Relativistic Electron Precipitation Near Midnight: Drivers, Distribution, and Properties

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Key Points:

- We use POES data to analyze the relativistic electron precipitation (REP) near midnight (22–02 MLT), which is found to occur over L ~ 4–7
- We study REP events due to a single driver: either caused by waves (isolated REP) or current sheet scattering (energy-dependent REP)
- Both mechanisms drive precipitation during field line stretching and most wave-driven events occur in association with EMIC waves

Abstract

We analyze the drivers, distribution, and properties of the relativistic electron precipitation (REP) detected near midnight by the Polar Orbiting Environmental Satellites (POES) and Meteorological Operational (MetOp) satellites, critical for understanding radiation belt losses and nightside atmospheric energy input. REP is either driven by wave-particle interactions (isolated precipitation within the outer radiation belt), or current sheet scattering (CSS; precipitation with energy dispersion), or a combination of the two. We evaluate the L-MLT distribution for the identified REP events in which only one process evidently drove the precipitation (~10% of the REP near midnight). We show that the two mechanisms coexist and drive precipitation in a broad *L*-shell range (4–7). However, wave-driven REP was also observed at $L < 4$, whereas CSS-driven REP was also detected at $L > 7$. Both processes drive REP in association with a stretched magnetotail, although CSS-driven REP potentially shows more pronounced stretching. ~73% wave-driven REP events are associated with electromagnetic ion cyclotron (EMIC) waves and occur on spatial scales of <0.3 *L*.

Plain Language Summary

Relativistic electrons are typically stably trapped in the outer radiation belt that surrounds the Earth at distances from ~3–4 Earth radii (R_E) up to 7–8 R_E. However, magnetospheric plasma waves can potentially interact with electrons, causing them to precipitate into the Earth's atmosphere. Electron precipitation also occurs when the magnetic field lines are stretched away from the Earth such that their curvature radius is comparable to the gyroradius of the electrons. Here, we specifically focus on precipitation events that occur near midnight. We categorize events by the driver (waves or field line stretching) depending on the shape of precipitation observed at low Earth orbit. We find that the two mechanisms overall overlap. We also show that REP is associated with field line stretching for both mechanisms and that most of the wave-driven precipitation is caused by a specific type of plasma waves, called electromagnetic ion cyclotron waves. Our findings are critical for understanding the driver of REP events near the midnight sector, which is important to account for radiation belt losses, as well as for quantifying the source of the energy input into the Earth's atmosphere that subsequently affects the atmospheric chemistry and conductivity.

1 Introduction

Relativistic electron precipitation (REP) is an important loss mechanism of the Earth's outer radiation belt electrons (Li & Hudson, 2019 and references therein), as well as a source of energy input into the Earth's atmosphere. It is widely accepted that electron precipitation is caused by wave-particle interactions that occur in the Earth's magnetosphere (e.g., Millan and Thorne, 2007; Thorne, 2010); however, sufficient stretching of magnetic field lines is another potential driver of electron and proton precipitation (e.g., Buchner & Zelenyi, 1989; Dugyagin et al., 2020; Sergeev et al., 1983, 1993; Sivadas et al., 2019), sometimes even more efficient than wave-driven precipitation (Artemyev et al., 2013). If the field line curvature radius becomes comparable to the particle gyroradius, pitch-angle scattering occurs and particles are lost. This process demarcates the so-called isotropic boundary (IB) for each species (e.g., Dubyagin et al., 2018; Ganushkina et al., 2005; Gilson et al., 2012; Liang et al., 2014): at latitudes poleward of this boundary, the pitch-angle distribution is isotropic, resulting in particle precipitation. Since this mechanism typically occurs in the nightside magnetosphere (where field lines stretch as the current sheet becomes thinner), it is also referred to as current sheet scattering (CSS).

Precipitating electrons are likely to cause ozone depletion reactions (e.g., Fytterer et al., 2015; Meraner & Shmidt, 2018; Mironova et al., 2015) and enhance ionospheric conductance (Robinson et al., 1987; Khazanov et al., 2018; Yu et al., 2018), thus understanding the drivers of the precipitation, as well as its location and intensity, is fundamental to improve current atmospheric models for space weather and climate predictions. Previous statistical studies based on either Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX; Comess et al., 2013; Smith et al., 2016) or the Polar Orbiting Environmental Satellites (POES) and Meteorological Operational (MetOp) satellite constellation (e.g., Gasque et al., 2021; Shekhar et al 2017; 2018) at low-Earth-orbit (LEO) found that REP occurs at almost all magnetic local times (MLTs), although it is predominant from the pre-dusk to the early morning sectors, peaking at pre-midnight. Relativistic microburst precipitation is also observed on the dawnside (e.g., Blum et al., 2015a; Greeley et al., 2019). Overall, REP occurs on localized spatial scales of an order of a few tenths of *L*-shells, independently of MLT. A recent study using high-resolution POES data by Gasque et al. (2021) indeed clarifies that the midnight REP events with wider spatial extent (ΔL ~1–2.5) reported by Shekhar et al. (2017) based on 16s-resolution POES data also exhibit localized scales. Additionally, some works studied the association of REP with proton precipitation as a proxy for EMIC wave activity, or with in-situ or ground-based EMIC waves (e.g., Capannolo et al., 2021; Carson et al, 2012; Hendry et al., 2016). EMIC-driven precipitation seems to occur predominantly near dusk, although Carson et al. (2012) showed that it could also extend until ~3 MLT, with a peak in occurrence at midnight. Smith et al. (2016) suggested that the midnight REP associated with proton precipitation could be an indicator of CSS-driven precipitation rather than EMIC waves, since CSS-driven electron precipitation occurs poleward of the proton IB, thus the proton population is precipitating simultaneously with electrons in this region. Studies have also shown that electron precipitation with harder spectra or *e*-folding energy (e.g., as defined in Smith et al. (2016)) predominantly occurs over dusk-to-midnight, peaking at L ~5, while spectra become softer towards midnight and into the dayside, which have been speculated to be driven by the CSS mechanism (Comess et al., 2013; Shekhar et al., 2018; Smith et al., 2016). By conducting a detailed analysis of REP events identified over a limited POES dataset (38 days in Yahnin et al. (2016) and 6 months in Yahnin et al. (2017)), Yahnin et al. (2016, 2017) attributed those occurring at midnight to CSS, while those over ~12–23 MLT potentially to EMIC waves.

