MLT dependence of relativistic electron scattering into the drift loss cone: Measurements from ELFIN-L on board Lomonosov spacecraft

Yuri Y Shprits¹, Ingo Michaelis², Dedong Wang³, Hayley J Allison⁴, Ruggero Vasile⁵, Andrei Runov⁶, Alexander Yurievich Drozdov⁶, Christopher T. Russell⁶, Vladimir V Kalegaev⁷, and Artem Smirnov⁸

¹Helmholtz Centre Potsdam
²GFZ German Research Centre For Geosciences
³GFZ German Research Centre for Geosciences
⁴GFZ
⁵GFZ German Research Centre for Geosciences
⁶University of California Los Angeles
⁷Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University
⁸GFZ- German Research Centre for Geosciences

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Abstract

There have been a number of theories proposed concerning the loss of relativistic electrons from the radiation belts. However, direct observations of loss were not possible on a number of previous missions due to the large field of view of the instruments and often high-altitude orbits of satellites that did not allow researchers to isolate the precipitating electrons from the stably trapped. We use measurements from the ELFIN-L suit of instruments flown on Lomonosov spacecraft at LEO orbit, which allows us to distinguish stably trapped from the drift loss cone electrons. The sun-synchronous orbit of Lomonosov allows us to quantify scattering that occurred into the loss cone on the dawn-side and the dusk-side magnetosphere. The loss at MeV energies is observed predominantly on the dawn-side, consistent with the loss induced by the chorus waves. The companion data publication provides processed measurements.

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¹GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany ²University of California Los Angeles, Los Angeles, CA, United States ³Institute for Physics and Astronomy, University of Potsdam, Germany ⁴Moscow State University, Moscow, Russia *Now at Meta Platforms, Inc

Key Points:

- ELFIN-L measurements allow comparing scattering into the loss cone on the dawn and dusk side
- Processed Level -3 measurements are provided in the data publication
- Most of the relativistic electrons are scattered into the drift loss cone on the dawn side

Abstract

There have been a number of theories proposed concerning the loss of relativistic electrons from the radiation belts. However, direct observations of loss were not possible on a number of previous missions due to the large field of view of the instruments and often high-altitude orbits of satellites that did not allow researchers to isolate the precipitating electrons from the stably trapped. We use measurements from the ELFIN-L suit of instruments flown on Lomonosov spacecraft at LEO orbit, which allows us to distinguish stably trapped from the drift loss cone electrons. The sun-synchronous orbit of Lomonosov allows us to quantify scattering that occurred into the loss cone on the dawn-side and the dusk-side magnetosphere. The loss at MeV energies is observed predominantly on the dawn-side, consistent with the loss induced by the chorus waves. The companion data publication provides processed measurements.

Plain Language Summary

There have been a number of models proposed concerning the loss of relativistic electrons from radiation belts. However, the direct observations of loss have been missing, as for most of the previous missions; the large aperture telescopes could not isolate the precipitating electrons from being stably trapped. In this study, we use measurements from ELFIN-L on Lomonosov that allow for such separation and allow us to distinguish stably trapped from precipitating particles. We can also identify the particles that will be lost within one drift around the Earth, the so-called drift loss cone. For understanding the loss processes and differentiating between them, it's crucially important to quantify where in local magnetic time these electrons will be scattered into the drift loss cone. Measurements from the ELFIN-L instrument show that the loss at MeV energies is observed predominantly on the dawn side, consistent with the loss induced by the so-called chorus plasma waves.

1 Introduction

Significant advances in the understanding of the acceleration of the radiation belt particles have been obtained due to historical measurements on CRRES satellite (Johnson and Kierein, 1992) and new measurements provided by the Van Allen Probes mission (Mauk et al., 2012). The mechanisms for the acceleration of relativistic electrons were validated by the newly developed codes solving the full three-dimensional Fokker-Planck equation, such as ONERA Salammbô code (Varatsou et al., 2008), the British Antarctic Survey (BAS) Radiation Belt Code (e.g., Glauert et al., 2014a, 2014b; Kersten et al., 2014; Allison et al., 2019), the Versatile Electron Radiation Belt (VERB) code (e.g., Shprits et al., 2008b; Subbotin and Shprits, 2009; Shprits et al., 2009; Subbotin et al., 2010, 2011a; Kim et al., 2012; Drozdov et al., 2017; Wang and Shprits, 2019; Wang et al., 2020) and DREAM-3D code (eg., Reeves et al., 2012; Tu et al., 2013.) Various combinations of 1-D, 2D or combination of convection and 2D simulations have also been presented in recent studies (e.g., Fok et al, 2011; Li et al., 2016; Ripoll et al., 2019). Advances in modeling and observations have allowed us to significantly advance our understanding of the acceleration mechanisms in the radiation belts (Shprits et al., 2008a,b; Millan and Thorne, 2007; Thorne 2010; Shprits et al., 2022). However, the understanding of loss processes is still incomplete. Fundamental questions about the loss of electrons remain to be debated and the direct observational evidence for several proposed loss mechanisms (Shprits et al., 2008a, b) remains lacking. To directly evaluate the loss of electrons from the radiation belts, measurements should be able to accurately resolve the loss cone and be able

to distinguish between the quasi-trapped, trapped, and precipitating populations, which is difficult to achieve from a near-equatorial orbit where recent satellite missions operated. In particular, one of the most compelling questions related to loss is where does the scattering of the radiation belt elections occur? Answering these questions can help identify the wave modes and physical mechanisms responsible for such scattering.

