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Quantifying Electron Precipitation in the Van Allen Radiation Belts

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Abstract

The spatial and temporal distribution of high energy electron precipitation from the Van Allen radiation belts is not currently well-understood. The FIREBIRD-II mission (2015–present) and the Van Allen Probes (2012–2019) provide a unique opportunity to examine the behaviors and drivers of high energy electron precipitation. This study quantifies electron precipitation observed by FIREBIRD-II as a function of radial distance (L-shell), magnetic local time (MLT), hemisphere, and geomagnetic indices (Kp). Electron precipitation was observed to peak at L-shell 4.5–5. Regions of elevated electron precipitation were identified at L-shell 4–6 at dawn (MLT 6–9) and dusk (MLT 15–21). Hemisphere filtering indicated very distinct regions of increased precipitation at late dawn and early dusk at L-shell 4–6 in the Northern Hemisphere, while the Southern Hemisphere showed more overall activity as well as increased activity at early dawn and late dusk. Precipitation at high Kp indices (Kp >= 4) displayed elevated activity at all local times. In addition, multiple studies have proposed electromagnetic ion cyclotron (EMIC) waves as a potential driver of electron precipitation. This work searches for connections between EMIC waves observed by the Van Allen Probes and electron precipitation observed by FIREBIRD-II. During times of observed EMIC activity by the Van Allen Probes the FIREBIRD-II satellites recorded increased precipitation during MLT 0–3, MLT 6–9, and MLT 12–18, with activity being especially notable at MLT 15–18. Electron precipitation in the afternoon sector corresponds well with elevated EMIC wave occurrence rates reported in a previous study [Saikin et al., 2015].
1 Introduction

The Earth's magnetic field serves an important purpose in shielding the Earth from the stream of charged particles from the Sun known as the solar wind, composed of electrons, protons, and alpha particles. This magnetic field is produced by convection currents of molten iron in the Earth's outer core, producing a field that approximates a dipole. Earth’s local magnetic field is also impacted by the interplanetary magnetic field, a portion of the Sun's own magnetic field that accompanies the solar wind. The Earth's magnetic field both shields the planet from the solar wind as well as traps these charged particles inside the magnetic field as shown in Figure 1. Regions of particular interest in this study are the radiation belts, two locations in the magnetic field which hold a high amount of charged particles with energies ranging from a few hundred keV to several MeV [Kivelson and Russell, 1995].

![Figure 1. Illustration depicting the Van Allen radiation belts. Included are the orbits of various spacecraft, including the Van Allen Probes. [NASA]](image)

When looking at geomagnetic activity, the roughly dipole shape of the magnetic field and the effect of the solar wind on the magnetic field necessitate specific coordinate systems to describe location in the magnetosphere, namely L-shell and Magnetic Local Time (MLT). L-shell describes the magnetic field lines at a distance from the Earth’s magnetic equator, with integer L-shell values describing the field lines located that many Earth radii from the Earth’s center. Since the specific shape of the Earth’s magnetic field is not simply a dipole but is also impacted by the solar wind, L-shell is generally calculated using magnetic field models. Measurements made at low L-shells do not need as precise of a magnetic field model to describe position as measurements made at higher L-shell. As such, magnetic field models used in the calculations represent a trade-off between computation costs and precision. MLT is a much more straightforward parameter, representing a polar coordinate around the Earth with respect to the
MLT is expressed in terms of hours, with an MLT of 12 being directly between the Earth and the Sun, often referred to as noon, and an MLT of 0 or 24 representing a location with the Earth directly between it and the Sun, referred to as midnight. MLT is also described with terms such as dawn/dusk (representing regions where the satellite’s position is rotating towards the Sun and away from the Sun, respectively).

![Visualization of L-shell using a simple dipole model of the Earth’s magnetic field. [Wikipedia, 2007]](image)

An important descriptor of geomagnetic activity around the Earth is the planetary K-index (Kp), a measurement of maximum horizontal fluctuations in the magnetic field relative to a period of little disturbance. Kp is calculated from a series of magnetometers stationed around the world, each calibrated such that the historical distribution of measured K-indexes is roughly equal. Discrepancies in data at each magnetometer can occur due to differences in geomagnetic latitude. After the data from each magnetometer is calibrated according to that location’s historical distribution, data from all of the stations are then averaged to produce the planetary K-index. Kp is measured on a scale from 0 to 9, with measurements of 0 representing very little to no activity and measurements of 9 representing extreme fluctuations in the magnetic field.