Overall, it remains unclear which is the main driver of the REP observed across midnight, since studies like Carson et al. (2012) identified EMIC-driven precipitation in that region, while others (e.g., Yahnin et al., 2017; Smith et al., 2016) only found potentially CSS-driven REP there. In the present study, we focus specifically on the REP events observed near midnight (22–02 MLT) over 8 years of POES data, aiming to associate each REP event with either a wave driver or CSS, depending on its distinct spatial characteristic (in a similar manner to Yahnin et al. (2016; 2017)). While wave-driven REP shows a rather spatially isolated precipitation feature (typically corresponding to the region where pitch-angle scattering due to wave-particle interactions is efficient), CSS-driven REP exhibits a well-known energy dispersion with higher energy electrons precipitating at lower *L*-shells than lower energy electrons (e.g., Yahnin et al., 2016; 2017) due to the radially decreasing curvature radius of magnetic field lines. After categorizing events by driver, we analyze the precipitation distribution and intensity, in order to highlight similarities or differences between wave-driven and CSS-driven REP. Finally, we estimate the field line stretching using Geostationary Operational Environmental Satellite (GOES) and associate precipitation events with EMIC wave activity.

2 Selection and Classification of REP Events

For this study, we used 2 s data (01/2012–12/2020) from the POES/MetOp satellite constellation at LEO (~800–850 km). These satellites cover a broad range of *L*-shells and MLTs and allow to observe both precipitating (0° telescope, pointed at zenith) and trapped (90° telescope, perpendicular to zenith) populations (Evans & Greer, 2004; Rodger et al., 2010). A strong indication of precipitation is evident when the particle flux measured by the 0° telescope approaches that observed in the 90° telescope. The newest data release includes relativistic electron flux measurements (channel E4, >700 keV) obtained from the comparison between the proton channels P5 (2.5–6.9 MeV) and P6 (>6.9 MeV, heavily contaminated by >700 keV electrons; Yando et al., 2011), as described in Green (2013). We developed an algorithm to identify REP events from the E4 channel (details are provided in the Supporting Information, SI).

Then, we performed a visual inspection of the ~4,500 REP events identified by the algorithm over the midnight sector (22–02 MLT). As expected, we noticed that REP was either occurring within the outer radiation belt, or right at the outer boundary (identified by the decay with *L*-shell of the 90° E4 flux) and accompanied by lower energy electron precipitation as well (observed in the E1 (>30 keV), E2 (>100 keV), and E3 (>300 keV) POES electron channels). The spatial characteristic of the REP along the LEO satellite trajectory as well as its location with respect to the outer radiation belt boundary allows us to associate it with either waves (1) or CSS (2). We found 235 wave-driven and 156 CSS-driven REP events. Note that this dataset corresponds to < ~10% of the total number of REP events found near midnight because we have been very conservative in the classification (described below) such that the catalogued events are truly driven by one mechanism alone.

For wave-driven REP (1), we required a well-isolated REP, showing a transition from strong precipitation within the event boundaries to no/low precipitation outside of it. Figure 1a shows an example: clear isolated REP (peak of precipitating electrons, solid red line) was observed within the outer radiation belt (high flux of trapped relativistic electrons, dotted red line), showing no precipitation before/after the main event (vertical dashed lines). We additionally required that POES observed at least one data point with precipitating-to-trapped ratio <0.4 outside of the event identified by the algorithm, thus excluding all events that are close to other unclear nearby precipitation or truncated because of missing data.

CSS-driven REP (2) is identified by the energy dispersion in the *L*-shell precipitation profile: lower-energy electrons precipitate at higher *L*-shells than relativistic electrons because magnetic field lines are more stretched with increasing *L*-shells, thus the *L*-shell at which the gyroradius of lower-energy electrons is comparable to the curvature radius of the associated field line is larger than that for higher-energy electrons. For this category, we required that the energy dispersion is clearly visible for at least one data point between electron channels (*i.e.*, shift of one data point from the IB of E4) and occurring poleward of the proton IB, and that electron fluxes at all energies reach a full loss cone distribution (*i.e.*, IB is identifiable for all energies). Figure 1b shows a CSS-driven example event. We further discarded events with energy dispersion due to proton contamination, events where additional low-energy electron precipitation is observed during the energy dispersion, and events where isolated REP occurs contiguously to the energy dispersion (indicating potential overlap between CSS and wave-driven mechanisms in that region). One additional important distinction between the two categories is that wave-driven events must not show the energy dispersion which instead characterizes all CSS-driven events.