In this study, we utilize the measurements from the electron particle detector (EPD) of the ELFIN-L instrument suite (*Shprits et al.*, 2018) that has been flown on the Lomonosov spacecraft. The satellite was launched on April 28, 2016 into a polar, sun-synchronous orbit. The inclination was 97.3° at a mean altitude of about 485 km. The orbit period is 94.2 minutes. The orbit of the Lomonosov satellite allows us to routinely sample and compare the measurements in the vicinity of noon and midnight (11.11±1.64 and 23.27±1.68). EPD was designed to have a relatively narrow field of view (22.5°), to be able to differentiate between Drift Loss Cone (DLC), Bounce Loss Cone (BLC), and Trapped populations. The data rate is two measurements per second on eight physical electron detectors with 12 sub-channels from 21 keV to 4.7 MeV. The data is available from August to November 2016. Some of the electron detector channels do not show valid measurements, most likely due to insufficient particle counts. The usable channels are with central energies of 21 keV, 30 keV, 44 keV, 1.006 MeV, and 1.600 MeV.

2 Data processing

To understand the loss of electrons, we, first of all, need to understand if the instruments are measuring stably trapped fluxes, locally precipitating fluxes or particles that will be lost within one drift orbit in the region where the magnetic field will be weak enough so that the mirror point will be lowered to the level of the atmosphere. Such particles that are lost during one drift orbit are referred to as particles in the drift loss cone (DLC), and particles that will precipitate locally on the time scale of one bounce are referred to as particles in the bounce loss cone (BLC). To identify the BLC, the magnetic field where particle mirrors B_m should be calculated from the instrument look direction and local at the spacecraft magnetic field. The mirror point magnetic field should be compared to an estimated magnetic field at the top of the atmosphere or footprint of the field line B_{foot} , which for this study, we assume to be at 100km. If B_m is lower than B_{foot} the particle will mirror above the atmosphere where the magnetic field is lower than in the atmosphere and will not be lost during the bounce. If B_m is lower than Bfoot, the particle will be lost during the bounce as BLC.

To identify the DLC measurements the magnetic field at the mirror point, which is conserved along the drift path due to the conservation of the second adiabatic invariant, should be compared with the minimum magnetic field that the particle will encounter along the entire drift motion. If the mirror point magnetic field B_m is greater than the minimum value of the magnetic field at 100 km for a given L-shell B_{drift_min} , then the particle will be lost over the drift orbit and should be labeled as DLC. If B_m is smaller than B_{drift_min} the particle will be stably trapped and in the absence of pitch angle diffusion, will not be lost from the system.

To simplify this calculation, we pre-calculated B_{foot} as a function of McIlwain Lm (*McIlwain*, 1961) and quasi-dipole longitude (QDLON) using International Geomagnetic Reference Field (IGRF) 12 (*Thébault et al.*, n.d.) geomagnetic model. The field lines are traced using

International Radiation Belt Environment Modeling (IRBEM) library version 6.1.2 (*Boscher et al.* 2013). The minimum between the northern and southern hemispheres of B_{foot} , is shown on Figure 1.



Figure 1: Calculated smallest of the northern and southern hemisphere magnetic foot point at the altitude of 100 km as a function of L and quasi-dipole longitude (IGRF).

The method was validated by reproducing the previously published results in (*Tu et al.*, 2009), see supplemental material Figure S1. The Geodetic coordinates (GDZ) are calculated from the Geographic Coordinate system (GEO) using the IRBEM library. Position in these coordinates is used to calculate the QDLON using the "apexpy" which is a Python wrapper for the Apex fortran library based on Richmond (1995) and Emmert et al. (2010). For the calculation of Lm we use McIlwain's look-up table (*McIlwain*, 1961), which calculates Lm from invariant I and B_m values. B_m can be calculated using the IRBEM library. For the calculation of invariant and tracing field lines, we use an approach by Orlova and Shprits (2011). Using the pre-calculated *B_{foot}* and McIlwain Lm and QDLON at each satellite position and pre-calculated table as discussed above, we determine if we measure particles in the DLC.

To compare dawn and dusk-side scattering, we need to compare measurements on the day and night sides at the same geographic location. The DLC measurements on the day and night side can only be observed in the Alaska geographic sector, and for this study, we focus on measurements over this geographic location. Another complication comes from the fact that the instrument has a finite field of view, and each corner of the instrument's aperture is associated with a slightly different pitch angle. The estimates that are usually done for the central angle of the instrument field of view may be deceptive as even a small amount of trapped particles may by far outnumber the measured drift loss cone or bounce loss cone particles and can significantly contaminate the measurements. As the focus of this study is the drift loss cone population, we chose the most conservative estimates and checked that all four corners of the instrument satisfy the DLC condition when determining the measurements that we assigned to DLC. The same conservative approach is applied to the determination of the BLC. We consider a measurement to be in the BLC only when all four vectors go through the corners of the instrument point into the BLC.