The Van Allen radiation belts were first discovered in 1958 by a research group at the University of Iowa. The 2 belts are regions in the Earth’s magnetic field in which charged particles become trapped [Ganushkina et al., 2011]. Of the two, the inner belt is more stable, generally located between L-shells of 1 to 3. This radiation belt is largely composed of protons, in comparison to the outer belt, which is primarily populated by electrons. The outer radiation belt, located in L-shells 3 and above, is much more dynamic and susceptible to incoming particles from the solar wind [Kivelson and Russell, 1995]. Because of the outer belt’s more dynamic nature, the interactions of the electrons within the belt with the solar wind are of particular interest.

Electrons trapped in the outer radiation belt are constantly in motion, spiraling around the magnetic field lines. As electrons move around these field lines and approach the Earth’s poles, the density of magnetic field lines increases as the field lines converge, causing a greater force to be exerted on the electrons, slowing them and eventually stopping most of them and redirecting them along the magnetic field line to the opposite pole [Kivelson and Russell, 1995]. Sufficiently energetic electrons with very small pitch angles, the angle between the electron’s motion and the magnetic field lines, are not completely mirrored by the magnetic field and enter the Earth’s atmosphere, a process known as electron precipitation. Precipitation of electrons into the
atmosphere can alter the chemistry of the atmosphere, as the electrons strike molecules in the air, causing reactions that form ions and lower energy free electrons. This interaction is known to lead to the formation of nitric oxide (NO) in the atmosphere [Randall et al., 2005, 2015; Sinnhuber et al., 2012]. High energy electrons in the radiation belts also pose a threat to orbiting spacecraft. These electrons are capable of penetrating the outer protective layer of satellites and causing a buildup of internal charge. This can lead to damage of a satellite’s internal equipment and limit the lifespan of these spacecraft.

Previous studies using SAMPEX, POES satellite data and balloon measurements [Tu et al., 2010; Capannello et al., 2019; Jordanova et al., 2008] showed the complex nature of electron precipitation with respect to the location, time and drivers. In addition to this relationship, electromagnetic ion cyclotron waves (EMIC) waves in the Earth’s magnetosphere have been suggested as a possible driver of electron precipitation [Capannello et al., 2019; Zhang et al., 2016]. There are a variety of waves in the magnetosphere that can cause electrons to precipitate into the atmosphere, including chorus waves, plasmaspheric hiss, and EMIC waves [Thorne, 2010]. In this study I will focus on the association of EMIC waves with electron precipitation. EMIC waves are electromagnetic waves produced by the plasma present in the Earth’s plasmasphere, a region of Earth’s magnetic field in which large amounts of low energy (cold) plasmas reside. The plasmasphere encompasses the Earth at a distance of up to 7 Earth radii, though geomagnetic activity can cause the plasmasphere to recede [Saikin et al., 2016]. EMIC waves are generated when cold ions in the plasmasphere are excited by an injection of hot ring current ions from the plasmasheet [Jordanova et al., 2008; Capannello et al., 2019].

Figure 3. Depiction of electron motion within the Earth’s magnetic field from Bortnik et al. [2008]
This work uses measurements at low Earth orbit (LEO) (in the precipitation altitude) as well as in the radiation belts to develop a better understanding of the variability and drivers of radiation belt precipitation into the atmosphere. The broad scientific questions that this study contributes to are:

1. What is the spatial and temporal variation of electron precipitation from the radiation belt?
2. What drives the dynamics of electron precipitation?

This study aims to provide observational evidence to help answer these questions by quantifying the behavior of electron precipitation at varying L-shell, MLT, Kp, and Hemisphere. In addition, the behavior of electron precipitation during observed EMIC waves is observed. The behavior of electron precipitation during observed EMIC waves is then compared to EMIC wave occurrence rates determined in a previous study [Saikin et al. 2015] in order to identify patterns.

