These observations were captured during a prolonged interval of elevated geomagnetic activity, with the auroral index, SML, remaining below $-300nT$ and ring current index, SMR, below $-20nT$ (Gjerloev, 2012) for the majority of the time, due to a series of plasma injections (see Fig. 1(a)). The ELFIN energetic particle detector, EPDe, measures electron energy, pitch-angle distributions over $[50, 6000]keV$ in 16 logarithmically distributed energy channels (Angelopoulos et al., 2020). ELFIN's polar, low-altitude ($\sim 450km$) orbit allows it to quickly traverse a wide range of magnetic field lines, in the inner magnetosphere to the plasma sheet, within $\sim 5min$. The temporal resolution of EPDe measurements is 3s, i.e. the ELFIN spin rate. To examine the precipitation from the equatorial magnetosphere, we mainly use two data products: the energy spectrum of locally trapped electrons (outside the bounce loss-cone), j_{trap} , and the energy spectrum of precipitating electrons (inside the bounce loss-cone), j_{prec} (Angelopoulos et al., 2023). Their ratio, j_{prec}/j_{trap} , signifies the intensity of electron scattering around the equator (Kennel & Petschek, 1966; Li et al., 2013).

Figure 1(b1-d3) shows ELFIN observations during three orbits on 11 June 2021: the trapped spectra in panels (b), precipitating-to-trapped flux ratios in panels (c), and ELFIN MLT and L-shell (calculated using the model Tsyganenko, 1989) in panels (d). Note that there can be large uncertainties for the night-side in projecting ELFIN to the equator to estimate L-shell, especially during substorms when magnetic field lines are very deformed in the magnetotail region (see discussions in Sitnov et al., 2019; Artemyev, Angelopoulos, et al., 2022). Thus, we only trust the low L values in the inner magnetosphere, and use j_{trap} and j_{prec}/j_{trap} to identify different magnetospheric regions in ELFIN measurements. Let us illustrate this identification procedure using panels (b1, c1). Before 02:50:10 UT, ELFIN measures locally trapped fluxes below $200keV$ with a strong flux anisotropy, $j_{prec}/j_{trap} < 0.1$. This is consistent with the plasmasphere, which is often replenished by freshly injected electrons in the night-side. Between 02:50:10 and 02:50:25 UT, ELFIN observed enhanced relativistic electron fluxes, mostly trapped with sporadic precipitation bursts, $j_{prec}/j_{trap} > 0.1$ and j_{prec}/j_{trap} decreases with energy. This is the outer radiation belt region, whereas precipitation bursts are due to electron scattering by whistler-mode (chorus) waves: for these waves, the pitch-angle diffusion coefficient decreases with the energy increase (e.g., Summers et al., 2007; Ni et al., 2008), in agreement with the observed j_{prec}/j_{trap} . Around 02:50:30 UT, ELFIN traversed the isotropy boundary – transitioning between the outer radiation belt with $j_{prec}/j_{trap} < 1$ and the plasma sheet with $j_{prec}/j_{trap} \approx 1$. Such strong energetic electron precipitation is due to curvature scattering in the magnetotail current sheet (Imhof et al., 1979; Sergeev et al., 1983, 2012). The plasma sheet region is characterized by $< 200keV$ electron fluxes, usually isotropic, $j_{prec}/j_{trap} \approx 1$ (Artemyev, Angelopoulos, et al., 2022). A characteristic feature of the isotropy boundary is the energy/L-shell dispersion (for an excellent example see Figure 2 in Wilkins et al., 2023): electrons at higher energies start to experience the curvature scattering at lower L-shells (with larger curvature radius) and hence show $j_{prec}/j_{trap} \approx 1$ closer to the Earth (Sergeev et al., 2012). The high energy and pitch-angle

resolution of ELFIN EPDe allows us to distinguish precipitation due to curvature scattering and due to the whistler-mode wave scattering (see discussions in Tsai et al., 2022; Artemyev, Neishtadt, & Angelopoulos, 2022). As shown in Fig. 1(b1-d1), ELFIN measurements were captured during the substorm growth phase, where the absence of plasma injections explains the lack of intense chorus waves, but the very thin magnetotail current sheet can drive strong curvature scattering and electron precipitation below 200keV.

