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COMMENTARY
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Unraveling the Mystery of Earth's Space Radiation Environment Loss Processes: Meeting Report

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Key Points:

- We investigate several physical mechanisms that may contribute to ring current electron losses not captured by the model
- Additional scattering by ECH waves is not sufficient to fully explain the missing loss in the simulations
- Future ring current simulations should include the scattering by time domain structures and inductive electric fields

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Abstract On 10 June and 27 September 2024, two workshops were held at GFZ Potsdam under the umbrella of the Geo. X Research Network of Geosciences to discuss the unresolved question of the overestimation and lack of scattering of modeled ring current electrons during geomagnetic storms. At the workshops, we discussed the potential contributions to the lack of scattering of electron cyclotron harmonic (ECH) waves, chorus waves, time-domain-structures (TDS), the non-linear effects of wave-particle interactions, and induced electric fields. A case study shows that the scattering by ECH waves is insufficient to account fully for the missing electron loss. More work must be done to understand the potential effects of inaccuracies in the assumed chorus wave models, TDS, and the non-linear effects of wave-particle interactions. Including induced electric fields in ring current simulations is an important step to describe the electron drifts more accurately. Explaining the missing loss process is crucial for space weather applications of surface charging effects, which rely on accurate predictions of ring current electron fluxes.

1. Introduction

Earth's magnetic field perpetually interacts with the ever-fluctuating stream of charged particles from the Sun. This dynamic process causes significant changes in the particle population within the Earth's inner magnetosphere. Energetic ring current electrons of 1–100 keV, often called the source population of the radiation belts, are one of the most challenging systems to model in the inner magnetosphere. These electrons can also cause surface charging effects that damage electronics or solar panels, posing a threat to the rapidly growing satellite infrastructure. Electrons with an energy of around 10 keV are most efficient for charging many spacecraft surface materials, because they generate significantly fewer secondary electrons from the surface (Thomsen et al., 2013). Accurate prediction of stormtime flux versus energy spectra, especially in operational settings, is therefore particularly important for space weather applications (Minow et al., 2024).

Strong solar wind driving can trigger geomagnetic storms, as follows. An enhanced global electric field draws particles from a distant nightside region known as the plasmasheet, and transports them earthward to the inner magnetosphere (e.g., Ganushkina et al., 2017). The resulting surge of particles builds into a highly asymmetric ring current. The storm surge generates plasma waves on the night- and dawn side, which in turn interact with electrons of both ring current and radiation belts (e.g., Thorne et al., 2010). Wave-particle interactions can scatter electrons into the ionosphere, a process known as electron precipitation that causes changes in the ionospheric conductance and the convective paths of particles in both the ionosphere and inner magnetosphere (Fang et al., 2008; Liemohn et al., 2005; Yu et al., 2016). During all these rapid dynamical changes, the energetic electron flux can vary by orders of magnitude within hours during geomagnetic storms (e.g., Haas et al., 2022).

Modern physics-based ring current models calculate the earthward transport of particles by the ambient magnetic and electric fields. Critically, these models must also account for how particles are lost from the ring current, primarily through (largely wave-driven) electron precipitation. Therefore, electron ring current modeling requires accurate representations of the plasma sheet source, the electric and magnetic fields in the inner magnetosphere, and the populations of plasma waves. In simulation studies, the assumed electric field and plasma wave

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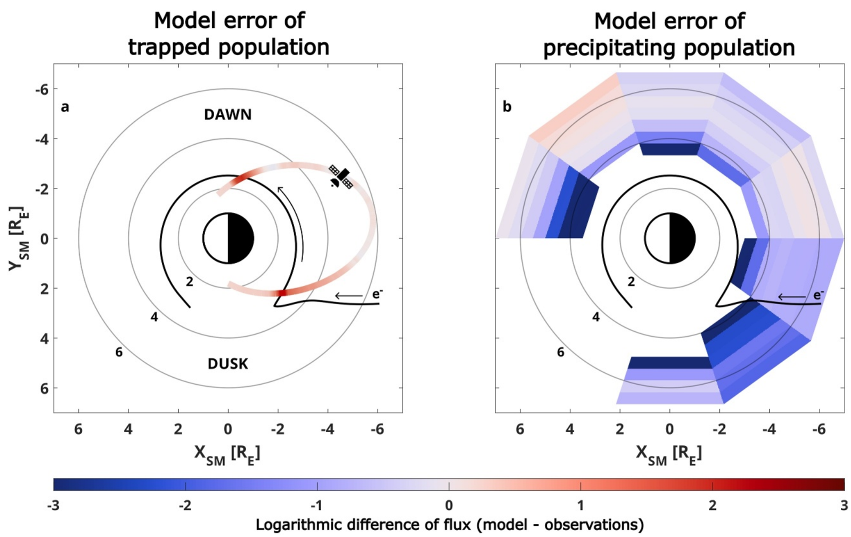

