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Key Points:
- Deepening minimums in PSD at ultra-relativistic energies show that these particles are subject to local loss
- Profiles of PSD at relativistic energies are monotonic, as they are not significantly affected by EMIC wave loss
- Deepening of minimums can be often observed at various radial distances

Supporting Information:
- Supporting Information S1

Correspondence to:
Y. Y. Shprits,
yshprits@gfz-potsdam.de

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Multi-MeV electron loss in the heart of the radiation belts

Yuri Y. Shprits[1,2,3], **Adam Kellerman**[2,3], **Nikita Aseev**[1], **Alexander Y. Drozdov**[2,3], **and Ingo Michaelis**[1]

[1]Helmholtz Centre Potsdam, GFZ, German Research Centre for Geosciences, Potsdam, Germany, [2]Institute of Physics and Astronomy, University of Potsdam, Potsdam, Germany, [3]Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, California, USA

Abstract Significant progress has been made in recent years in understanding acceleration mechanisms in the Earth's radiation belts. In particular, a number of studies demonstrated the importance of the local acceleration by analyzing the radial profiles of phase space density (PSD) and observing building up peaks in PSD. In this study, we focus on understanding of the local loss using very similar tools. The profiles of PSD for various values of the first adiabatic invariants during the previously studied 17 January 2013 storm are presented and discussed. The profiles of PSD show clear deepening minimums consistent with the scattering by electromagnetic ion cyclotron waves. Long-term evolution shows that local minimums in PSD can persist for relatively long times. During considered interval of time the deepening minimums were observed around $L^* = 4$ during 17 January 2013 storm and around $L^* = 3.5$ during 1 March 2013 storm. This study shows a new method that can help identify the location, magnitude, and time of the local loss and will help quantify local loss in the future. This study also provides additional clear and definitive evidence that local loss plays a major role for the dynamics of the multi-MeV electrons.

1. Introduction

The analysis of the dynamics of the radiation belts is complicated by the fact that some of the variations are reversible, or adiabatic, and others are irreversible. Observations of particle fluxes do not allow us to distinguish the reversible and irreversible changes. In recent years, significant efforts have been made in separating adiabatic and nonadiabatic changes by inferring phase space density (PSD) as a function of three adiabatic invariants L^*, μ and K or J [*Haerendel*, 1968; *Roederer*, 1970; *Schulz and Lanzerotti*, 1974]. This transformation allows us to filter out adiabatic changes and track the evolution related to the nonreversible violation of the adiabatic invariants. Analysis of the time evolution of the PSD further allows us to distinguish between acceleration mechanisms [*Selesnick and Blake*, 2000; *Green and Kivelson*, 2004]. Monotonic profiles indicate that particles are accelerated by means of radial diffusion while growing peaks in PSD can be only produced by a local (in physical space) source of particles. Detailed analysis of the PSD allowed us to routinely identify times when local acceleration operates in the radiation belts and shows its effectiveness at a very broad range of energies [*Green and Kivelson*, 2001; *Iles et al.*, 2006; *Shprits et al.*, 2007; *Shprits et al.*, 2006a; *Chen et al.*, 2007; *Reeves et al.*, 2013].

In this study, we apply the same general principle to differentiate between the different loss mechanisms in the radiation belts. As dropouts extended to very low radial distances, significantly below the magnetopause location, it was traditionally assumed that particles are all lost to the atmosphere [*Green et al.*, 2004]. The fast nature of dropouts during the main phase of a storm was attributed to EMIC waves that can reach 1–25 nT [*Engebretson et al.*, 2015] and are capable of providing fast loss of electrons [*Thorne and Kennel*, 1971]. Previous modeling studies [e.g., *Thorne and Andreoli*, 1980; *Meredith et al.*, 2003; *Chen et al.*, 2009; *Ukhorskiy et al.*, 2010] estimated that electrons at MeV and below MeV may be affected by EMIC wave scattering. However, the majority of the previous theoretical studies have been done with an assumption of the cold plasma theory which may misrepresent minimum resonant energies [*Silin et al.*, 2011]. Observations at different energies on SAMPEX, HEO, and CRRES showed that dropouts extend to 100 s of keV that cannot be affected by EMIC waves alone [*Shprits et al.*, 2006b]. *Shprits et al.* [2006b] also showed that dropouts occur at times when magnetopause and electrons close to the magnetopause are lost to the interplanetary space. Modeling and comparison with CRRES observations provided additional support for this loss mechanism. A number of follow-up studies confirmed that this loss process was operational [*Ohtani et al.*, 2009; *Turner et al.*, 2012, 2014].