Figures 1(b2-d3) show ELFIN observations during two orbits after a substorm injection: the plasma sheet is only captured fragmentally, likely due to near-Earth dipolarization that prevents electron curvature scattering (see discussions in Shen et al., 2023; Lukin et al., 2021); the outer radiation belt is filled by hot injected electrons as a viable source for chorus wave generation (e.g., Tao et al., 2011; Malaspina et al., 2018). Electron precipitation due to chorus wave scattering has a very clear energy dispersion, with the precipitating-to-trapped flux ratio decreasing with energy increase (panels (c2, c3)). This precipitation pattern exhibits several spatially localized bursts (likely associated with the chorus wave generation regions around plasma injections, see discussions in Zhang et al., 2023; Artemyev et al., 2024). Energies of precipitating electrons can reach 500 – 700keV, and in panel (c3) 700keV precipitating electrons show precipitating-to-trapped flux ratio around one, i.e., relativistic electrons are precipitated at the strong diffusion limit.

Figures 1(b4-d6) show ELFIN observations during three orbits on 12 June 2021. Similar to the three orbits in 1(b1-d3), the first orbit during substorm growth phase shows a very clear isotropy boundary reaching 1MeV in energy (panel (c4)). Two subsequent orbits show electron precipitation bursts in the outer radiation belt after the injections. This precipitation is likely due to electron scattering by chorus waves. As shown in the observations, these electron precipitation, likely driven by chorus waves at the strong diffusion limit, can reach 1 – 2MeV. Therefore, Fig. 1 demonstrates multiple examples of unusually strong precipitation bursts of relativistic electrons observed on the night-side.

Although the ELFIN measurements in Fig. 1 were not in conjunction with equatorial spacecraft measurements, there is nevertheless good coverage of equatorial plasma and wave dynamics provided by MMS (Burch et al., 2016), Arase (Miyoshi et al., 2018), THEMIS (Angelopoulos, 2008), and GOES-16. Based on these satellite observations, the occurrence of a number of related phenomena were confirmed during the events depicted in Figure 1. These phenomena included injection events (measured by energetic particle detectors, see S. Kasahara et al., 2018; Blake et al., 2016), cold plasma density structures (derived from spacecraft potential, see Nishimura et al., 2011), and whistler-mode chorus waves (measured by electric field instruments and search-coil magnetometers, see Auster et al., 2008; Le Contel et al., 2008; Bonnell et al., 2008; Y. Kasahara et al., 2018). Consequently, ELFIN observations of strong electron precipitation are linked to periods of multiple plasma sheet injections, which act as the free energy source for chorus wave generation (Tao et al., 2011; Fu et al., 2014; Malaspina et al., 2018). These injections also reduce the f_{pe}/f_{ce} ratio (Agapitov et al., 2019), which plays a crucial role in the scattering and precipitation of relativistic electrons (see discussions in Tsai et al., 2024). For a more detailed description of these supplemental observations, see Supplementary Information.

3 Simulation results

To probe the mechanism driving the observed night-side relativistic electron precipitation within the strong diffusion regime, we conduct event-based modeling for ducted and unducted chorus waves, respectively. The chorus wave-particle interaction model employed in this study follows the same methodology as in (Kang et al., 2022a; Kang et al., 2024), whose basic procedure are described below. Utilizing ray tracing techniques, we trace the ray paths of chorus waves originating from an equatorial

chorus wave source, with Landau damping included which yields the amplitude attenuation of waves. From the ray paths and wave amplitudes along ray paths, we can reconstruct the latitudinal distribution of wave amplitude along a certain field line from all the rays that cross the field line. Subsequently, quasi-linear electron scattering calculations are performed on the field lines, yielding the energy-time ($E - t$) spectrum for the j_{prec} , and thus the j_{prec}/j_{trap} ratio at each field line's footprint. (For technical details about this model see discussions in Kang et al., 2022b; Kang et al., 2024; J. Bortnik, 2006).