Figure 1. Model errors observed during strong geomagnetic storms. (a) Overestimation of the trapped population as predicted by the ring current model compared to a Van Allen Probes satellite. The black path shows the drift trajectory of electrons. (b) Underestimation of the precipitating flux as predicted by the ring current model compared to the POES satellites. Figure adapted from Haas et al. (2023, 2024). For details, we refer to these references.

populations are the deciding factors in determining whether a local enhancement of the electron ring current develops during a geomagnetic storm (Haas et al., 2022).

Whereas some simulations rely on empirical models for specifying the electric field, others calculate the electric field self-consistently, promising a more realistic description (Ilie et al., 2017; Wu et al., 2022; Yu et al., 2017). Until now, only empirical models have been used to estimate the inner magnetospheric waves, because a self-consistent treatment has not yet been developed. The interaction between the waves and particles is typically included with a quasilinear treatment (Kennel & Engelmann, 1966). This approach simplifies the complex wave-particle interactions, but often neglects nonlinear effects that become important for strong waves (e.g., Albert et al., 2021). Whistler-mode chorus and hiss waves are efficient in scattering ring current electrons (Orlova et al., 2016; Thorne et al., 2010) and thus have typically been included in the models. Other types of waves, such as kinetic Alfvén waves, electron cyclotron harmonic waves, or time-domain structures, have not been included in ring current models because they are assumed not to be crucial for electron ring current dynamics (Jordanova, 2020; Thorne et al., 2010).

How are ring current simulations performing? Several recent independent studies (Chen et al., 2019; Haas et al., 2023; Yu et al., 2022) have shown that ring current models can overestimate the trapped electron population between 10 and 50 keV by over two orders of magnitude during strong geomagnetic storms (see Figure 1). The overestimation of modeled fluxes can either be caused by excessive earthward convection due to inaccuracies in the assumed global electric fields or by insufficient losses by the assumed wave properties and the lack of a self-consistent model for wave-particle interactions. A recent study proposed that the overestimation is the outcome of insufficient predicted scattering of electrons in the pre-midnight sector (Haas et al., 2023). Another independent study also acknowledges modeling errors "from dusk to premidnight where there are large uncertainties in the electron loss model" due to the assumed static electron lifetimes in the dusk region (Chen et al., 2019).

To investigate this hypothesis, model-predicted particle precipitation has been compared with observations by low-Earth-orbit satellites (Haas et al., 2024). It was found that the underestimation of scattering losses enables simulated electrons to access regions closer to Earth, resulting in significant discrepancies between model results and measurements. Whereas the severity of underestimation has been estimated (Haas et al., 2023), the physical process responsible for the scattering unaccounted in the simulation is undetermined.

The mystery behind the hypothesized missing loss process and the role of the electric field were discussed in two recent workshops hosted at GFZ Potsdam on 10 June and 27 September 2024. The commentary herein summarizes the discussion results and potential plans for validating the electron ring current models. Note that in this

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report, we specify energy ranges as they were given in cited studies or presented at the meeting. We believe this approach provides an objective perspective of the state of the art in our field.

2. Discussion

2.1. Minima in Phase Space Density

One of the approaches to studying radiation belt losses is the analysis of phase space density (PSD) profiles. This method can provide insight into the physical mechanisms responsible for electron loss. Deepening minima in PSD profiles can be used to identify rapid, localized loss processes in the radiation belts and ring current, such as those driven by electromagnetic ion cyclotron (EMIC) waves (Drozdov et al., 2022). A recent and relevant finding regarding the missing loss discussed by Drozdov et al. (2024) is the identification of deepening PSD minima for lower-energy electrons in the range of 10–100 s of keV, which had not been thoroughly studied before. The discovered distribution of deepening PSD minima at these energies is strongly influenced by the L-shell-dependent variations in electron lifetimes due to scattering by hiss waves.