2 Methods

2.1 FIREBIRD-II and Van Allen Probes Data

This research uses electron precipitation data from the Focused Investigations of Relativistic Electron Burst Intensity, Range and Dynamics (FIREBIRD-II) and magnetic field data from the Van Allen Probes. The first of these missions, FIREBIRD-II, is a NSF funded collaboration between the University of New Hampshire, Montana State University, the Los Alamos national laboratory, and the Aerospace Corporation. The mission consists of two cubesats, named FIREBIRD units 3 and 4 (FU3 and FU4), that were launched into orbit and began collecting data in February 2015. FU3 collected data until October 2019 and FU4
continues to provide data to the present day. These two satellites are in low Earth orbit, at an altitude of approximately 500 km with a period of approximately 90 minutes. This polar orbit allowing the satellites to quickly pass through a large range of L-shells. The low altitude enables FIREBIRD-II to observe particles within the “drift loss cone” throughout most of its orbit, so that most observed particles will generally precipitate into the atmosphere throughout one drift cycle. When oriented parallel to the magnetic field lines and zenith-pointing, the instruments are more likely to sample particles within the “bounce loss cone” that precipitate directly into the atmosphere. The data provided by this mission is collected in approximately 3 week periods, called campaigns, with a variable amount of downtime, generally 1 to 3 weeks, between campaigns for downloading data from the cubesats, due to limitations in how quickly the satellite can transmit the data it has captured.

FIREBIRD-II’s satellites detect electrons through the use of FIREBIRD Instrument for Relativistic Electrons (FIRE) particle detectors. These detectors are calibrated to detect electrons from 200 keV to >1 MeV [Crew et al. 2016; Johnson et al. 2020]. Data generated from these particles detectors is sorted into context data and high-resolution data. Context data is taken continuously during FIREBIRD-II’s campaigns at 6 second intervals and uses 2 energy ranges, one a differential channel centered around 300 keV and the second an integral channel of energies above approximately 1 MeV. Downloaded high resolution data from the FIREBIRD-II cubesats targets known periods of electron microbursts and conjunctions with other satellites. High resolution data uses 6 energy and records data at 0.01875 second intervals. This research uses the context data from the higher energy integral channel from both satellites (>1055 keV for FU3 and >985 keV for FU4).

Figure 5. Depiction of orbits of Van Allen probes and FIREBIRD-II satellites, along with depiction of radiation belts. [UNH, 2015]
The Van Allen Probes also consists of two satellites, referred to as probe A and probe B. These satellites orbited the Earth in an elliptical, equatorial orbit, with a perigee of 1.1 Earth radii and an apogee at 5.8 Earth radii [Kletzing et al., 2013 Zhang et al., 2016]. The Van Allen Probes were first launched in August 2012, and the satellites were deactivated in 2019. The probes were outfitted with a suite of instruments in order to more closely study the Van Allen radiation belts. This research using the EMFISIS magnetometer onboard the spacecraft [Kletzing et al., 2013] to identify EMIC wave events. EMFISIS data from the probes is continuously taken at a frequency of 64 Hz.

2.2 Data Analysis

FIREBIRD-II context data was analyzed with respect to both L-shell and MLT. This analysis relies on polar heat maps of electron precipitation, with L-shell being the radial component of the plot, ranging from an L-shell of 3 to an L-shell of 8, and with MLT being the angular component. These plots consist of 960 total regions, each describing a portion of the magnetic field that is 0.5 L-shell by 15 minutes MLT. Figure 3 displays one such map, showing the dwell time of the FIREBIRD-II unit 3 satellite. The dwell time of a satellite is a description of how much time the satellite spent in any particular region of space.