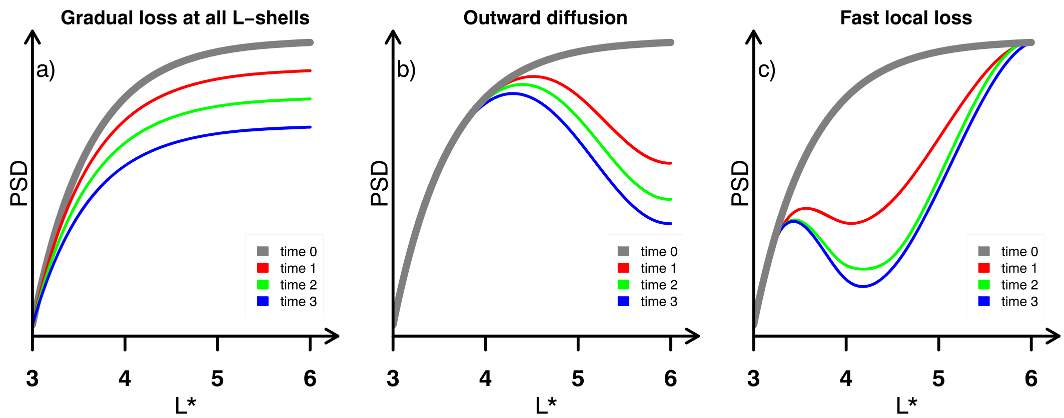

Figure 1. Illustration of the three scenarios for the evolution of the PSD during the times when particles are lost from the radiation belts. (a) The evolution of electrons subjected to gradual loss; (b) evolution during the sudden loss to the magnetopause and the outward diffusion; and (c) fast localized loss that can be provided by EMIC waves that are often confined to a narrow range of *L* shells.

Observations and modeling of the September 2012 storm during the first days of the Van Allen Probe era showed a very narrow remnant belt that was present only at multi-MeV energies [*Baker et al.*, 2013]. *Shprits et al.* [2013] presented modeling of the three-zone structure. They showed that simulations without EMIC waves could not reproduce the observed narrow remnant belts for energies between 3 MeV and 6.2 MeV, while simulations with EMIC waves accurately reproduced the dynamics of the belts for the energy range from 2 to 6.2 MeV. They suggested that additional loss driven by EMIC waves operated only above approximately 3–4 MeV, while the effects of EMIC waves were negligible below approximately 2 MeV. Long-term modeling also showed that while MeV energies can be successfully modeled with the Versatile Electron Radiation Belts (VERB)-3-D code [*Subbotin and Shprits*, 2009], additional loss mechanism, and most likely EMIC-induced wave scattering, was present above ~2 MeV [*Drozdov et al.*, 2015].

Additional evidence came from observations of the unique event during the 17 January 2013 storm, where MeV and multi-MeV belts were spatially separated which allowed us to distinguish between a number of competing loss and acceleration mechanisms [*Shprits et al.*, 2016]. Multi-MeV electrons showed clear telltale signatures of the EMIC wave scattering in energy spectrum and pitch angle distributions. Observations showed a decrease in fluxes at multi-MeV energies and an increase in MeV energies. Dynamics of the pitch angle distributions were also very different at relativistic and ultrarelativistic energies. While relativistic particles showed a broadening of the spectrum, electrons above 4 MeV showed a narrowing of the spectrum during the main phase of the storm. Comparison of the results of 3-D modeling at various energies, pitch angles, and radial distances provided additional evidence that ultrarelativistic electrons can experience additional scattering at multi-MeV energies.