We establish our model based on the observations discussed in the preceding section, with a particular focus on the precipitation signature at $L = 8.7$, where ELFIN has detected significant relativistic electron precipitation (whistler mode wave induced precipitation is between $7.5 < L < 10$, and the precipitation due to isotropic boundary occurs beyond $L = 10$, e.g. Figure 1 (c,d3) and (c,d5)). For the unducted case, we adopt an empirical night-side density model (Carpenter & Anderson, 1992), adjusting it to ensure that the equatorial density at $L = 8.7$ maintains $f_{pe}/f_{ce} \approx 3$, consistent with observations from THEMIS (further insights on the role of f_{pe}/f_{ce} are provided in the Discussion section). For the ducted case, we introduce a relatively large (yet realistic, see Thomas et al., 2021; Gu et al., 2022; R. Chen et al., 2021; Ke et al., 2021; Li, Bortnik, Thorne, Nishimura, et al., 2011) density-enhanced duct with a 50% enhancement factor and a half-width of $0.2R_E$ centered around the field line $L = 8.7$, expressed as $n_{ducted} = n_{unducted} (0.5e^{-\frac{(L-8.7)^2}{0.2^2}} + 1)$ (see observations and simulations of similar ducts in Shen et al., 2021; Ke et al., 2021; R. Chen et al., 2021; Gu et al., 2022). Considering the parallel propagation characteristics of chorus waves within such ducts (e.g., R. Chen et al., 2021), we position the equatorial chorus wave source region at the center of the duct ($L = 8.7$). In contrast, unducted chorus waves, while propagating to higher latitudes and attaining relativistic resonance energies, also extend to higher L shells (see Figure 3 of Kang et al., 2022b). Hence, for the unducted case, we initialize the chorus wave source region at $L = 8$, ensuring that as the wave rays propagate to the target field line at $L = 8.7$, they have already reached relativistic resonance energy (see Figure 2(b2)). We initialize the chorus waves with a frequency span of $0.1f_{ce} < f < 0.5f_{ce}$ and an initial quasi-parallel wave normal angle (WNA) distribution with a bandwidth of 15° (Equation 4 of Kang et al., 2024). During the ray tracing process, the electron velocity distribution utilized for Landau damping calculations (see L. Chen et al., 2013; Brinca, 1972) is derived from electron flux data obtained by THEMIS during the event. Since there is no direct conjugate observation of equatorial chorus wave amplitude, we assume a relatively large value of $B_w = 200pT$ for the chorus wave amplitude (e.g., Li, Bortnik, Thorne, & Angelopoulos, 2011). It is worth noting that the wave amplitude B_w scales linearly with the amplitude of electron pitch-angle scattering rate, $\Delta\alpha$, in the quasi-linear regime. Thus, this parameter should be viewed as a normalization factor for $j_{prec}/j_{trap} \propto \Delta\alpha \propto B_w$.

Figure 2 shows the ray tracing results for the ducted (panels (a1) and (b1)) and unducted (panels (a2) and (b2)) cases. Panels (a1) and (a2) depict the ray paths with varying frequencies (color-coded according to the top-right color bar), while panels (b1) and (b2) display the cyclotron resonance energy along the ray paths at a fixed frequency of $f = 0.25f_{ce}$. Power reduction due to Landau damping is indicated by the fading of ray paths, i.e., increasing transparency of the ray paths. From panel (a1), we can see that all waves are effectively guided by the duct, with only minor leakage of high-frequency waves. Ducted waves experience minimal damping as they remain quasi-parallel within the duct (R. Chen et al., 2021; Lu et al., 2019), retaining significant wave power even at high latitudes ($> 50^\circ$). In contrast, panel (a2) reveals that unducted waves undergo substantial damping (L. Chen et al., 2021), with the majority of wave power lost after propagating above a latitude of 20° . This difference in the latitudinal extent of the strong-wave-power region between ducted and unducted cases is crucial for their distinct j_{prec}/j_{trap} ratios

in the $\sim MeV$ energy range. From panels (b1) and (b2), we can see that in both cases, chorus waves do not attain $\sim MeV$ resonance energy until they propagate beyond 20° in latitude (Lorentzen et al., 2001; Kang et al., 2022b; L. Chen et al., 2022; Miyoshi et al., 2020). Therefore it is crucial for chorus waves to convey sufficient wave power to the high-latitude, MeV resonance region to enable strong diffusion at the MeV energy range, thereby making ducting the only plausible explanation for the observed night-side strong $\sim MeV$ precipitation, as demonstrated later.