These criteria result in discarding probably more CSS-driven events than wave-driven ones. Therefore, it is important to note that the higher number of identified wave-driven REP events is not necessarily indicating that waves dominate the REP near the midnight sector, rather that CSS-driven events often show a complex energy dispersion (*i.e.*, overlapping peaks of precipitation during the energy dispersion, energy dispersion not captured by the POES/MetOp 2s resolution data, etc.) and that REP is often the superposition of both mechanisms.

3 Distribution and Intensity of REP near Midnight

In order to highlight potential similarities or differences of the midnight REP due to waves or CSS, Figures 2a-2c show an overview of the distribution in *L* and MLT (from the T05 model, Tsyganenko and Sitnov, 2005) for the 391 events, separated by their driver. Points in the scatter plot (Figure 2a) are located at the average *L* and MLT values (calculated within the event boundaries, vertical lines in Figure 1a) during the wave-driven REP (blue) and at the minimum *L* (vertical line in Figure 1b) and corresponding MLT during the CSS-driven REP (gray). Figures 2b-2c display the REP distribution in MLT and *L*, for wave-driven (blue) and CSS-driven (gray) events, with both the number of events in each bin and the occurrence rate (event number normalized to the total number of events, 391) indicated on the plots. These panels highlight that REP overall occurs over *L*-shells of ~4–7, in the heart of the outer radiation belt, as expected. Although some wave-driven REP can extend to $L < 4$ and CSS-driven REP is also observed at $L > 7$, there is no evident preferential *L*-MLT region where one driving mechanism dominates over the other, similarly to what Yahnin et al. (2016, 2017) found on a shorter time span in the POES data. This strongly suggests that wave-driven and CSS-driven precipitation coexist near midnight, contrary to common expectations of electron CSS occurring only at high *L*-shells. This is not entirely surprising because the magnetotail is highly dynamic, thus current sheet thinning can occur frequently and at a wide variety of distances from the Earth. Nevertheless, it is certainly interesting that field lines can stretch enough to cause CSS at relatively low *L*-shells (<~6).

Figures 2d-2e are relative to the wave-driven REP events only, for which we can estimate an *L*-shell extent (ΔL), as defined in Figure 1a. From the scatter plot of ΔL versus MLT (Figure 2d), events identified in the pre-midnight sector tend to be wider than those identified in the post-midnight sector, though the majority of the events have extents of <0.3 *L*. This could be the result of different wave or plasma background properties across midnight which in turn determine spatial differences where conditions for pitch-angle scattering are more favorable (as suggested in Capannolo et al. (2021)). Although the choice of the ΔL definition is not unique and could affect the minimum/maximum extent (as also mentioned in the SI and Gasque et al. (2021)), the wave-driven REP events overall occur on localized scales (average ~0.25 *L*, standard deviation ~0.14), consistent with previous results (Capannolo et al., 2021; Gasque et al., 2021).

Furthermore, we estimated the average intensity of REP driven by each mechanism near midnight (details in Table S1). The averaged precipitating relativistic (>700 keV) electron flux (0° telescope) driven by waves (~$4.4\text{x}10^3$ $s^{-1}cm^{-2}sr^{-1}$, standard deviation ~$5.2\text{x}10^3$ $s^{-1}cm^{-2}sr^{-1}$) is at least twice of that driven by CSS (~$2.1\text{x}10^3$ $s^{-1}cm^{-2}sr^{-1}$, standard deviation ~$1.4\text{x}10^3$ $s^{-1}cm^{-2}sr^{-1}$), reaching average peaks of ~$1.4\text{x}10^4$ $s^{-1}cm^{-2}sr^{-1}$, as opposed to average peaks from CSS-driven precipitation of ~$0.4\text{x}10^4$ $s^{-1}cm^{-2}sr^{-1}$. It is noteworthy that such high levels of precipitation fluxes are also possible because there is a significantly high amount of relativistic electron population trapped (90° telescope) in the outer radiation belt during the wave-driven REP events (on average, ~1.2x10^4 s^{-1}cm^{-2}sr^{-1}) compared to that during CCS-driven events (~0.3x10^4 s^{-1}cm^{-2}sr^{-1}). Such result is not surprising since CSS-driven events are typically expected to occur at the outer boundary of the outer radiation belt, where the trapped population flux is lower than that in the heart of the belt. On the other hand, wave-driven events occur in the core of the outer belt and thus are associated with higher levels of trapped relativistic electron flux. The average precipitating-to-trapped ratios are ~0.35 for wave-driven REP and ~0.77 for CSS-driven REP, indicating that although waves scatter higher fluxes of relativistic electrons into the atmosphere, they efficiently precipitate a smaller percentage of trapped relativistic electron flux, whereas CSS ultimately leads to an almost isotropic pitch angle distribution, as expected.