3 Results

3.1 Separating different populations near the edge of the loss cone

Using the methodology as discussed above, we have separated all the measurements into BLC, DLC, and trapped. Figure 2 shows the DLC and trapped populations. As the ELFIN-L direction is inclined at 60 degrees with respect to the plane defined by zenith and satellite velocity, the orientation of the instrument allows us to measure various populations of particles at different geographical locations. In the outer belt, trapped fluxed was only observed in the southern hemisphere near the minimum in the magnetic field along the lines of constant L-shell. Trapped fluxes are also observed in the inner belt and may be contaminated by the highly energetic trapped protons that are clearly seen around latitudes of Africa on the day side. The DLC fluxes can be observed in the northern and southern hemispheres. Clearly seen is the trend of increasing fluxes as electrons drift eastwards, and more particles can be scattered into the DLC before they are lost in the region close to the minimum magnetic field, which is marked by stars on the constant Lm contour white lines.



Figure 2: ELFIN-L measured differential electron flux at 1006 keV from August to November 2016. The top row shows drift loss cone measurements for a) day-side, b) night-side, and the bottom row trapped electrons measured on the day side c) and night side d). Grey lines show contours of magnetic field intensity, while white lines show contours of Lm. White stars show the location of *B*_{foot_min} along iso-lines of Lm. For DLC on the day side, a) we focused on the northern hemisphere since a clean distinction between DLC and trapped is difficult for the southern hemisphere.

3.2 Comparison of the dawn and dusk-side scattering.

The orbit of Lomonosov allows for comparing measurements on the night side with the measurements on the day side. The measurements of DLC fluxes on the night side will be

dominated by particles that were scattered into the loss cone on the dawn side, and the measurements on the day side will be dominated by the particles that were scattered on the dusk side as electrons are drifting westward. The exact range of MLT at which electrons may be scattered into the DLC will depend on the MLT of the minimum B for a given Lm. In particular, all electrons may be scattered in the loss cone eastward of the point where the measurement is made and westward of the minimum B. The minimum B for a given L-shell we henceforth refer to as South Atlantic Anomaly (SAA) as the latitude of the SAA approximately coincides with the minimum B for a given Lm (see stars depicting minimum B in Figure 2).

To further confine the region where particles can be scattered into the loss cone, we choose SAA to be on the dusk side when we are considering the measurements on the day side so that we can observe the scattering into the DLC that occurred on the dawn side. Similarly, when observing the night side DLC fluxes, we only consider measurements when SSA is on the dawn side so that we can be sure that the scattering occurred westward of the SAA. Figure 3 shows how SAA location is restricted for the day-side and night-side measurements. Such selection of SAA does not entirely limit the scattering to the dawn or dusk side. Ideally, SAA should be located at noon for the near-midnight measurements and at midnight for the near-dayside measurements. However, such restriction would eliminate most of the measurements and would not allow obtaining statistically significant results. Such analysis should be possible in the future for longer-term missions such as ELFIN (*Angelopoulos et al.*, 2020).



Figure 3. Definition of a) Dawn and b) Dusk precipitation with respect to local time location of ELFIN-L and South Atlantic Anomaly.



Figure 4. ELFIN-L differential Flux at 1006 keV in log10((cm2 * sec * sr * keV) ⁻¹) from August to November 2016 over Alaska measuring electrons in the DLC that were predominantly scattered in the a) dawn sector and b) dusk sector. Panel c) shows the ratio between Dawn and Dusk precipitation. White lines show contours of Lm; gray lines show contours of magnetic field intensity. The noise level has been cut at $-0.5 \log 10$ (cm2 * sec *

 $sr * keV)^{-1}$).

Figure 4c shows that the scattering over the dawn side exceeds the scattering over the dusk side. Such a scenario is consistent with loss of electrons mostly due to chorus waves. It is difficult to exactly quantify this ratio due to the lack of data; some measurements of the dawn side precipitation may be mixed with the dusk side precipitation and vice versa, as discussed above. Similar observations and similar conclusions have been made by Allison et al. (2017) but for lower energy electrons using Polar Operational Environmental Satellite (POES) measurements. Exactly the same analysis has been conducted for the NOAA POES-19 measurements and is presented in the supporting material section S3.

Summary and discussion

In this study, we performed a statistical analysis of the data collected from the ELFIN-L instrument on board the Lomonosov spacecraft. The small field of view of the instrument provides a unique opportunity to clearly separate the BLC, DLC, and trapped electron fluxes. Separating the populations of BLC, DLC, and trapped is a technically challenging task and requires careful consideration of the geometry of the instrument and exclusion of the geographic locations where all three populations can be simultaneously observed, and measurements are difficult to classify as either of these populations as most of them contain a mixture of populations. The observed trapped fluxes maximize around the minimum in the magnetic field consistent with the physical expectations. The observed statistical DLC fluxes increase as electrons drift eastwards, increasing up to the minimum B along the given L-shell before showing a sudden drop close to the minimum B point, also consistent with physical expectations. This seemingly obvious sanity check should be performed for similar analysis in future studies to verify that the inferred precipitating fluxes are, in fact, realistic and are not contaminated by the trapped fluxes that can exceed the precipitating fluxes by several orders of magnitude. These findings are also consistent with Electromagnetic Ion Cyclotron (EMIC) waves that are usually observed on the dusk side, predominantly scattering multi-MeV while not significantly affecting MeV electrons (Shprits et al., 2013; 2016; 017; 2022; Drozdov et al.,