In a similar manner, as radial profiles can be used to identify local acceleration, they can be also used to identify local loss. The presence of deepening local minimums in the heart of the belts can certainly be indicative of a localized loss and cannot be produced by outward radial diffusion. In this study, we focus on the analysis of the PSD during the 17 January 2013 storm discussed in detail and modeled in *Shprits et al.* [2016].

Figure 1 illustrates the evolution of the electron radiation belt PSD when the existing particles are subject to (a) gradual loss such as hiss or chorus waves; (b) loss to the magnetopause and the outward radial diffusion; and (c) fast localized loss that can be provided by EMIC waves that are often confined to a narrow range of *L* shells.

2. Evolution of the PSD During the 17 January 2013 Storm

Figure 1 illustrates three potential scenarios for PSD evolution of particle loss in the radiation belts in the absence of acceleration. In the first (Figure 1a scenario which is usually considered in the literature), particles are resonantly scattered by whistler mode waves and are gradually lost to the atmosphere [e.g., *Thorne et al.*,

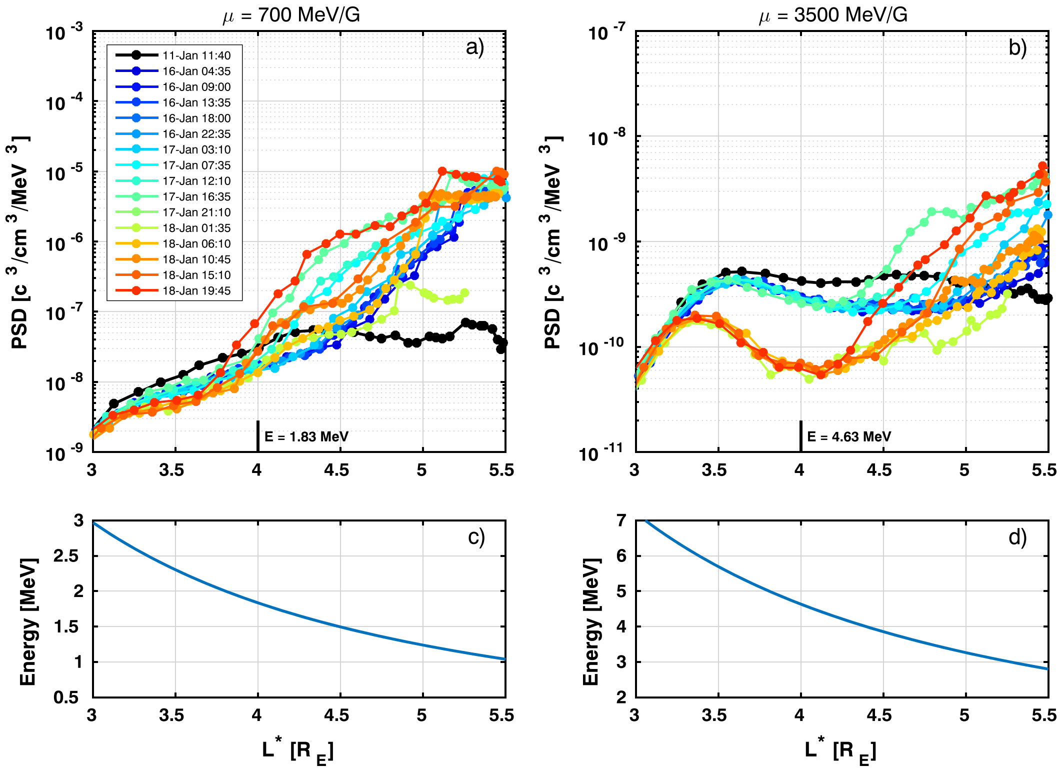

Figure 2. Profiles of PSD for (a) relativistic ($\mu = 700$ MeV/G) and (b) ultrarelativistic ($\mu = 3500$ MeV/G) electrons for $K = 0.1\ G^{1/2}R_E$ measured by RBSP-B. Black line shows undisturbed prestorm conditions, and colors show evolution during the storm (time indicates the end of the inbound and outbound orbital passes). (c and d) Energy for this value of the first invariant inferred using the dipole field. Profiles of PSD were calculated with TS07D model.