4 Association with Field-Line Stretching

To quantify the magnetic field stretching associated with the REP events in each category, we calculated the elevation angle from the magnetic field components measured by GOES. Similarly to previous works (Green et al., 2004; Shekhar et al., 2017, 2018), we define the elevation angle as that between the poleward (H_p) and earthward (H_e) magnetic field components, calculated as $\theta = \arctan(H_p/H_e)$. This value provides an estimate of the approximate stretching of the field line: the smaller the angle, the more stretched the magnetic field line. To calculate the angle as accurately as possible, we searched for magnetic conjunctions between POES and GOES during the identified REP events, with conjunction criteria of ΔL & ΔMLT ≤ 2. Although these criteria do not always allow a one-to-one comparison, finding conjunctions with equatorial spacecraft still provides insightful information near the conjugate location of the REP events observed at LEO. We found 76 and 69 conjunctions for wave-driven and CSS-driven events, respectively. An example of a POES & GOES conjunction during a CSS-driven event is shown in Figure 3 (left). Figure 3a shows the typical energy dispersion of a CSS-driven event. Figures 3b-3c show the GOES elevation angle (b) and the magnetic field components (c) around the REP UT (identified by the vertical line). θ decreased towards the REP UT, similarly to H_p. Together with the increasing trend of H_e, this event shows a clear field line stretching, reaching a low value of θ~30° at the REP UT.

Figures 3d and 3e indicate the histogram (gray) of the θ values for each magnetic conjunction during wave-driven and CSS-driven events, respectively. We also overplotted the monthly average angle distribution (orange, peak~53°) observed by GOES, which provides the typical elevation angle values observed by GOES near midnight (details in the SI). The distribution of the angles calculated at POES & GOES conjunctions (gray) is shifted towards lower values for both wave-driven and CSS-driven REP, indicating that for both mechanisms there is some field line stretching compared to the monthly averages. The CSS-driven REP distribution is peaked at lower angles (~35°, more stretched magnetotail) than the wave-driven one (~47°); however, given the small data sample, this difference is not statistically significant (from the Kolmogorov-Smirnoff and Anderson-Darling tests).

5 Association with EMIC Waves for Wave-Driven Precipitation Events

Previous studies (Carson et al., 2012; Shekhar et al., 2017; Smith et al., 2016) have associated some REP near midnight with EMIC waves. In this section, we used typical EMIC-driven precipitation signatures and in-situ EMIC wave observations to quantify how many of the wave-driven REP events are indeed associated with EMIC waves. Several literature studies show that EMIC waves drive simultaneous precipitation of protons and electrons (e.g., Capannolo et al., 2019a; Hendry et al., 2016; Miyoshi et al., 2008). In order to use proton precipitation as a proxy of EMIC waves, proton precipitation must occur equatorward of the proton IB and be isolated with clear peaks coinciding with REP (as shown in Figure S1). Using POES 10s–100s keV proton flux measurements, we were able to identify 161 wave-driven events (out of the total 235 wave-driven events) that coincided with proton precipitation. The rest of the events either did not show clear proton precipitation (20 events), or occurred at/within the proton IB (54 events), where it was not possible to clearly identify EMIC-driven proton precipitation simultaneously occurring with the REP. For 9 of these 74 events, it was possible to identify EMIC wave activity from the POES & GOES conjunctions, within ~1h from the REP UT (one example is shown in Figure S2 in the SI). Similarly, we used POES & RBSP (Radiation Belt Storm Probes or Van Allen Probes; Mauk et al., 2013; ΔL & ΔMLT ≤ 2) to associate 2 other wave-driven events with EMIC waves observed by RBSP. As a result, 172 out of 235 wave-driven events (~73%) are associated with typical EMIC-driven precipitation or in-situ EMIC waves. Their distribution is similar to that in Figure 2 (blue; not shown). For CSS-driven REP, instead, only <~14% events (from 69 POES & GOES and 38 POES & RBSP conjunctions) are associated with in-situ EMIC waves.

Previous studies also indicated that EMIC waves are typically more efficient in scattering relativistic electrons in weak magnetic field and high-density regions (e.g., Jordanova et al., 2008; Meredith et al., 2003; Summers & Thorne, 2003; Woodger et al., 2018), thus EMIC-driven REP events are often observed from post-noon to pre-midnight (e.g., Blum et al., 2015b; Capannolo et al., 2021; Clilverd et al., 2015; Qin et al., 2018). Our study shows that EMIC-driven REP is indeed occurring near pre-midnight, but is also observed near post-midnight, similar to the results of Carson et al. (2012). To understand if the REP events occur within or outside the plasmasphere, we used the plasma density estimated from the upper hybrid resonance frequency (from Electric and Magnetic Field Instrument Suite and Integrated Science, EMFISIS, Kurth et al., 2015) measured at the POES & RBSP conjunctions. Out of 35 conjunctions with density data available at the REP UT, 60% of them show $\geq$40 cm^{-3} density. Although we were able to obtain in-situ plasma density for only a small subset of the wave-driven events, the qualitative results suggest that, for most conjunctions, wave-driven events occur in high-density regions, where EMIC waves are efficient in driving pitch-angle scattering. In contrast, the majority (70%) of the POES & RBSP conjunctions during CSS-driven events are associated with low density (< 40 cm^{-3}), suggesting that CSS likely drives precipitation outside the plasmasphere. These results are consistent with the findings by Yahnin et al. (2016) indicating that the majority of CSS-driven events (their second group) are associated with low density regions, while those associated with proton spikes (their third group) occur in regions with density enhancements. Smith et al. (2016) also found that for EMIC-driven events the plasmasphere is more extended than when CSS-driven precipitation occurs.