2015; 2017; 2020; 2022, *Usanova et al.*, 2014; *Aseev et al.*, 2017; *Qin et al.*, 2015). Similar results are obtained using the POES satellite data and presented in the supporting material. The companion data publications provide all Level 1, 2, and 3 data, including flagged data points that would allow to reproduce of this investigation and conduct additional investigations of individual events and conjunction studies.

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Data Availability Statement

All data used can be found for the period of peer review at <u>https://nextcloud.gfz-potsdam.de/s/9xLeW2Q8gZwP2mL</u>. We have already prepared and submitted the data publications to GFZ library services. The doi mentioned already exist. They are just not active yet. They will be active on March 16th when the person who deals with the publications comes back from vacation. That will be a permanent link to a permanent repository. The data will be exactly the same as currently provided on nextcloud above. At the time of the next review or time of acceptance of this manuscript, the data will be published in the accompanying data publications Michaelis and Shprits, 2023a,b,c,d,e, and Shprits and Michaelis, 2023. NOAA POES data that is used for the supporting material of this study is publically available and can be obtained from <u>ftp://satdat.ngdc.noaa.gov/sem/poes/data/processed/ngdc/uncorrected/full/</u>.

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MLT dependence of relativistic electron scattering into the drift loss cone: Measurements from ELFIN-L on board Lomonosov spacecraft

Yuri Shprits^{1,2,3}, Ingo Michaelis¹, Dedong Wang¹, Hayley Allison¹, Ruggero Vasile^{1,*}, Andrei Runov², Alexander Drozdov², Christopher T. Russell², Vladimir Kalegaev⁴, Artem Smirnov^{1,3}

¹GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany ²University of California Los Angeles, Los Angeles, CA, United States ³Institute for Physics and Astronomy, University of Potsdam, Germany ⁴Moscow State University, Moscow, Russia *Now at Meta Platforms, Inc

Key Points:

- ELFIN-L measurements allow comparing scattering into the loss cone on the dawn and dusk side
- Processed Level -3 measurements are provided in the data publication
- Most of the relativistic electrons are scattered into the drift loss cone on the dawn side

Abstract

There have been a number of theories proposed concerning the loss of relativistic electrons from the radiation belts. However, direct observations of loss were not possible on a number of previous missions due to the large field of view of the instruments and often high-altitude orbits of satellites that did not allow researchers to isolate the precipitating electrons from the stably trapped. We use measurements from the ELFIN-L suit of instruments flown on Lomonosov spacecraft at LEO orbit, which allows us to distinguish stably trapped from the drift loss cone electrons. The sun-synchronous orbit of Lomonosov allows us to quantify scattering that occurred into the loss cone on the dawn-side and the dusk-side magnetosphere. The loss at MeV energies is observed predominantly on the dawn-side, consistent with the loss induced by the chorus waves. The companion data publication provides processed measurements.

Plain Language Summary

There have been a number of models proposed concerning the loss of relativistic electrons from radiation belts. However, the direct observations of loss have been missing, as for most of the previous missions; the large aperture telescopes could not isolate the precipitating electrons from being stably trapped. In this study, we use measurements from ELFIN-L on Lomonosov that allow for such separation and allow us to distinguish stably trapped from precipitating particles. We can also identify the particles that will be lost within one drift around the Earth, the so-called drift loss cone. For understanding the loss processes and differentiating between them, it's crucially important to quantify where in local magnetic time these electrons will be scattered into the drift loss cone. Measurements from the ELFIN-L instrument show that the loss at MeV energies is observed predominantly on the dawn side, consistent with the loss induced by the so-called chorus plasma waves.

1 Introduction

Significant advances in the understanding of the acceleration of the radiation belt particles have been obtained due to historical measurements on CRRES satellite (Johnson and Kierein, 1992) and new measurements provided by the Van Allen Probes mission (Mauk et al., 2012). The mechanisms for the acceleration of relativistic electrons were validated by the newly developed codes solving the full three-dimensional Fokker-Planck equation, such as ONERA Salammbô code (Varatsou et al., 2008), the British Antarctic Survey (BAS) Radiation Belt Code (e.g., Glauert et al., 2014a, 2014b; Kersten et al., 2014; Allison et al., 2019), the Versatile Electron Radiation Belt (VERB) code (e.g., Shprits et al., 2008b; Subbotin and Shprits, 2009; Shprits et al., 2009; Subbotin et al., 2010, 2011a; Kim et al., 2012; Drozdov et al., 2017; Wang and Shprits, 2019; Wang et al., 2020) and DREAM-3D code (eg., Reeves et al., 2012; Tu et al., 2013.) Various combinations of 1-D, 2D or combination of convection and 2D simulations have also been presented in recent studies (e.g., Fok et al, 2011; Li et al., 2016; Ripoll et al., 2019). Advances in modeling and observations have allowed us to significantly advance our understanding of the acceleration mechanisms in the radiation belts (Shprits et al., 2008a,b; Millan and Thorne, 2007; Thorne 2010; Shprits et al., 2022). However, the understanding of loss processes is still incomplete. Fundamental questions about the loss of electrons remain to be debated and the direct observational evidence for several proposed loss mechanisms (Shprits et al., 2008a, b) remains lacking. To directly evaluate the loss of electrons from the radiation belts, measurements should be able to accurately resolve the loss cone and be able