![Figure 6. Dwell time (in seconds) of FIREBIRD-II unit 3, displayed using a polar heat map.](image)

EMIC waves were identified in this study through the use of magnetic field data from the Van Allen Probes EMFISIS instrument. This was done by first aligning the magnetic field data to the background field, in this case considered to be a 10 second mean of the magnetic field data. Using this background field, the magnetic field data was then rotated from GSE coordinates to field aligned coordinates in order to detect EMIC waves traveling along magnetic field lines. Field aligned data was then processed through the Fast Fourier Transform to produce power spectrum plots of magnetic field data. An example of one of these power spectrum plots is shown in Figure 7. These plots were then visually analyzed to identify EMIC waves, using the criteria of a minimum power threshold of 0.01 nT^2/Hz and a minimum duration of 5 minutes. This process of identifying EMIC waves was previously used in Zhang et al. [2014, 2016] and Saikin et al. [2015, 2016]. Identified EMIC waves were then compiled into a list identifying start and end times of the waves. FIREBIRD-II electron count data was then filtered to match times when EMIC waves occurred as detected by the Van Allen Probes using this list.
3 Results

When presenting data from the FIREBIRD-II satellites, unit 4 has a noticeably higher electron counts than unit 3. This difference could be related to energy threshold (>1055 keV for FU3 and >985 keV for FU4). However, since this discrepancy is apparent in all energy channels, another suggestion is that unit 4 is oriented at an angle compared to unit 3. If the satellite is not oriented along the magnetic field lines than it is possible for the particle detectors on board to not only identify precipitating electrons, but also quasi-trapped electrons that will be lost to the atmosphere within one drift orbit. For this reason, the presentation in this thesis focuses on unit 3 data. Despite this difference in total electron counts, observed spatial distribution of electron counts between units 3 and 4 were very similar. Plots of units 3 and 4 median counts are shown in Figure 8. When displaying electron count data on the polar heat maps, median count is used (as opposed to the mean) to avoid domination by several early FIREBIRD-II campaigns with elevated electron count events. While the data from these early campaigns is real data, and not erroneous, these early campaigns make detection of patterns in the heat maps based on arithmetic average difficult. Median counts prove much more useful in discovering trends in the behavior of electron precipitation.

Figure 7. Example of a power spectrum plot of an EMIC wave as detected by Van Allen Probe A on January 26, 2018.
Figure 8 displays behavior of electron distributions during the first 23 campaigns of FIREBIRD-II data coverage (February 2015 through July 2019). In both units 3 and unit 4, there are notable peaks in electron counts near MLT 6-8 and also from MLT 16-19, with the latter peak being the larger of the two. Both peaks occur between L-shells 4-6.

Figure 8. Median high energy electron counts per 6 seconds as measured by FIREBIRD-II unit 3 (left) and unit 4 (right). While there is no significant change in spatial behavior between the data captured by the two satellites, data from unit 4 displays significantly higher electron counts.

Figure 9. L-profile plot of FIREBIRD-II unit 3 data. Data is displayed using the 75\textsuperscript{th} percentile, the 50\textsuperscript{th} percentile, and 25\textsuperscript{th} percentile. Each percentile displays a peak in electron precipitation between L-shells of 4.5 to 5.

Figure 9. L-profile plot of FIREBIRD-II unit 3 data. Data is displayed using the 75\textsuperscript{th} percentile, the 50\textsuperscript{th} percentile, and 25\textsuperscript{th} percentile. Each percentile displays a peak in electron precipitation between L-shells of 4.5 to 5.

In addition to polar heat maps, electron precipitation count data from FIREBIRD-II unit 3 was also plotted as a function of L-shell, referred to as L profile plots. These L-profile plots
display the distribution of electron counts at varying L-shells according to 25th, 50th, and 75th percentiles of the data within each L-shell bin. Electron count data during the first 23 campaigns shows a visible peak between L-shells of 4.5 to 5 for all percentiles which is consistent with the L distribution of the outer belt electrons at the same energy range (personal communication, Van Allen Probes RBSP-ECT team). The 75th percentile peaks at a value of 487 counts. The 75th percentile peak also occurs at slightly lower L-shells, 4.6 in comparison with 4.9 for the median and 4.8 for the 25th percentile. These sets of plots displaying electron precipitation data during the entirety of FIREBIRD-II establish the general behavior of electron precipitation and serve as an important reference point for precipitation data under more restrictive conditions.

Figure 10. Median High energy counts per 6 seconds in the Northern (left) and Southern (right) Hemispheres as measured by FIREBIRD-II unit 3.

Figure 11. L-Profile plots for FIREBIRD-II unit 3 at the Northern (left) and Southern (right) Hemispheres.