The Versatile Electron Radiation Belt (VERB) code simulations demonstrate that the shortest lifetimes for 100–150 keV seed electrons occur in regions of the radiation belts where hiss wave scattering is most effective, leading to rapid localized losses and the formation of PSD minima. The simulation results indicate that the timescale for electron loss due to hiss waves is much shorter (on the order of less than a day) than the timescale for radial diffusion, indicating that hiss waves play an important role in seed electron dynamics.

Other fast-localized scattering processes, relative to the smoothing of PSD profiles by radial diffusion, may also contribute to the observed distribution of PSD deepening minima. The dynamics of low-energy electrons can be significantly affected by convective transport, which requires advanced modeling approaches, such as 4-D simulations, to capture these effects accurately. Mechanisms discussed later in the text, such as scattering by electron cyclotron harmonic (ECH) waves and time-domain structures (TDS) might also influence the formation of PSD deepening minima. Future simulation improvements should consider them and more detailed parameterizations of hiss waves. Additionally, a thorough analysis of PSD profiles for low-energy electrons during strong storm times can help to further validate the spatial location and strength of the missing loss process.

2.2. Considerations Regarding Chorus Waves

It is worth looking at the limitations of developing empirical wave models. Traditionally, such models are constructed by averaging long-term wave measurements (e.g., D. Wang et al., 2019). However, this approach can obscure the infrequent occurrence of waves in certain regions, such as the pre-midnight sector, where chorus wave occurrence rates are relatively low. Moreover, wave statistics are often sparse during strong geomagnetic storms. These limitations can lead to an underestimation of wave intensity in the pre-midnight sector during storm times, which in turn contributes to an overestimation of electron flux in ring current models. Consequently, the accuracy of electron scattering rates due to chorus waves may be compromised during these events.

Another underlying controlling factor not included in modern ring current models is the dependency of the scattering rates on the cold plasma density. It has been shown that wave-particle interactions strongly depend on the background cold plasma conditions (Allison et al., 2021). Therefore, the time-dependent global density distribution is important, and yet simple empirical cold plasma models (e.g., Sheeley et al., 2001) independent of geomagnetic activity are usually used to calculate scattering rates. Alwin Roy presented electron lifetimes due to scattering by upper-band chorus waves for extremely low density conditions compared to empirical models and showed that lower plasma density leads to faster scattering of electrons with energies relevant to the missing loss process. Such low-density conditions are observed in the pre-midnight sector during geomagnetic storms (Ripoll et al., 2024), making the density dependency of chorus waves a viable candidate for explaining the missing loss.

We concluded that chorus wave statistics from multiple missions should be intercalibrated and combined into one unified empirical wave model to improve the accuracy of derived scattering rates during strong geomagnetic storms. Furthermore, the cold plasma density should also be considered as an input in ring current models to test the contribution of the density-dependent electron lifetimes to the missing loss process.

2.3. Realistic Scattering by ECH Waves in the Inner Magnetosphere

ECH waves are high-frequency waves observed in bands between the harmonics of the electron gyrofrequency. They occur predominantly on the nightside (20 < MLT < 06) of the inner magnetosphere ($4 < L < 8$, Meredith et al. (2009); Ni et al. (2017)), but have also been observed in the outer magnetosphere ($L \geq 12$, X. Zhang et al. (2013)). It is known that resonant interactions between ECH waves and plasma sheet electrons can lead to electron scattering into the atmospheric loss cone. ECH waves are often associated with diffuse auroral precipitation of electrons with energies of a few hundred eV to keV (e.g., Horne & Thorne, 2000; Lyons, 1974). The scattering rates due to wave-particle interactions with ECH waves increase with increasing geomagnetic activity (Ni et al., 2011). Therefore, depending on the ambient conditions in the plasma sheet, they can produce loss of electrons of several keV (Fukizawa et al., 2022; Stoll et al., 2023) and are a potential candidate to explain the missing loss process. However, ECH waves have not yet been included in quasi-linear radiation belts and ring current dynamics studies.

In the workshop, we reported on our progress in studying an ECH wave event that occurred during the 17 March 2013 geomagnetic storm and was observed by the RBSP-A spacecraft. We used the "full diffusion code" (Shprits & Ni, 2009) to calculate bounce-averaged pitch angle diffusion coefficients, from which we inferred electron lifetimes and implemented them in the loss term of the VERB-4D code setup provided by Haas et al. (2023). The workshop participants discussed many assumptions needed for calculating the diffusion coefficients, such as plasma density, background magnetic field, initial phase space density distribution, and wave normal angle distribution. Considering these uncertainties, the shortest possible electron lifetimes due to the scattering by ECH waves are still up to 100 times longer than the lifetimes required to explain the missing loss process. It is, therefore, concluded that the loss produced by ECH waves in the inner magnetosphere ($2.5 \leq L \leq 5$) for the event in question is most likely too small to contribute significantly to the unaccounted ring current electron loss (Stoll et al., 2025).