to distinguish between the quasi-trapped, trapped, and precipitating populations, which is difficult to achieve from a near-equatorial orbit where recent satellite missions operated. In particular, one of the most compelling questions related to loss is where does the scattering of the radiation belt elections occur? Answering these questions can help identify the wave modes and physical mechanisms responsible for such scattering.

In this study, we utilize the measurements from the electron particle detector (EPD) of the ELFIN-L instrument suite (*Shprits et al.*, 2018) that has been flown on the Lomonosov spacecraft. The satellite was launched on April 28, 2016 into a polar, sun-synchronous orbit. The inclination was 97.3° at a mean altitude of about 485 km. The orbit period is 94.2 minutes. The orbit of the Lomonosov satellite allows us to routinely sample and compare the measurements in the vicinity of noon and midnight (11.11±1.64 and 23.27±1.68). EPD was designed to have a relatively narrow field of view (22.5°), to be able to differentiate between Drift Loss Cone (DLC), Bounce Loss Cone (BLC), and Trapped populations. The data rate is two measurements per second on eight physical electron detectors with 12 sub-channels from 21 keV to 4.7 MeV. The data is available from August to November 2016. Some of the electron detector channels do not show valid measurements, most likely due to insufficient particle counts. The usable channels are with central energies of 21 keV, 30 keV, 44 keV, 1.006 MeV, and 1.600 MeV.

2 Data processing

To understand the loss of electrons, we, first of all, need to understand if the instruments are measuring stably trapped fluxes, locally precipitating fluxes or particles that will be lost within one drift orbit in the region where the magnetic field will be weak enough so that the mirror point will be lowered to the level of the atmosphere. Such particles that are lost during one drift orbit are referred to as particles in the drift loss cone (DLC), and particles that will precipitate locally on the time scale of one bounce are referred to as particles in the bounce loss cone (BLC). To identify the BLC, the magnetic field where particle mirrors B_m should be calculated from the instrument look direction and local at the spacecraft magnetic field. The mirror point magnetic field should be compared to an estimated magnetic field at the top of the atmosphere or footprint of the field line B_{foot} , which for this study, we assume to be at 100km. If B_m is lower than B_{foot} the particle will mirror above the atmosphere where the magnetic field is lower than in the atmosphere and will not be lost during the bounce. If B_m is lower than Bfoot, the particle will be lost during the bounce as BLC.

To identify the DLC measurements the magnetic field at the mirror point, which is conserved along the drift path due to the conservation of the second adiabatic invariant, should be compared with the minimum magnetic field that the particle will encounter along the entire drift motion. If the mirror point magnetic field B_m is greater than the minimum value of the magnetic field at 100 km for a given L-shell B_{drift_min} , then the particle will be lost over the drift orbit and should be labeled as DLC. If B_m is smaller than B_{drift_min} the particle will be stably trapped and in the absence of pitch angle diffusion, will not be lost from the system.

To simplify this calculation, we pre-calculated B_{foot} as a function of McIlwain Lm (*McIlwain*, 1961) and quasi-dipole longitude (QDLON) using International Geomagnetic Reference Field (IGRF) 12 (*Thébault et al.*, n.d.) geomagnetic model. The field lines are traced using

International Radiation Belt Environment Modeling (IRBEM) library version 6.1.2 (*Boscher et al.* 2013). The minimum between the northern and southern hemispheres of B_{foot} , is shown on Figure 1.



Figure 1: Calculated smallest of the northern and southern hemisphere magnetic foot point at the altitude of 100 km as a function of L and quasi-dipole longitude (IGRF).

The method was validated by reproducing the previously published results in (*Tu et al.*, 2009), see supplemental material Figure S1. The Geodetic coordinates (GDZ) are calculated from the Geographic Coordinate system (GEO) using the IRBEM library. Position in these coordinates is used to calculate the QDLON using the "apexpy" which is a Python wrapper for the Apex fortran library based on Richmond (1995) and Emmert et al. (2010). For the calculation of Lm we use McIlwain's look-up table (*McIlwain*, 1961), which calculates Lm from invariant I and B_m values. B_m can be calculated using the IRBEM library. For the calculation of invariant and tracing field lines, we use an approach by Orlova and Shprits (2011). Using the pre-calculated *B_{foot}* and McIlwain Lm and QDLON at each satellite position and pre-calculated table as discussed above, we determine if we measure particles in the DLC.