Figure 3 shows the energy-time ($E - t$) spectra of j_{prec}/j_{trap} ratio at various field line footpoints for both ducted and unducted cases. Panels in the left column depict results for the unducted case, while those on the right represent the ducted case. We examine the precipitation signatures at five different field lines: $L = 8, 8.3, 8.5, 8.7$, and 8.9 . Note that $L = 8$ is the chorus wave source region for the unducted case, whereas $L = 8.7$ is the source region for the ducted case. It is evident that the unducted and ducted waves exhibit their strongest precipitation at distinct locations and energy ranges. In the unducted case, strong precipitation is solely observed at $L = 8$, around the wave source region, at energies below $100keV$, typical of night-side chorus waves (e.g., Allison et al., 2021). By comparing the energy range with Figure 2 (b2), we can further determine that the scattering occurs below latitudes of 20° . Conversely, in the ducted case, intense scattering is only observed at $L = 8.7$, the center of the duct. Here, precipitation spans a wide energy range from several tens of keV up to several MeV . Combining with Figure 2 (b1), we discern efficient scattering that occurs from the equator all the way up to latitudes of 50° . From Figure 3, we can see that relativistic precipitation ($E \gtrsim 1MeV$) is only possible in the ducted case, and relativistic precipitation near strong diffusion limit is solely attainable at the duct's center.

To examine the locations and energy ranges where the strong diffusion limit can be attained, and to depict how the $j_{prec}/j_{trap} - E$ relation evolves with L-shells, we present in Figure 3(f) and (g) the maximum j_{prec}/j_{trap} over the entire time period ($\max(j_{prec}/j_{trap})$) versus energy at different L-shells for both the ducted and unducted cases. Panel (f) shows the results for the ducted case, while panel (g) shows the unducted case, with curves of varying colors corresponding to different L-shell distance ΔL to chorus wave source region L_{src} as delineated by the color bar on the right. Panel (g) shows that in the unducted case, the strongest precipitation occurs near the source region ($\Delta L = 0$, or $L = 8$) within a lower energy range of $< 100keV$; at field lines farther from the source region, precipitation at increasingly higher energies is observed, albeit with a dramatic decrease in intensity. This is because unducted chorus waves reach higher L-shells at higher latitudes, where the waves resonate with higher energy electrons but much weaker wave amplitude due to strong Landau damping on the night-side (see Figure 2 (b2)). Conversely, in the ducted case (panel (f)), the center of the duct ($\Delta L = 0$, or $L = 8.7$) exhibits the highest precipitation intensity compared to all other field lines (as indicated by the orange curve); the strong diffusion limit is achieved between $20 \sim 200keV$ and maintains a significant j_{prec}/j_{trap} ratio of > 0.1 up to several MeV . Field lines near the duct boundary ($\Delta L = \pm 0.2$, or $L = 8.5, 8.9$) show similar relativistic precipitation energy range, although with lower intensity, indicative of very effective wave power guiding within the duct. This ducting effect traps almost all wave power at the duct's center, where weak Landau damping allows a significant amount of the wave power to persist to high latitudes, producing the scattering of relativistic electrons and thus generating strong relativistic precipitation at the duct's center.

4 Discussion and Conclusions

We show that only ducted wave propagation enables chorus waves to reach sufficiently high latitudes to scatter and precipitate relativistic electrons close to the strong diffusion limit. However, the efficiency of ducting and wave-particle resonant interactions relies on the characteristics of cold plasma density, which are not directly measured during these events and must be inferred from statistical models. The

background density magnitude (determining $f_{pe}/f_{ce} = 3$) under the assumed duct amplitude of 50% deviates from typical values: empirical models suggest $f_{pe}/f_{ce} \sim 8$ for $L \sim 8$ (Sheeley et al., 2001). Nevertheless, the modeled events of relativistic electron precipitation occur during strong substorm activity (see Fig. 1(a)), which is usually associated with a decrease in the night-side f_{pe}/f_{ce} to 2–4 (Agapitov et al., 2019), likely due to enhanced earthward transport of cold plasma. For $L \sim 8$, $f_{pe}/f_{ce} = 3$ indicates that the background density is only $0.4cm^{-3}$ and $0.6cm^{-3}$ within the duct. Although these density differences may seem substantial in relative terms, they are not uncommon for the night-side inner magnetosphere during plasma sheet injections (e.g., Gkioulidou et al., 2014; Liu et al., 2016).