Distribution of electron precipitation is significantly different in the Northern and Southern Hemispheres (Figure 10 and Figure 11). The general location of the peaks observed in both hemispheres match, but peaks in the Southern Hemisphere are present earlier in dawn.
compared to the Northern Hemisphere. At dusk the Southern Hemisphere data experiences its peak much later than the Northern Hemisphere, with the Southern Hemisphere’s peak at approximately 20 MLT, while the Northern Hemisphere’s peak is observed at approximately 17 MLT. The dawn side peak of the Southern Hemisphere is also notably larger than the dusk side peak, but in the Northern Hemisphere the dusk side peak is significantly more pronounced than the peak in the dawn side. The Southern Hemisphere additionally has elevated counts between L-shells 4-5 from 7-11 MLT. Most notably, however, the overall counts in the Southern Hemisphere are much higher than in the Northern Hemisphere. This is likely due to the South Atlantic Anomaly, a region in the Southern Hemisphere where the magnetic field is weaker because the intersection between the magnetic and rotation axes of the Earth is not located at the Earth’s center. This causes the electrons trapped in the radiation belts to mirror at lower altitudes over this region resulting in more electron precipitation [Kivelson and Russell, 1995].

L-profile plots for each of the two Hemispheres display the difference in electron precipitation between the two Hemispheres (Figure 11). The Southern Hemisphere displays significantly increased counts compared to the Northern Hemisphere at all percentiles, while the Northern Hemisphere displays reduced counts compared to both the Southern Hemisphere and combined data from the first 23 campaigns (Figure 9). This reduction in electron precipitation is most noticeable in the median peak of the Northern Hemisphere, which is notably more flat compared to the median peak of the Southern Hemisphere. The value of the differences between the peak counts between the hemispheres are 853 at the 75th percentile,184 electron counts at the 50th percentile, and 35 counts in the 25th percentile. These plots effectively establish that hemisphere has a major effect on the behavior of electron distribution, with greater precipitation in the Southern Hemisphere than in the Northern Hemisphere.

![Figure 12](image_url)

Figure 12. Median high energy electron count at planetary K-index <= 2 (left), and at planetary K-index >= 4 (right) as measured by FIREBIRD-II unit 3.

Figure 12 compares electron counts during periods of high and low planetary K index. When comparing electron precipitation at low values of Kp with high values of Kp, it is necessary to note that the amount of data for low Kp is much greater than the amount of data for high Kp. This is at least partially responsible for the greater variance between adjacent regions in the heat map. In addition, the data for high Kp is scarce enough that the aforementioned high electron counts during early campaigns begin to more seriously affect the data. This is present in
the narrow strips of high electron counts at MLT 7 and MLT 19. This region also overlaps with expected peaks in the dawn side, making it hard to distinguish what represents overall behavior and what represents those early campaigns. The elevated counts at dusk side match what was previously seen in other figures. The data for low Kp closely resembles the data for FIREBIRD-II unit 3 with no filtering, which is to be expected as this data represents 69.5% of all data measured by FIREBIRD-II.

![Graphs showing L-profile plots for FIREBIRD-II unit 3 data during periods of low and high geomagnetic activity.](image)

Figure 13. L-Profile plots for FIREBIRD-II unit 3 data during periods of low geomagnetic activity (left, Kp <= 2), and high geomagnetic activity (right, Kp >= 4)