To compare dawn and dusk-side scattering, we need to compare measurements on the day and night sides at the same geographic location. The DLC measurements on the day and night side can only be observed in the Alaska geographic sector, and for this study, we focus on measurements over this geographic location. Another complication comes from the fact that the instrument has a finite field of view, and each corner of the instrument's aperture is associated with a slightly different pitch angle. The estimates that are usually done for the central angle of the instrument field of view may be deceptive as even a small amount of trapped particles may by far outnumber the measured drift loss cone or bounce loss cone particles and can significantly contaminate the measurements. As the focus of this study is the drift loss cone population, we chose the most conservative estimates and checked that all four corners of the instrument satisfy the DLC condition when determining the measurements that we assigned to DLC. The same conservative approach is applied to the determination of the BLC. We consider a measurement to be in the BLC only when all four vectors go through the corners of the instrument point into the BLC.

3 Results

3.1 Separating different populations near the edge of the loss cone

Using the methodology as discussed above, we have separated all the measurements into BLC, DLC, and trapped. Figure 2 shows the DLC and trapped populations. As the ELFIN-L direction is inclined at 60 degrees with respect to the plane defined by zenith and satellite velocity, the orientation of the instrument allows us to measure various populations of particles at different geographical locations. In the outer belt, trapped fluxed was only observed in the southern hemisphere near the minimum in the magnetic field along the lines of constant L-shell. Trapped fluxes are also observed in the inner belt and may be contaminated by the highly energetic trapped protons that are clearly seen around latitudes of Africa on the day side. The DLC fluxes can be observed in the northern and southern hemispheres. Clearly seen is the trend of increasing fluxes as electrons drift eastwards, and more particles can be scattered into the DLC before they are lost in the region close to the minimum magnetic field, which is marked by stars on the constant Lm contour white lines.



Figure 2: ELFIN-L measured differential electron flux at 1006 keV from August to November 2016. The top row shows drift loss cone measurements for a) day-side, b) night-side, and the bottom row trapped electrons measured on the day side c) and night side d). Grey lines show contours of magnetic field intensity, while white lines show contours of Lm. White stars show the location of *B*_{foot_min} along iso-lines of Lm. For DLC on the day side, a) we focused on the northern hemisphere since a clean distinction between DLC and trapped is difficult for the southern hemisphere.

3.2 Comparison of the dawn and dusk-side scattering.

The orbit of Lomonosov allows for comparing measurements on the night side with the measurements on the day side. The measurements of DLC fluxes on the night side will be

dominated by particles that were scattered into the loss cone on the dawn side, and the measurements on the day side will be dominated by the particles that were scattered on the dusk side as electrons are drifting westward. The exact range of MLT at which electrons may be scattered into the DLC will depend on the MLT of the minimum B for a given Lm. In particular, all electrons may be scattered in the loss cone eastward of the point where the measurement is made and westward of the minimum B. The minimum B for a given L-shell we henceforth refer to as South Atlantic Anomaly (SAA) as the latitude of the SAA approximately coincides with the minimum B for a given Lm (see stars depicting minimum B in Figure 2).

To further confine the region where particles can be scattered into the loss cone, we choose SAA to be on the dusk side when we are considering the measurements on the day side so that we can observe the scattering into the DLC that occurred on the dawn side. Similarly, when observing the night side DLC fluxes, we only consider measurements when SSA is on the dawn side so that we can be sure that the scattering occurred westward of the SAA. Figure 3 shows how SAA location is restricted for the day-side and night-side measurements. Such selection of SAA does not entirely limit the scattering to the dawn or dusk side. Ideally, SAA should be located at noon for the near-midnight measurements and at midnight for the near-dayside measurements. However, such restriction would eliminate most of the measurements and would not allow obtaining statistically significant results. Such analysis should be possible in the future for longer-term missions such as ELFIN (*Angelopoulos et al.*, 2020).



Figure 3. Definition of a) Dawn and b) Dusk precipitation with respect to local time location of ELFIN-L and South Atlantic Anomaly.



Figure 4. ELFIN-L differential Flux at 1006 keV in log10((cm2 * sec * sr * keV) ⁻¹) from August to November 2016 over Alaska measuring electrons in the DLC that were predominantly scattered in the a) dawn sector and b) dusk sector. Panel c) shows the ratio between Dawn and Dusk precipitation. White lines show contours of Lm; gray lines show contours of magnetic field intensity. The noise level has been cut at $-0.5 \log 10$ (cm2 * sec *

 $sr * keV)^{-1}$).

Figure 4c shows that the scattering over the dawn side exceeds the scattering over the dusk side. Such a scenario is consistent with loss of electrons mostly due to chorus waves. It is difficult to exactly quantify this ratio due to the lack of data; some measurements of the dawn side precipitation may be mixed with the dusk side precipitation and vice versa, as discussed above. Similar observations and similar conclusions have been made by Allison et al. (2017) but for lower energy electrons using Polar Operational Environmental Satellite (POES) measurements. Exactly the same analysis has been conducted for the NOAA POES-19 measurements and is presented in the supporting material section S3.