Our modeling results indicate that a strong chorus-driven, night-side relativistic precipitation can only occur in the presence of a density duct. Interestingly, considering that night-side relativistic precipitation is not rare at all (Artemyev et al., 2024; Shumko et al., 2021; H. Chen et al., 2023; Shekhar et al., 2017), it is suggested that relativistic microbursts are either dominated by the night-side or have a comparable occurrence rate as dawn and day sides. If we acknowledge that chorus waves are a main driver of relativistic microbursts (Breneman et al., 2017; Tsurutani et al., 2013; Lorentzen et al., 2001; Kersten et al., 2011), it naturally leads to the implication that ducts should exist on the night-side and potentially be quite common, so that they can account for the high occurrence rate of night-side relativistic precipitation. This aligns with the statistical results of density irregularities (Thomas et al., 2021; Gu et al., 2022), where both works report a non-negligible occurrence rate on the night-side.

In this study, utilizing data from the ELFIN CubeSats, we examine a night-side relativistic precipitation event that reaches the strong diffusion limit ($j_{prec}/j_{trap} \sim 1$). By analyzing the energy dispersion and spatial burst signatures, we identify the presence of whistler-mode chorus wave-driven precipitation. Concurrent observations from multiple spacecraft (MMS, THEMIS, Arase, and GOES) reveal that this event is accompanied by substorm activity, hot electron injection, a low f_{pe}/f_{ce} ratio, and chorus wave activity. To elucidate the potential mechanism whereby night-side chorus waves produce relativistic precipitation at the strong diffusion limit, we conduct simulations modeling the chorus wave-driven precipitation for both the unducted and ducted cases. The model is event-based, with the density model and electron flux model configured based on observations during this event. The modeling results indicate that unducted night-side chorus waves are quickly damped before reaching relativistic resonance energies, and thus are unlikely to be responsible for strong relativistic precipitation; conversely, when chorus waves are effectively guided by a duct, they are able to produce very intense precipitation ($j_{prec}/j_{trap} > 0.1$) across the relativistic energy range. Therefore, strong relativistic precipitation driven by chorus waves on the night-side can only be accompanied by the ducting effect. These results underline the critical role of density ducts in the dynamics of substorm radiation belts.

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Open Research

Fluxes measured by ELFEN are available in the ELFEN data archive <https://data.elfin.ucla.edu/> in CDF format. Data analysis was done using SPEDAS V4.1 (Angelopoulos et al., 2019). The software can be downloaded from http://spedas.org/wiki/index.php?title=Downloads_and_Installation. Simulation data can be accessed from (Kang, 2024).

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Figure Captions

Figure 1: Overview of ELFIN A&B observations during two substorms on 11-12 June 2021. Panel (a) shows SuperMag indices. Panels (b1-d3) show LFIN observations during three orbits during the first substorm at 02:00-05:00 UT on June 11: locally trapped fluxes (b1, b2, b3), precipitating-to-trapped flux ratio (c1, c2, c3), and ELFIN L-shell and MLT (d1, d2, d3). Panels (b4-d6) show ELFIN observations during three orbits during the second substorm at 00:00-05:00 UT on June 12: locally trapped fluxes (b4, b5, b6), precipitating-to-trapped flux ratio (c4, c5, c6), and ELFIN L-shell and MLT (d4, d5, d6). Horizontal lines in panels (c) mark two key energy levels: 500keV in solid line and 1MeV in dashed line. In panels (c), we also indicate precipitation patterns as identified by their location and energy dispersion: isotropic fluxes at large L-shell are due to electron curvature scattering in the plasma sheet (PS); L-shell/energy dispersion with higher-energy electron precipitation at lower L-shell is a signature of the electron isotropy boundary (IBe); precipitation bursts with a lower precipitating-to-trapped ratio at higher energies are due to electron scattering by whistler-mode waves.