L-profile plots for Kp displays similar values at low percentiles. Median percentiles increase slightly at high Kp compared to low Kp. The 75th percentiles show an increase of nearly double between the peak of high Kp and low Kp, with consistent increases at most L-shells, at a lower ratio than the increase at the peak. The distinct peak in electron counts at an L-shell of 4.5 in the 75th percentile for high Kp data is likely a byproduct of the aforementioned lower amount of electron count data. In summary, the effect of magnetospheric activity on electron counts based on Kp indices is more pronounced at higher percentiles and there is little to no Kp dependence associated with MLT.
Figure 14 presents L-profiles of data filtered for EMIC wave events, showing notable increases at the 75th percentile, minor increases at the median, and a slight decrease in the 25th percentile in comparison to data from the first 23 FIREBIRD-II campaigns shown in Figure 9. Since EMIC event data represents a small amount of total FIREBIRD-II data, this decrease in the 25th percentile could be statistical variance. When looking at the distribution of which hemisphere FIREBIRD-II unit 3 was in during recorded EMIC wave events it was found that 71.1% of Unit 3’s dwell time during EMIC events occurred in the Northern Hemisphere. The disproportionate increase in high percentile counts compared to background data seems to be in agreement with the idea that EMIC waves cause precipitation. While the FIREBIRD-II cubesats are not necessarily in conjunction with the Van Allen Probes at the time of the EMIC waves detection, EMIC waves may be able to affect electron precipitation at a range of MLT [Capannolo et al., 2019]. The Van Allen Probes may also not detect the full range of the EMIC wave; when an EMIC wave is detected by the Van Allen Probes it does not identify the full range of MLT and L-shell values that the EMIC wave exists in, it only detects it at the probes position at that time. When comparing the change in precipitation between the data from all campaigns and the data during EMIC wave events, the greatest increase was seen in the 75th percentile, an increase of 223, or 45%. The 50th percentile had a smaller increase of 22, or 19%. In the 25th percentile the counts actually decreased during EMIC events by 4, a change of 6%. This variation in how electron count data changes from the two sets of data suggests that FIREBIRD-II is detecting elevated levels of precipitation when it is in close enough position to the detected EMIC event, but is not always in position to do so. The elevated levels of electron precipitation during recorded EMIC wave events suggest that EMIC waves are a driver of electron precipitation.

4 Discussion

In order to further compare electron precipitation to EMIC wave occurrences, electron precipitation data during EMIC wave events was compared to analysis from Saikin et al., [2015]. This analysis consists of EMIC wave occurrence rates at all MLT between L-shells 2-8. The methods used in Saikin et al., [2015] to create the occurrence rate was consistent with the method...
used in this study: data from the Van Allen Probes EMFISIS magnetometer was aligned to the background magnetic field and then processed through the Fast Fourier Transform to create wave power spectrum plots, using 4096 data points per step, and an input step length of 512 data points, representing time periods of 64 and 8 seconds, respectively. From these plots EMIC waves were then detected by visually analyzing the wave power spectrum plots, identifying EMIC waves as activity with a magnitude of over 0.01 nT²/Hz, over a time of at least 5 minutes. The occurrence rate map was then produced by comparing the amount of time the spacecraft detected EMIC waves to the total amount of time the spacecraft spent in that region.

The EMIC wave occurrence map from Saikin et al. [2015], and the heat map of electron precipitation during EMIC wave events share some similarities (Figure 15). Both detect elevated activity in the daytime, with a peak in activity around dusk. In addition, the majority of elevated activity takes place between L-shells 4 and 6. However, there is a significant difference in the morning sector, with elevated FIRBIRD-II electron precipitation during EMIC events between MLT 6-9 and peak observed EMIC wave occurrence between MLT 10-12.

While both the FIREBIRD-II satellites and Van Allen Probes recorded data in the same region of L-shell and MLT, the two satellites are not necessarily in a matching L-shell and MLT as these wave events occur. Periods of time where the two parameters do match between the satellite are called conjunctions and are not particularly common. FIREBIRD-II data was not matched to conjunction times, and as such its satellites may be in different positions as the Van Allen Probes detect EMIC waves. In addition to this, a recent study has suggested that only 20-30% of EMIC waves will cause precipitation [Qin et al., 2018]. Despite these disclaimers, electron precipitation counts are noticeably elevated during EMIC wave events detected by the Van Allen Probes, suggesting a link between EMIC wave occurrences and electron precipitation. In order to conduct a larger scale study of >1 MeV electron precipitation directly associated with individual EMIC wave events, a pair of satellites that possess both FIREBIRD-II and the Van Allen Probes detection capabilities and a much greater amount of conjunction time would be needed.

Figure 15. Comparison of EMIC wave occurrence rate detected by the Van Allen probes, from Saikin et al. [2015] (left) to median electron precipitation counts as detected by FIREIRD-II unit 3 during EMIC waves detected by the Van Allen probes (right).