Summary and discussion

In this study, we performed a statistical analysis of the data collected from the ELFIN-L instrument on board the Lomonosov spacecraft. The small field of view of the instrument provides a unique opportunity to clearly separate the BLC, DLC, and trapped electron fluxes. Separating the populations of BLC, DLC, and trapped is a technically challenging task and requires careful consideration of the geometry of the instrument and exclusion of the geographic locations where all three populations can be simultaneously observed, and measurements are difficult to classify as either of these populations as most of them contain a mixture of populations. The observed trapped fluxes maximize around the minimum in the magnetic field consistent with the physical expectations. The observed statistical DLC fluxes increase as electrons drift eastwards, increasing up to the minimum B along the given L-shell before showing a sudden drop close to the minimum B point, also consistent with physical expectations. This seemingly obvious sanity check should be performed for similar analysis in future studies to verify that the inferred precipitating fluxes are, in fact, realistic and are not contaminated by the trapped fluxes that can exceed the precipitating fluxes by several orders of magnitude. These findings are also consistent with Electromagnetic Ion Cyclotron (EMIC) waves that are usually observed on the dusk side, predominantly scattering multi-MeV while not significantly affecting MeV electrons (Shprits et al., 2013; 2016; 017; 2022; Drozdov et al.,

2015; 2017; 2020; 2022, *Usanova et al.*, 2014; *Aseev et al.*, 2017; *Qin et al.*, 2015). Similar results are obtained using the POES satellite data and presented in the supporting material. The companion data publications provide all Level 1, 2, and 3 data, including flagged data points that would allow to reproduce of this investigation and conduct additional investigations of individual events and conjunction studies.

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Data Availability Statement

All data used can be found for the period of peer review at <u>https://nextcloud.gfz-potsdam.de/s/9xLeW2Q8gZwP2mL</u>. We have already prepared and submitted the data publications to GFZ library services. The doi mentioned already exist. They are just not active yet. They will be active on March 16th when the person who deals with the publications comes back from vacation. That will be a permanent link to a permanent repository. The data will be exactly the same as currently provided on nextcloud above. At the time of the next review or time of acceptance of this manuscript, the data will be published in the accompanying data publications Michaelis and Shprits, 2023a,b,c,d,e, and Shprits and Michaelis, 2023. NOAA POES data that is used for the supporting material of this study is publically available and can be obtained from <u>ftp://satdat.ngdc.noaa.gov/sem/poes/data/processed/ngdc/uncorrected/full/</u>.

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Supporting Information for

MLT dependence of relativistic electron scattering into the drift loss cone: Measurements from ELFIN-L on board Lomonosov spacecraft

Yuri Shprits^{1,2,3}, Ingo Michaelis¹, Dedong Wang¹, Hayley Allison¹, Drew Turner ⁴, Vassilis Angelopoulos², Andrei Runov², Alexander Drozdov², Christopher Russell², Artem Smirnov¹

¹GFZ German Research Centre for Geosciences, Potsdam, Germany
 ²University of California Los Angeles, Los Angeles, CA, United States
 ³Institute for Physics and Astronomy, University of Potsdam, Germany
 ⁴ John Hopkins University Applied Physics Laboratory, Maryland, United States

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Introduction

The supporting information discusses several technical points that are mentioned in the manuscript. In particular, S1 presents a comparison of our calculations of the DLC and BLC with previous studies, which validates our calculations; S2 compares POES measurement to ELFIN-L measurements and performs the same analysis as presented in the main manuscript but using NOAA POES data, which provides additional validation for the conclusions of the paper; S3 discusses how POES data was processed, and integral channels converted into the differential; S4 gives additional details on the processing of the ELFIN-L data.

Text S1. Comparison with previous studies

To validate the result of the classification of particles into trapped, lost over one bounce, or lost over one drift, we reproduced the figures from (*Tu et al.*, 2009) which

shows the regions of trapped, DLC, and BLC areas in the space of pitch angle and MLT for L= 4.5. The results shown in Figure S1 are practically identical to the previously published results.

Text S2. Validation using NOAA-19 measurements

To validate the ELFIN-L measurements, we performed a detailed comparison of ELFIN-L measurements with MEPED measurements on NOAA-19 satellite (ftp://satdat.ngdc.noaa.gov/sem/poes/data/processed/ngdc/uncorrected/full/). Note that the direct comparison is complicated by the fact that the altitudes of spacecraft are different, and ELFIN-L is measuring differential fluxes, while POES provides broad in energy integral channels. The difference in the orientation of the instruments with respect to the magnetic field also provides systematic biases. The results of the comparison of measurements are shown in Figure S2.

The presented results show that the general evolution of fluxes measured on both of the spacecraft are similar. Moreover, for the purpose of this study, we are mainly interested not in the absolute values of the fluxes but in ratios of the fluxes on the day and night sides.

The same analysis of comparison of day-side and night-side measurements for ELFIN-L as performed for Figure 4 has been done with NOAA-19 MEPED measurements. Figure S4 clearly shows that dawn-side scattering into the DLC is significantly higher than dusk-side scattering. Similar results that can be found for NOAA19 and METOP02 combination are not shown here.