Figure 2: Overview of ray paths and resonance energies for both ducted (left) and unducted (right) cases. Panels (a1) and (a2) show the ray paths of waves with different frequencies, color-coded as indicated in the top-right color bar. Panels (b1) and (b2) illustrate the (cyclotron) resonance energy along the ray paths of waves at a fixed frequency of $0.25f_{ce}$, with colors denoting the resonance energy as shown in the bottom-right color bar. Panels (a1) and (b1) are for the ducted case, whereas panels (a2) and (b2) are for the unducted case. The transparency of ray paths in all panels reflects their wave power, with fading rays illustrating damping. Thin dashed lines denote field lines with an L shell interval of 1 and latitude lines with a latitude interval of 10° ; the two thick dashed lines represent field lines for $L = 8.5$ and $L = 8.9$, which, in the ducted case, mark the half-width boundary for the enhanced density duct.

Figure 3: Panels (a)~(e) are $E - t$ spectra of j_{prec}/j_{trap} ratio at different field line footpoints for ducted and un- ducted cases separately. Panels (a1)-(e1) represent field line footpoints at $L = 8, 8.3, 8.5, 8.7$ and 8.9 , respectively, for the unducted case, whereas panels (a2)~(e2) depict the same for the ducted case. The ratio contour is color-coded according to the top-right color bar, with the horizontal white dashed line marking the $1MeV$ energy. Panels (f) and (g) are the $max(j_{prec}/j_{trap}) - E$ curves at different L-shells for both the ducted and unducted cases. Panel (f) shows the ducted case, while panel (g) shows the unducted case. Curves at different L shells are color-coded with their distance to the L shell of chorus wave source region, as indicated by the color bar on the right. Note that $L_{src} = 8.7$ for ducted case and $L_{src} = 8$ for unducted case.

Figure 1.