2005]. For MeV energies, time scales of loss are on the scale of 5–8 days [*Orlova et al.*, 2014, 2016], and chorus wave-induced loss is on the scale of days [*Orlova and Shprits*, 2014]. The exact loss rates show very weak dependence on radial distance and strong dependence on geomagnetic activity [*Orlova and Shprits*, 2014; *Orlova et al.*, 2014]. At multi-MeV, scattering rates by hiss become slower and may reach weeks [*Shprits et al.*, 2013]. In this case the radial profile should preserve monotonicity as the radial diffusion rates will likely dominate the loss rates, and this loss process has little radial dependence. The second scenario, Figure 1b, describes the loss to the magnetopause that drives the outward radial diffusion [*Shprits et al.*, 2006b; *Turner et al.*, 2012]. In this case, profiles of PSD will show decreasing peaks in PSD and negative gradients at higher L shells as the outer boundary decreases and the diffusion is smoothing the peak in PSD [*Selesnick and Blake*, 2000]. The third scenario (Figure 3c) presents a localized and fast loss which can be driven by EMIC waves that can produce loss rates on the scale of an hour [e.g., *Summers and Thorne*, 2003; *Li et al.*, 2007; *Ukhorskiy et al.*, 2010].

Figure 2 shows the profiles of PSD during the 17 January 2013 storms. At 700 MeV/G corresponding to relativistic energies, the radial profile is mostly monotonic, increasing in the heart of the belts with increasing radial distance. There is a small increase due to the radial diffusion and local acceleration discussed in detail in *Shprits et al.* [2016]. Figure 2b shows radial PSD profile for $\mu = 3500$ MeV/G, corresponding to energy of 4.63 at $L^* = 4$ as estimated using dipole approximation. Profiles at other values of the first invariant are presented in Figures S1 and S2 in the supporting information. There is a clear formation of the local minimum followed by the deepening during the times when the outer boundary is increasing, clearly indicated the presence of a localized and very efficient loss process.

PSD radial profiles for the lower energies ($\mu < 700$ MeV) (Figure S1 in the supporting information) are monotonic consistent with the absence of the localized loss at these energies. The minimum becomes gradually more pronounced for the first invariant increasing from 700 MeV/G to 3500 MeV (Figure S2 in the supporting information). Figures S3 and S4 in the supporting information show similar deepening local minimums in PSD