2.4. Anomalous Diffusion

The concept of "anomalous diffusion" could help to incorporate non-linear effects of wave-particle interactions into ring current models. Anomalous diffusion (Metzler et al., 2014), featuring a power-law form of the mean-squared displacement $\langle x^2(t) \rangle = \int_{-\infty}^{\infty} x^2 P(x,t) dx = 2D_\alpha t^\alpha$ where D_α is the generalized diffusion coefficient, α is the exponent of anomalous diffusion, and $P(x,t)$ is the probability density function of the displacement, has been observed across a wide range of physical systems and space-time scales. Since we are dealing with anomalous diffusion, it is worth noting that alpha is not equal to 1. Subdiffusion features an anomalous diffusion exponent in the range $0 < \alpha < 1$, superdiffusion is realized for $1 < \alpha < 2$, Brownian motion (W. Wang et al., 2023) corresponds to $\alpha = 1$, and $\alpha = 2$ describes ballistic transport.

Superdiffusion has been discussed at plasma boundaries, such as the magnetopause (Cowee et al., 2009; Treumann, 1997), where hybrid simulations (kinetic ions, fluid electrons) have shown that the diffusion characteristics exhibit superdiffusive behavior. The authors showed that the jump length, defined as the mean displacement of a particle from its starting position, does not follow a Gaussian probability distribution function. As the variance of fitted Gaussians does not increase linearly but follows a power law, the particles undergo superdiffusive behavior. A similar analysis could be applied to diffusive processes in the radiation belts and the ring current. When wave amplitudes become sufficiently high, non-linear scattering effects can no longer be ignored (Allanson et al., 2021), unlike in the quasi-linear theory, which underlies all ring current models. Particles undergoing resonant phase trapping in coherent, high-amplitude waves experience ballistic transport toward higher energies. These jumps lead to the formation of non-Gaussian, heavy-tailed distributions (X.-J. Zhang et al., 2020), which could potentially be modeled through superdiffusion. However, it is still debated how these effects can be included in ring current and radiation belt simulations and what their impact is on the global population. The efficiency of transport and its convergence toward stochastic behavior depend on the fine structure of the wave fields (Hanzelka et al., 2025; Mourenas et al., 2022), which needs to be carefully modeled based on spacecraft measurements and self-consistent simulations (X.-J. Zhang et al., 2021).

Wave amplitudes usually increase with increasing geomagnetic activity. Non-linear effects should therefore be more pronounced during strong storms (Kondrashov et al., 2024), which is also when we observe the missing loss. Frameworks for incorporating non-linear wave-particle interactions into radiation belts and ring current models are currently under development (Artemyev et al., 2022). Once they are available, the role of non-linear effects in the missing loss process should be studied in detail.

2.5. The Effect of Inductive Electric Fields

The significance of self-consistent treatment of the magnetic and electric fields in inner magnetosphere models, particularly regarding the inclusion and treatment of inductive electric fields sourced by local changes in the ambient magnetic field, is not fully understood. Recent studies have demonstrated that the inductive electric field persists even during steady solar driving, providing an additional source for long-lasting plasma drifts. Under certain solar wind conditions, the magnitude of the inductive field can reach several mV/m, often dominating the potential component of the electric field (Ilie et al., 2017; Liu & Ilie, 2021; Liu et al., 2025).

Even a localized rapid change in the magnetic field can induce a global electric field, affecting the electron and proton ring current particles. Thus, the inductive electric field can provide effective energization or de-energization for the trapped ring current particles.

Moreover, during geomagnetic storms, the inductive component of the electric field could act to reduce the overall strength of the local electric field by counteracting the potential component. This would result in less energization of the ring current and help explain why models that neglect the induced electric fields tend to overestimate the low-energy electron ring current population.

We concluded that the effect of the induced electric fields on the electron ring current populations should be studied in more detail in the future.