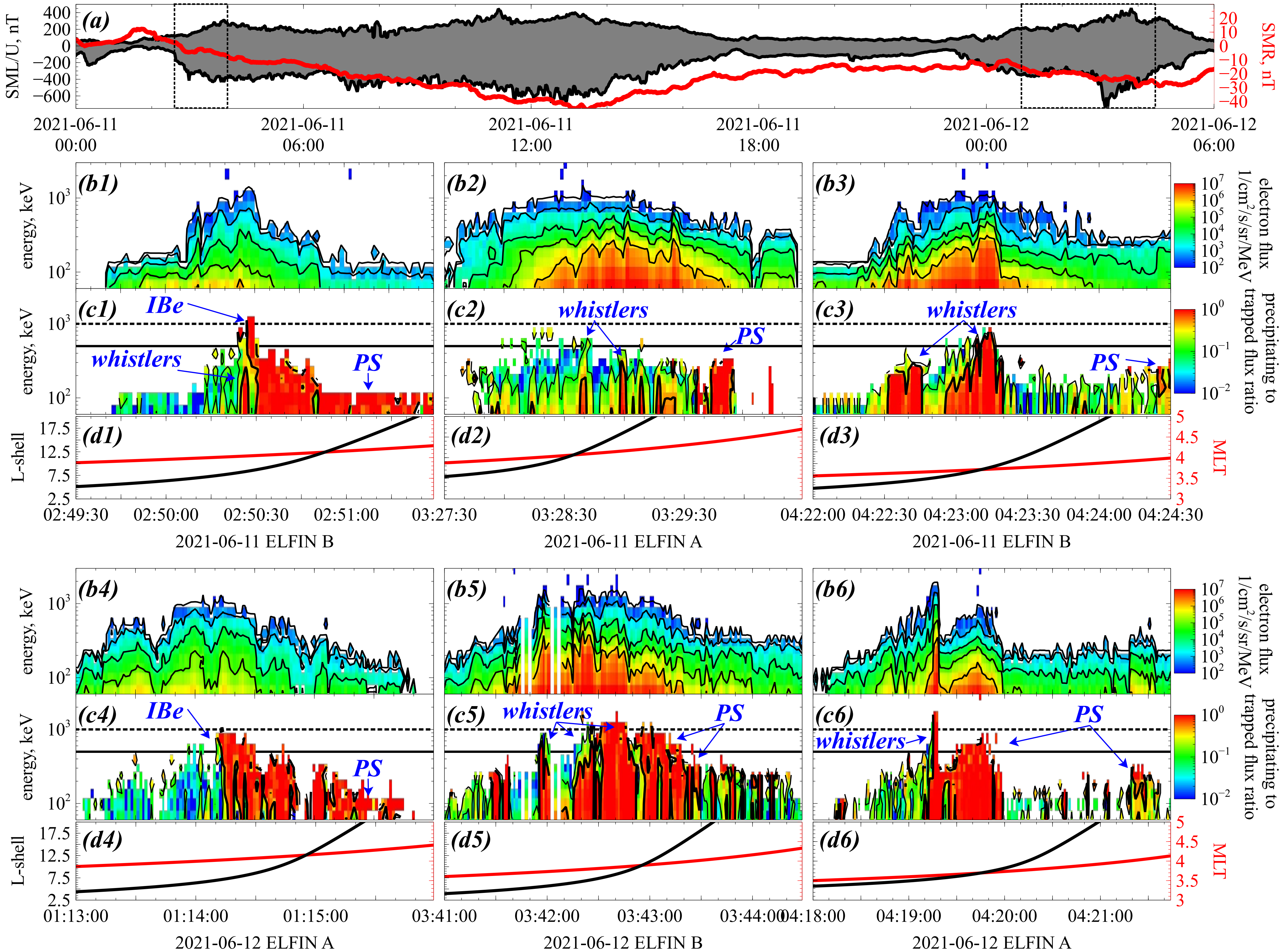


Figure 2.