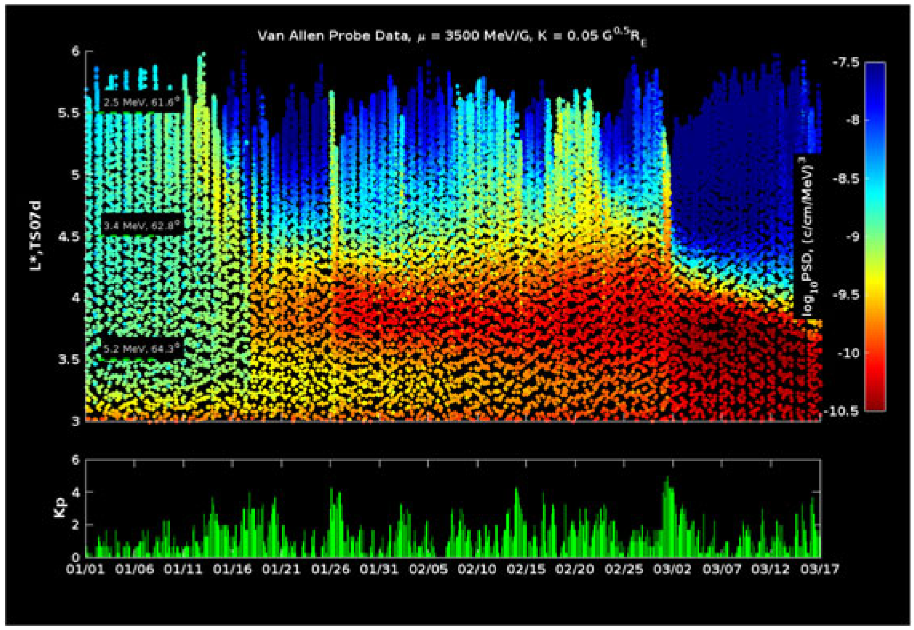

Figure 3. Evolution of the PSD from 1 January 2017 until 17 March 2017. For a fixed value of the first invariant, $\mu = 3500$ MeV/G and $K = 0.05\ G^{1/2} \cdot R_E$ as a function of tie and L^*. (bottom) The evolution of the *Kp* index.

radial profiles when calculated with two other magnetic field models (T89 [*Tsyganenko*, 1989], T04S [*Tsyganenko and Sitnov*, 2005], and TS07 [*Tsyganenko and Sitnov*, 2007]), indicating that the presence of deepening minimums is not produced by the inaccuracies of the model. These observations are consistent with the conclusions made by *Shprits et al*. [2016] that EMIC only affect electrons above several MeV and do not affect MeV population. The observation of the evolution of PSD helps clearly identify and visualize the location where the loss process is most efficient.

Figure 3 provides a longer-term evolution of the radial profile of PSD at $\mu = 3500$ MeV/G for the entire month of January 2013. Starting on 17 January 2013, we can clearly see the pronounced minimum in the PSD that is formed on 17–18 January at $L^* = 4$ and persists for over 2 weeks. Simultaneously with the deepening of the minimum, there is an intensification in the PSD above approximately $L^* = 4.5$. Such a decrease in fluxes clearly cannot be produced by the outward radial diffusion, as fluxes in the outer region of the outer belt are increasing. Such localized and fast loss cannot be explained by the hiss or chorus losses that operate in the entire radiation belts and can only account for slow loss. The minimum in fluxes is once again deepened during the 1 March 2017 storm. The minimum moves to lower *L* shells ($L^* = 3.5$) corresponding to energy of approximately 5 MeV, while PSD above $L^* = 4$ increases to reach maximum levels for the considered period of time.

3. Summary and Discussion

Observations of important waves that determine the dynamics of the radiation belts is a challenging task as the region where waves interact with electrons may be very small and wave-observing spacecraft is likely to be a different MLT. As particle populations drift around the Earth on the time scales of minutes, particle distributions can show signatures of loss or acceleration at all MLT sectors. This study not only provides a clear evidence for the local loss of multi-MeV electrons from the analysis of particle distributions but also presents an important way to differentiate between various loss mechanisms. This study also shows that the locations of different loss mechanisms and their effectiveness may be estimated from the observations of particle distributions in the future with the analysis tools such as suggested by [O'Brien et al., 2008; *O'Brien et al*., 2016].

Profiles of phase space density during the 17 January 2013 storm clearly show deepening local minimum for all considered magnetic fields models. Such evolution of PSD can only be explained by intense local loss. The loss mechanism affects only electrons above several MeV, consistent with EMIC-induced scattering into the loss cone. This observation provides a clear observational evidence for the importance of scattering of the ultrarelativistic electrons into the atmosphere by EMIC waves. These results are consistent with previous analysis of this storm based on pitch angle distributions and modeling [*Shprits et al.*, 2016]. The evolution of PSD over the long term provides further insight into the effects of the EMIC waves. The 17 January 2013 storms produced a PSD minimum around $L^* = 4$, while the next storm on 1 March produces even deeper PSD minimum and even closer to the Earth at $L^* \sim 3.5$. The fact that the deep minimums persist for such a long time is also very interesting. Two possible explanations can account for it. The first scenario is a continuous presence of EMIC waves that provides loss at these energies and depletes the PSD at these radial locations. The second potential explanation is a very slow radial diffusion at these energies that is not capable of refilling the local PSD depletion. The systematic analysis of the long-term evolution of PSD minimums will help identify conditions when EMIC scattering is most efficient and will also show at which radial distances they are most effective. Such a systematic analysis of PSD profiles at ultrarelativistic energies will be a subject of future research.

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