6 Summary & Conclusions

We conducted an in-depth analysis of relativistic electron precipitation (REP) occurring near midnight (22–02 MLT) as observed by the POES/MetOp satellites, which appears to be caused by wave-particle interactions and CSS. ~10% of the REP was associated with one mechanism alone, showing either an isolated >700 keV precipitation feature (within the outer belt), or a precipitation pattern with energy dispersion covering energies from >30 keV up to >700 keV (at the outer boundary of the belt). In this study, we leveraged such a distinct spatial precipitation characteristic and associated the isolated 235 REP events with wave-driven scattering (e.g., Capannolo et al., 2019a; 2021) and the 156 REP events with energy dispersion with CSS (e.g., Yahnin et al., 2016). We have investigated the *L*-MLT distribution of REP, as well as the precipitation intensity for each category and the spatial extent of the wave-driven REP. Using POES & GOES conjunctions, we also provided an estimate of magnetic field stretching during wave-driven and CSS-driven precipitation. GOES and RBSP wave data have been used to find signatures of in-situ EMIC wave observations during the observed REP. Finally, the in-situ plasma density measured by RBSP allowed us to further understand if the REP was occurring within or outside the plasmasphere. Note that the analyzed dataset is dependent on the selection thresholds of REP described in the SI by limiting to the events with sufficient relativistic electron precipitation, which is required to unambiguously identify REP events driven by either waves or CSS. Nevertheless, the findings are expected to be robust for the not-too-weak REP events near midnight.

The key results are summarized as follows:

1. Both wave-driven and CSS-driven REP events predominantly occur over *L*-shells of ~4–7, showing that these two mechanisms coexist and drive precipitation in a similar region, without a clear difference in *L*-MLT dependence. Nevertheless, a few wave-driven events were observed at $L < 4$, while some CSS-driven events were also detected at $L > 7$.
2. For both driving mechanisms, the magnetotail is more stretched than average, although CSS-driven REP is likely associated with more field line stretching compared to wave-driven REP.
3. Most wave-driven REP events are associated with typical EMIC-driven proton precipitation or in-situ EMIC wave activity.
4. For a subset of events, wave-driven REP is observed within the plasmasphere, while CSS-driven REP is preferentially detected outside of it.

It is not surprising that both types of REP are associated with a stretched (thus active) magnetotail. While this is key to drive REP via CSS, waves are typically generated during injections from the tail (e.g., Li et al., 2008; Remya et al., 2018), which also occur during substorms and storms (intrinsically associated with magnetotail stretching). Shekhar et al. (2017) had already shown that midnight REP is preferentially associated with a more stretched magnetotail; however, since we distinguished the wave-driven REP from the CSS-driven one, we evaluated if the CSS mechanism is operating during more significant stretching. Our data sample is too small to draw a solid conclusion; however, it is noteworthy that CSS-driven REP is peaked at lower elevation angles than wave-driven REP, potentially suggesting that indeed CSS-driven REP is associated with more stretched field lines. Future studies could shed further light on this result by associating each event to a geomagnetic storm/substorm, to reveal if one type of REP preferentially occurs during a specific active phase.

Similar to previous studies (e.g., Gasque et al., 2021), the observed wave-driven REP occurs on small radial scales, typically <0.3 *L*, likely because the regions where wave-particle interactions drive efficient pitch angle scattering are just as localized. Additionally, we also showed that pre-midnight wave-driven REP events tend to exhibit a maximum radial spatial scale of ~0.7 *L*, while the ones detected in the post-midnight sector are typically <~0.5 *L*. This is an interesting result that requires further understanding of the wave properties and wave-electron interactions that could justify why the precipitation extent seems to be asymmetric with respect to midnight.

Although the precipitating >700 keV electron flux during wave-driven events is twice of that during CSS-driven events, they are of the same order of magnitude, thus they both provide important energy inputs into the atmosphere. On average, CSS is able to precipitate a larger percentage of trapped relativistic electrons into the Earth's atmosphere. Our work additionally showed CSS could occur at *L*-shells as low as 4, indicating that the magnetotail can undergo significant stretching also close to Earth. Furthermore, since CSS-driven precipitation is a direct result of the stretching of the magnetotail, improved understanding of the CSS-driven precipitation is important to potentially infer the configuration of the magnetic field using remote sensing techniques (e.g., Sergeev et al., 2018).

In conclusion, midnight REP appears to be driven by both waves and CSS, without an evident difference in *L*-MLT occurrence. These results indicate that the two mechanisms coexist and compete near midnight, thus should be both considered to understand the relativistic electron loss in the outer radiation belt (Artemyev et al., 2013), as well as the source of precipitation from the magnetosphere into the nightside upper atmosphere of the Earth.

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References

Artemyev, A. V., Orlova, K. G., Mourenas, D., Agapitov, O. V., and Krasnoselskikh, V. V.: Electron pitch-angle diffusion: resonant scattering by waves vs. nonadiabatic effects, Ann. Geophys., 31, 1485–1490, https://doi.org/10.5194/angeo-31-1485-2013, 2013.

Blum, L. W., et al. (2015), Observations of coincident EMIC wave activity and duskside energetic electron precipitation on 18-19 January 2013, Geophysical Research Letters, 42, 5727-5735, doi:10.1002/2015GL065245.

Blum, L., Li, X., and Denton, M. (2015), Rapid MeV electron precipitation as observed by SAMPEX/HILT during high-speed stream-driven storms. J. Geophys. Res. Space Physics, 120, 3783– 3794. doi: 10.1002/2014JA020633.

Büchner, J., and Zelenyi, L. M. (1989), Regular and chaotic charged particle motion in magnetotaillike field reversals: 1. Basic theory of trapped motion, J. Geophys. Res., 94(A9), 11821– 11842, doi:10.1029/JA094iA09p11821.