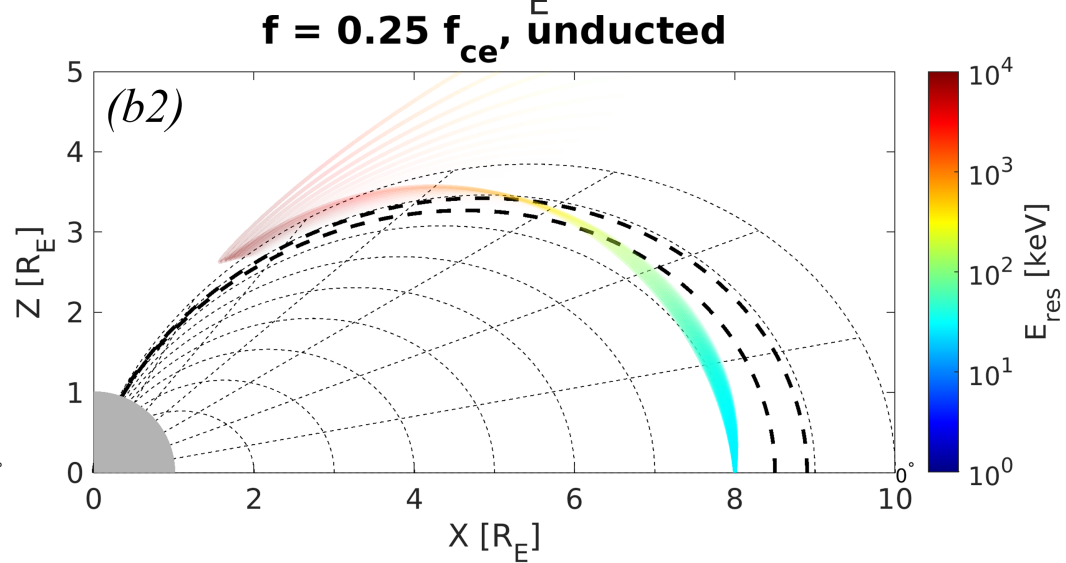
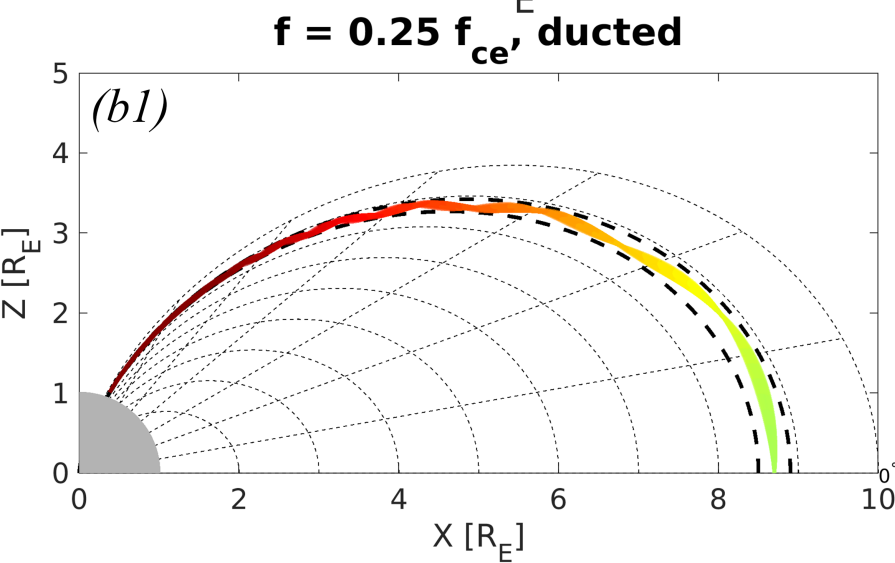
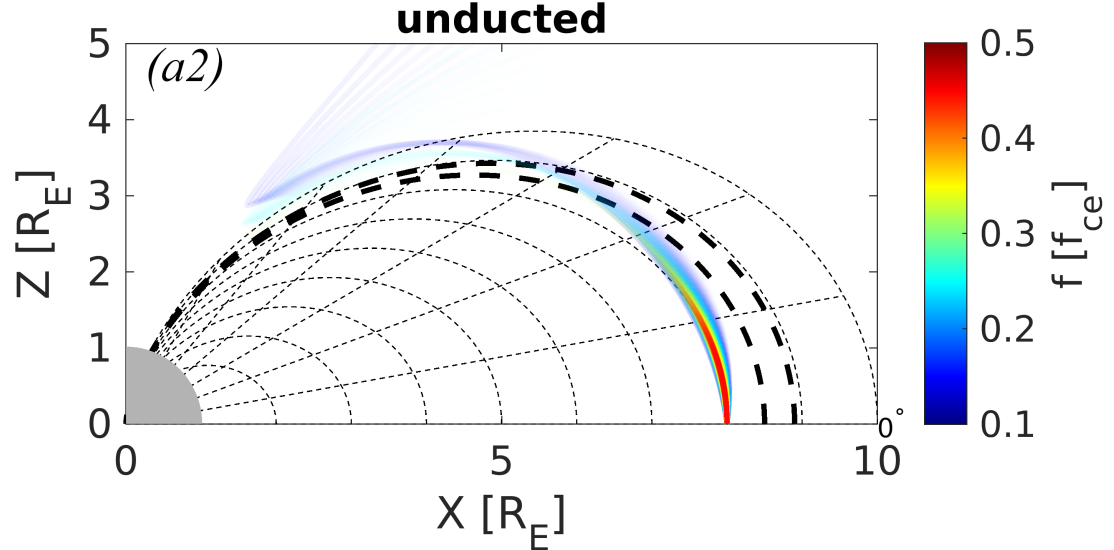
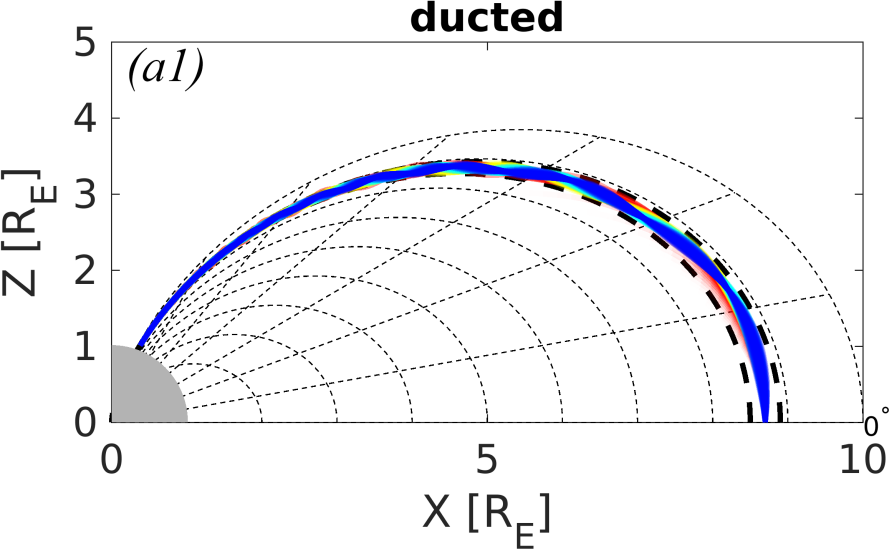


Figure 3.