2.6. Time Domain Structures

Broadband electric field fluctuations, also known as time-domain structures (TDS), can significantly scatter electrons in the magnetosphere. This broadband electrostatic noise has been known since 1976 (Gurnett et al., 1976) and can contribute significantly to the redline-dominated diffuse aurora (Shen et al., 2024). Still, the theory for calculating scattering rates due to electron phase space holes has only been developed recently (Vasko et al., 2017, 2018). Under reasonable assumptions, quasi-linear theory can be applied to the scattering problem, treating the scattering as a diffusion process, similar to interactions between electrons and whistler waves (Kennel & Engelmann, 1966). By utilizing statistical studies of the properties of electron holes (Lotekar et al., 2020; Malaspina et al., 2018), realistic bounce-averaged diffusion coefficients have been calculated for the inner magnetosphere ($L = 6$) and current sheet ($L = 12$) (Shen et al., 2021). The estimated scattering rates are comparable to the scattering rates of chorus or ECH waves and can reach the theoretical upper limit of strong diffusion for energies below 10 keV, if the amplitude of the waves is strong enough.

Given that almost all injections are accompanied by TDS (Malaspina et al., 2015), it was concluded at the workshop that TDS represent a strong candidate for the missing loss process. Realistic diffusion coefficients shall be calculated and used in ring current models to test the hypothesis that TDS represent the missing loss process. A reasonable approach could be to select storm events for which enough wave measurements are available in the pre-midnight sector to correctly estimate the scattering rates of TDS.

3. Summary

In two workshops held at GFZ Potsdam, we discussed the issue of missing loss in electron ring current models. We identified several strong candidates that could potentially explain the missing loss and discussed the next research directions to reveal this missing process. Our findings can be summarized as follows:

1. Chorus waves in the pre-midnight sector may not be accurately described by statistical models during storm times because the high values are averaged out due to their low occurrence rate.
2. The dependency of wave-particle interactions on the plasmaspheric density can have large effects on the scattering rates of electrons and should be included in ring current and radiation belt models.
3. Even strong ECH waves are not capable of fully explaining the missing loss in the inner magnetosphere.
4. Inductive electric fields can considerably change the particle dynamics in the inner magnetosphere and should be considered in MHD-kinetic coupled models.

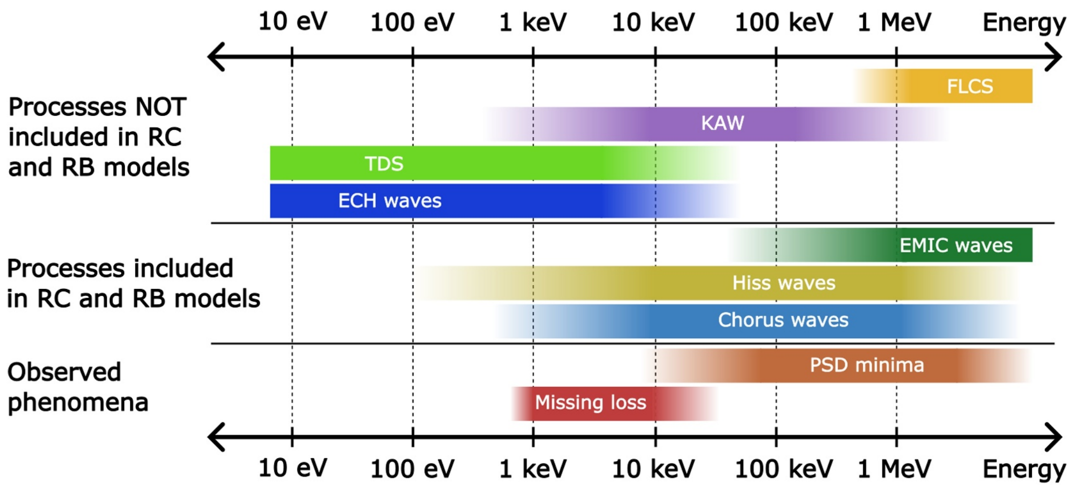

Figure 2. Energy ranges for processes and observed phenomena for the electron ring current (RC) and electron radiation belts (RB).

5. With the concept of anomalous diffusion, it may be possible to describe the wave-particle interactions more accurately.
6. TDS are a promising candidate to represent the missing loss. Future electron ring current models should include the scattering by them to test this hypothesis.

Figure 2 is an attempt at giving an overview of the processing acting on the electron ring current and electron radiation belts and their affecting energy ranges. The exact energy ranges are still objectives of active research, which is indicated by the color gradients. All energy ranges highly depend on L shell and may be quite different under extreme conditions like superstorms. Establishing the detailed interplay among different physical mechanisms remains an extremely challenging task, requiring dedicated input and expertise on each process, which should be pursued in the future.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data were not used, nor created for this research.

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