Capannolo, L., Li, W., Ma, Q., Chen, L., Shen, X.-C., Spence, H. E., et al. (2019b). Direct observation of subrelativistic electron precipitation potentially driven by EMIC waves. Geophysical Research Letters, 46, 12711– 12721. https://doi.org/10.1029/2019GL084202

Capannolo, L., Li, W., Ma, Q., Shen, X.-C., Zhang, X.-J., Redmon, R. J., et al. (2019a). Energetic electron precipitation: Multievent analysis of its spatial extent during EMIC wave activity. Journal of Geophysical Research: Space Physics, 124. https://doi.org/10.1029/2018JA026291

Capannolo, L., Li, W., Spence, H., Johnson, A. T., Shumko, M., Sample, J., & Klumpar, D. (2021). Energetic electron precipitation observed by FIREBIRD-II potentially driven by EMIC waves: Location, extent, and energy range from a multievent analysis. Geophysical Research Letters, 48, e2020GL091564. https://doi.org/10.1029/2020GL091564

Carson, B. R., Rodger, C. J., and Clilverd, M. A. (2012), POES satellite observations of EMIC-wave driven relativistic electron precipitation during 1998–2010, J. Geophys. Res. Space Physics, 118, 232– 243, doi:10.1029/2012JA017998.

Clilverd, M. A., Duthie, R., Hardman, R., Hendry, A. T., Rodger, C. J., Raita, T., Engebretson, M., Lessard, M. R., Danskin, D., and Milling, D. K. (2015), Electron precipitation from EMIC waves: A case study from 31 May 2013. J. Geophys. Res. Space Physics, 120, 3618– 3631. doi: 10.1002/2015JA021090.

Comess, M. D., Smith, D. M., Selesnick, R. S., Millan, R. M., and Sample, J. G. (2013), Duskside relativistic electron precipitation as measured by SAMPEX: A statistical survey, J. Geophys. Res. Space Physics, 118, 5050– 5058, doi:10.1002/jgra.50481.

Dubyagin, S., Apatenkov, S., Gordeev, E., Ganushkina, N., & Zheng, Y. (2021). Conditions of loss cone filling by scattering on the curved field lines for 30 keV protons during geomagnetic storm as inferred from numerical trajectory tracing. Journal of Geophysical Research: Space Physics, 126, e2020JA028490. https://doi.org/10.1029/2020JA028490

Dubyagin, S., Ganushkina, N., Apatenkov, S., Kubyshkina, M., Singer, H., and Liemohn, M.: Geometry of duskside equatorial current during magnetic storm main phase as deduced from magnetospheric and low-altitude observations, Ann. Geophys., 31, 395–408, https://doi.org/10.5194/angeo-31-395-2013, 2013.

Evans, D. S., and M. S. Greer (2004), Polar Orbiting Environmental Satellite Space Environment Monitor-2: Instrument Descriptions and Archive Data Documentation, NOAA Tech. Mem. 93, version 1.4, Space Weather Predict. Cent., Boulder, Colo.

Fytterer, T., Mlynczak, M. G., Nieder, H., Pérot, K., Sinnhuber, M., Stiller, G., and Urban, J.: Energetic particle induced intra-seasonal variability of ozone inside the Antarctic polar vortex observed in satellite data, Atmos. Chem. Phys., 15, 3327–3338, https://doi.org/10.5194/acp-15-3327-2015, 2015.

Ganushkina, N. Yu., Pulkkinen, T. I., Kubyshkina, M. V., Sergeev, V. A., Lvova, E. A., Yahnina, T. A., Yahnin, A. G., and Fritz, T.: Proton isotropy boundaries as measured on mid- and low-altitude satellites, Ann. Geophys., 23, 1839–1847, https://doi.org/10.5194/angeo-23-1839-2005, 2005.

Gasque, L. C., Millan, R. M., & Shekhar, S. (2021). Statistically determining the spatial extent of relativistic electron precipitation events using 2-s polar-orbiting satellite data. Journal of Geophysical Research: Space Physics, 126, e2020JA028675. https://doi.org/10.1029/2020JA028675

Gilson, M. L., Raeder, J., Donovan, E., Ge, Y. S., and Kepko, L. (2012), Global simulation of proton precipitation due to field line curvature during substorms, J. Geophys. Res., 117, A05216, doi:10.1029/2012JA017562.

Greeley, A. D., Kanekal, S. G., Baker, D. N., Klecker, B., & Schiller, Q. (2019). Quantifying the contribution of microbursts to global electron loss in the radiation belts. Journal of Geophysical Research: Space Physics, 124, 1111– 1124. https://doi.org/10.1029/2018JA026368

Green, J. C. (2013), MEPED Telescope Data Processing Algorithm Theoretical Basis Document, Natl. Oceanic and Atmos. Admin. National Geophysical Data Center, Boulder, Colorado

Green, J. C., Onsager, T. G., O'Brien, T. P., and Baker, D. N. (2004), Testing loss mechanisms capable of rapidly depleting relativistic electron flux in the Earth's outer radiation belt, J. Geophys. Res., 109, A12211, doi:10.1029/2004JA010579.

Hendry, A. T., Rodger, C. J., Clilverd, M. A., Engebretson, M. J., Mann, I. R., Lessard, M. R., Raita, T., and Milling, D. K. (2016), Confirmation of EMIC wave-driven relativistic electron precipitation, J. Geophys. Res. Space Physics, 121, 5366– 5383, doi:10.1002/2015JA022224.