Text S3. Processing of NOAA-19 measurements

Before using NOAA-19 MEPED instrument flux data, pre-processing had to be applied. The calculation of Lm has been done following a similar approach as discussed in the main part of the manuscript for ELFIN-L using a tracing routine following Orlova and Shprits (2011). To compare similar energy levels for ELFIN-L and NOAA-19, we extended the highest energy channel of 612 keV to 1 MeV using the exponential energy spectrum. For each detector, virtual pitch angles have been calculated according to the opening angle of +-15°. Afterward, both detectors were combined into one dataset, and for each measurement, the value for B_{drift_min} and B_m were calculated. According to the method described in the data processing chapter, a loss cone flag has been calculated. For Figures S2 and S3 we only used datasets with loss cone flags according to DLC.

$$\begin{split} J(E_1) &= e^{b \cdot (E_0 - E_1)} \cdot J(E_0) \\ &= e^{b \cdot (E_0 - E_1)} \cdot b \tilde{J}(E > E_0) \\ &= e^{\frac{7.068 \cdot 10^{-3}}{keV} \cdot (612keV - 1000keV)} \cdot (\frac{7.068e^{-3}}{keV}) \tilde{J}(E > 612keV) \\ J(1000keV) &= \frac{7.068 \cdot 10^{-3}}{15.52395} \frac{1}{keV} \tilde{J}(E > 612keV) \\ J: \text{ differential flux; J~: integral flux; E0, E1: Energies} \end{split}$$

$$b = rac{7.068}{MeV} = rac{7.068 \cdot 10^{-3}}{keV}$$

from (Shprits and Thorne, 2004) We have processed the full chain from binary raw data to the final Level 3 dataset.

- Level 0: split raw binary data into binary data for each instrument package
- Level 1: Converted raw binary data into electron count
- Level 2: Calculated satellite position and velocity, local and equatorial pitch angles, local and equatorial magnetic fields, calibrated differential flux
- Level 3: Added McIlwain Lm, MLT, loss cone flags and quality flags for bad data and bad position

Bad data flags have been computed on L1 data set using particle counts only and set when fulfilling all three conditions

• (0.6 · FluxCount(1600keV) > FluxCount(1006keV)) ∧ (F luxCount(1600keV) > 25) • FluxCount(30keV) < 5000

• (FluxCount(1600keV) > FluxCount(1006keV)) \land (FluxCount(1600keV) > 800) For removing noise from the different energy channels, the noise level boundary given in Table S1 has been used.

Text S4. Processing of ELFIN-L measurements

First, we performed the initial clean-up of the data, which included removing points that were potentially contaminated by the outside disturbances, and the points below the noise level defined as defined at 0.35 log10((cm2 * sec * sr * keV)⁻¹) were removed. All of the data points, including contaminated measurements, are provided in the supplementary data publication. Contaminated measurements that were not considered in the analysis are flagged as contaminated.



Figure S1. Distribution of trapped, BLC, and DLC population depending on equatorial pitch angles and geomagnetic longitude using GFZ B_{foot} table for a given L=4.5. For this figure, the same methods have been used for creating the B_{foot} Table 1. The result is practically identical to the results of Tu et al. (2009).



Figure S2. ELFIN-L differential flux at 1006 keV and NOAA19 MEPED differential Flux extended to 1000 keV from August to November for drift loss cone with respect to Time and McIlwain Lm (IGRF). The two top panels show all data (day and night side) for ELFIN-L (top) and NOAA19 (middle). The bottom panel shows the Kp index. Storm events are visible in both ELFIN-L and NOAA19, but NOAA19 shows higher flux values. We used all DLC measurements from ELFIN-L. For NOAA19, we used flux data from detector T90 with an opening angle of $\pm 15^{\circ}$. For determining DLC measurements we used the method described in the data processing chapter for ELFIN-L and NOAA19 B_m and B_{drift min} respectively.



Figure S3. NOAA19 differential Flux extended to 1 MeV from 612 keV energy channel (E4) for the period from August to November 2016 in the Alaska region for Dawn a) and Dusk b) precipitation. Panel c) shows the ratio of non-logarithmic Dawn and Dusk precipitation flux. For the separation of dawn and dusk, we have used the same selection as for ELFIN-L, described in Figure 3. White lines show contours of Lm; gray lines show contours of magnetic field intensity. NOAA19 MEPED flux data from detector T90 and an opening angle of +- 15° have been taken into account. For determining DLC measurements, we used the method described in the data processing chapter for NOAA19 B_m and B_{drift_min} .



Figure S4. This original figure A2 from Rodger et al. (2010) shows the population of radiation belt particles for the POES MEPED instrument for 90° detector. In the southern hemisphere in the range from 60°W to 120°E we see regions of changing population due to South Atlantic Anomaly which makes it difficult to distinguish between DLC and Trapped.

Channel No	Channel Name	Energy	Noise level $[\log 10((cm2 * sec * sr * keV)^{-1})]$
0	E1PHA	21 keV	1.9
1	E1PHB	30 keV	1.7

2	E1PHC	44 keV	1.55
10	ЕЗРНА	1.006 MeV	0.35
12	E4	1.600 MeV	-0.2

Table S1. The table contains the boundary for ELFIN-L differential flux that has been used to cut noise level data.

Supplementary references

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