5 Conclusions
The goals of this research were to answer the following two questions: what is the spatial and temporal variation in electron precipitation from the outer radiation belt, and what are the drivers of this precipitation? The data collected and analyzed in this research offers some supportive conclusions about the relation between high energy (>1 MeV) electron precipitation and EMIC wave events, further establishing these waves as a driver of this precipitation. Although studies have identified atmospheric precipitation associated with individual EMIC events [Capannolo et al., 2019], to our knowledge this is the first time widespread precipitation from EMIC events has been observed using a comprehensive dataset at low Earth orbit. In addition, this research provides an analysis of electron precipitation behavior and its relation to MLT, L-shell, geomagnetic activity, and hemisphere. High energy electron precipitation at LEO is observed to peak at L-shells 4.5 to 5, a similar result to the distribution of electrons in the Van Allen radiation belts. When observing peak counts of electron precipitation at varying percentiles, peaks in the 75th percentile occur at slightly lower L-shells than peaks at the median or 25th percentiles, which indicates the primary location of the wave particle interaction leading to electron precipitation. For all data from FIREBIRD-II unit 3 this peak is observed at 4.6 for the 75th percentile, 4.9 at the median, and 4.8 for the 25th percentile. Additionally, regions of elevated electron precipitation are consistently detected in the dawn and dusk regions of MLT, between L-shells of 4 and 6.

FIREBIRD-II electron precipitation data shows a distinct difference between hemispheres, with the Southern Hemisphere experiencing greatly elevated levels of electron precipitation compared to the Northern Hemisphere. The Southern Hemisphere peak precipitation occurs closer to the night side than the Northern Hemisphere. L-profiles show differences in peak electron counts between hemispheres that decrease from 853 at the 75th percentile, 184 electron counts at the 50th percentile, and 35 counts in the 25th percentile. Peak electron counts at the 75th percentile in the Southern Hemisphere are over 5 times greater than peak counts in the Northern Hemisphere. This difference in precipitation data between the Hemispheres is likely due to the South Atlantic Anomaly. Differences in electron precipitation during periods of high geomagnetic activity and low geomagnetic activity show increases in electron precipitation during periods of greater disturbance in the magnetic field (higher Kp index). Peak activity in electron counts at the 75th percentile displayed significantly increased electron counts. Significant difference in the spatial distribution between periods of high activity and low activity are not observed, however.

Electron precipitation during recorded EMIC wave events is observed to be noticeably higher than background activity. Spatial distribution of electron precipitation during EMIC wave activity also matched reasonably well with previous data on EMIC occurrence rates, with some discrepancy between in the morning sector. Observations of electron precipitation as a function of L-shell at varying percentiles displays significantly increased peak precipitation during EMIC wave activity at the 75th percentile, with peak electron count at the 75th percentile observed to be 223 counts greater than counts observed during all of FIREBIRD-II’s campaigns. Peak electron counts at median percentiles increase as well during EMIC wave events, though to a less significant degree, with peak counts at the median only climbing by 22 to a total of 138. Increases in electron precipitation count during detected EMIC waves can also not be accounted for by the difference in precipitation between the Hemispheres; 71.1% of FIREBIRD-II unit 3’s data coverage during EMIC events was in the Northern Hemisphere. This discrepancy in measurements made in the between the Hemispheres is likely due to statistical variance and the
fact that the FIREBIRD-II and Van Allen Probes are not always in conjunction. This discrepancy between the hemispheres further suggests that the effect of EMIC waves on electron precipitation may be greater than what is presented in this research. Isolating electron precipitation behavior during EMIC wave events by hemisphere would be a region of interest in further exploration of the relations between electron precipitation and its drivers.

Through the use of FIREBIRD-II context data to establish some of the baseline behaviors of high energy (> 1 MeV) electron precipitation under varying parameters, namely L-Shell, MLT, Hemisphere, and Kp. This research then used this context data to measure how the electron precipitation changed during the times associated a list of detected EMIC waves by the Van Allen Probes in order to find a connection between these electromagnetic waves and electron precipitation. The elevated electron counts during EMIC wave events and similarities in distribution between EMIC wave occurrence rates and electron precipitation during these events suggest a connection between the two phenomena. Overall, this work provides new quantitative understanding of radiation belt electron precipitation and its drivers, as well as evidence linking increased precipitation of high energy (> 1 MeV) electrons to EMIC waves.

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