Jordanova, V. K., Albert, J., & Miyoshi, Y. (2008). Relativistic electron precipitation by EMIC waves from self-consistent global simulations. Journal of Geophysical Research, 113, A00A10. https://doi.org/10.1029/2008JA013239Khazanov, G. V., Robinson, R. M., Zesta, E., Sibeck, D. G., Chu, M., & Grubbs, G. A. (2018). Impact of precipitating electrons and magnetosphere-ionosphere coupling processes on ionospheric conductance. Space Weather, 16, 829– 837. https://doi.org/10.1029/2018SW001837

Kurth, W. S., De Pascuale, S., Faden, J. B., Kletzing, C. A., Hospodarsky, G. B., Thaller, S., & Wygant, J. R. (2015). Electron densities inferred from plasma wave spectra obtained by the waves instrument on Van Allen Probes. Journal of Geophysical Research: Space Physics, 120, 904–914. https://doi.org/10.1002/2014JA020857

Li, W., & Hudson, M. K. (2019). Earth's Van Allen Radiation Belts: From Discovery to the Van Allen Probes Era. Journal of Geophysical Research: Space Physics, 124, 8319–8351. https://doi.org/10.1029/2018JA025940

Li, W., Thorne, R. M., Meredith, N. P., Horne, R. B., Bortnik, J., Shprits, Y. Y., and Ni, B. (2008), Evaluation of whistler mode chorus amplification during an injection event observed on CRRES, J. Geophys. Res., 113, A09210, doi:10.1029/2008JA013129.

Liang, J., Donovan, E., Ni, B., Yue, C., Jiang, F., and Angelopoulos, V. (2014), On an energy-latitude dispersion pattern of ion precipitation potentially associated with magnetospheric EMIC waves, *J. Geophys. Res. Space Physics*, 119, 8137– 8160, doi:10.1002/2014JA020226.

Mauk, B.H., Fox, N.J., Kanekal, S.G. et al. (2013), Science Objectives and Rationale for the Radiation Belt Storm Probes Mission, Space Science Reviews, 179: 3. https://doi.org/10.1007/s11214-012-9908-y.

Meraner, K. and Schmidt, H. (2018): Climate impact of idealized winter polar mesospheric and stratospheric ozone losses as caused by energetic particle precipitation, Atmospheric Chemistry and Physics, 18, 1079-1089, https://doi.org/10.5194/acp-18-1079-2018.

Meredith, N. P., Horne, R. B., Thorne, R. M., & Anderson, R. R. (2003). Favored regions for chorus-driven electron acceleration to relativistic energies in the Earth's outer radiation belt. Geophysical Research Letters, 30(16), 1871. https://doi.org/10.1029/2003GL017698

Millan, R. M., & Thorne, R. M. (2007). Review of radiation belt relativistic electron losses. Journal of Atmospheric and Solar-Terrestrial Physics, 69(3), 362–377. https://doi.org/10.1016/j.jastp.2006.06.019

Mironova, Irina A.; Aplin, Karen L.; Arnold, Frank; Bazilevskaya, Galina A.; Harrison, R. Giles; Krivolutsky, Alexei A.; Nicoll, Keri A.; Rozanov, Eugene V.; Turunen, Esa; Usoskin, Ilya G. (2015) Energetic Particle Influence on the Earth's Atmosphere, Space Science Reviews, Volume 194, Issue 1-4, pp. 1-96, doi 10.1007/s11214-015-0185-4

Miyoshi, Y., Sakaguchi, K., Shiokawa, K., Evans, D., Albert, J., Connors, M., and Jordanova, V. (2008), Precipitation of radiation belt electrons by EMIC waves, observed from ground and space, Geophys. Res. Lett., 35, L23101, doi:10.1029/2008GL035727.

Qin, M., Hudson, M., Millan, R., Woodger, L., & Shekhar, S. (2018). Statistical investigation of the efficiency of EMIC waves in precipitating relativistic electrons. Journal of Geophysical Research: Space Physics, 123. https://doi.org/10.1029/2018JA025419

Remya, B., Sibeck, D. G., Halford, A. J., Murphy, K. R., Reeves, G. D., Singer, H. J., et al. (2018). Ion injection triggered EMIC waves in the Earth's magnetosphere. Journal of Geophysical Research: Space Physics, 123, 4921–4938. https://doi.org/10.1029/2018JA025354

Robinson, R. M., Vondrak, R. R., Miller, K., Dabbs, T., and Hardy, D. (1987), On calculating ionospheric conductances from the flux and energy of precipitating electrons, J. Geophys. Res., 92(A3), 2565– 2569, doi:10.1029/JA092iA03p02565.

Rodger, C. J., M. A. Clilverd, J. C. Green, and M. M. Lam (2010), Use of POES SEM-2 observations to examine radiation belt dynamics and energetic electron precipitation into the atmosphere, Journal of Geophysics Research Space Physics, 115, A04202, doi:10.1029/2008JA014023.

Selesnick, R. S., Tu, W., Yando, K. B., Millan, R. M., & Redmon, R. J. (2020). POES/MEPED angular response functions and the precipitating radiation belt electron flux. Journal of Geophysical Research: Space Physics, 125, e2020JA028240. https://doi.org/10.1029/2020JA028240

Sergeev, V. A., Gordeev, E. I., Merkin, V. G., & Sitnov, M. I. (2018). Does a local B-minimum appear in the tail current sheet during a substorm growth phase?. Geophysical Research Letters, 45, 2566– 2573. https://doi.org/10.1002/2018GL077183

Sergeev, V. A., Malkov, M., and Mursula, K. (1993), Testing the isotropic boundary algorithm method to evaluate the magnetic field configuration in the tail, J. Geophys. Res., 98(A5), 7609– 7620, doi:10.1029/92JA02587.

Shekhar, S., Millan, R. M., & Hudson, M. K. (2018). A statistical study of spatial variation of relativistic electron precipitation energy spectra with Polar Operational Environmental Satellites. Journal of Geophysical Research: Space Physics, 123, 3349–3359. https://doi.org/10.1002/2017JA025041

Shekhar, S., Millan, R., & Smith, D. (2017), A statistical study of the spatial extent of relativistic electron precipitation with polar orbiting environmental satellites. Journal of Geophysical Research: Space Physics, 122, 11,274–11,284. https://doi.org/10.1002/2017JA024716

Sivadas, N., Semeter, J., Nishimura, Y. T., & Mrak, S. (2019). Optical signatures of the outer radiation belt boundary. Geophysical Research Letters, 46, 8588– 8596. https://doi.org/10.1029/2019GL083908

Smith, D. M., Casavant, E. P., Comess, M. D., Liang, X., Bowers, G. S., Selesnick, R. S., Clausen, L. B. N., Millan, R. M., and Sample, J. G. (2016), The causes of the hardest electron precipitation events seen with SAMPEX, J. Geophys. Res. Space Physics, 121, 8600– 8613, doi:10.1002/2016JA022346.

Summers, D., & Thorne, R. M. (2003). Relativistic electron pitch-angle scattering by electromagnetic ion cyclotron waves during geomagnetic storms. Journal of Geophysical Research, 108(A4), 1–12. https://doi.org/10.1029/2002JA009489

Thorne, R. M. (2010), Radiation belt dynamics: The importance of wave-particle interactions, Geophysical Research Letters, 37, L22107, doi:10.1029/2010GL044990.

Tsyganenko, N. A., and M. I. Sitnov (2005), Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms, Journal of Geophysics Research, 110, A03208, doi:10.1029/2004JA010798.

Sergeev, V.A., E.M. Sazhina, N.A. Tsyganenko, J.Å. Lundblad, F. Søraas, Pitch-angle scattering of energetic protons in the magnetotail current sheet as the dominant source of their isotropic precipitation into the nightside ionosphere, Planetary and Space Science, Volume 31, Issue 10, 1983, Pages 1147-1155, ISSN 0032-0633, https://doi.org/10.1016/0032-0633(83)90103-4.

Woodger, L. A., Millan, R. M., Li, Z., & Sample, J. G. (2018), Impact of background magnetic field for EMIC wave-driven electron precipitation. Journal of Geophysical Research: Space Physics, 123, 8518– 8532. https://doi.org/10.1029/2018JA025315

Yahnin, A. G., T. A. Yahnina, N. V. Semenova, B. B. Gvozdevsky, and A. B. Pashin (2016), Relativistic electron precipitation as seen by NOAA POES, Journal of Geophysics Research Space Physics, 121, doi:10.1002/2016JA022765.

Yahnin, A. G., T. A. Yahnina, T. Raita, and J. Manninen (2017), Ground pulsation magnetometer observations conjugated with relativistic electron precipitation, Journal of Geophysics Research Space Physics, 122, 9169-9182, doi:10.1002/2017JA024249.

Yando, K., Millan, R. M., Green, J. C., & Evans, D. S. (2011). A Monte Carlo simulation of the NOAA POES medium energy proton and Electron detector instrument. Journal of Geophysics Research, 116, A10231. https://doi.org/10.1029/2011JA016671

Yu, Y., Jordanova, V. K., McGranaghan, R. M., & Solomon, S. C. (2018). Self-consistent modeling of electron precipitation and responses in the ionosphere: Application to low-altitude energization during substorms. Geophysical Research Letters, 45, 6371– 6381. https://doi.org/10.1029/2018GL078828

Figure 1. Example of a wave-driven (a) and a CSS-driven (b) REP event, observed by NOAA-19 and NOAA-16, respectively. Dotted (solid) lines indicate the trapped (precipitating) electrons measured by the 90° (0°) telescope. Different colors specify different electron energy channels. Horizontal dashed lines indicate the flux thresholds used in the algorithm (details in SI). The vertical lines in a) identify the radial extent of the wave-driven event. The vertical line in b) shows the *L*-shell where the energy dispersion is starting.

Figure 2. a) Scatter plot of the location of the wave-driven (blue) and CSS-driven (gray) REP. Blue points are located at the average *L* and MLT calculated within the event boundaries (vertical lines in Figure 1a). Gray points are located at the *L*-shell (and relative MLT) that marks the energy dispersion (vertical line in Figure 1b). Histograms in MLT (b) and *L* (c) of wave-driven (blue) and CSS-driven (gray) REP. Occurrence (number of events in each bin normalized to the total 391 REP events) is shown in red (right axis). d) Scatter plot and e) histogram of radial extent (defined as in Figure 1a) for the wave-driven REP.

Figure 3. Left: example of a POES & GOES conjunction during a CSS-driven event; a) POES observation in a similar format to that in Figure 1b, b) elevation angle and c) magnetic field components from GOES. d) Distribution (gray) of the elevation angles for wave-driven and e) CSS-driven events during POES & GOES conjunctions. Distributions in orange are relative to the monthly average elevation angles (details in the SI).