Characteristics of pitch angle distributions of hundreds of keV electrons in the slot region and inner radiation belt

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Abstract The pitch angle distribution (PAD) of energetic electrons in the slot region and inner radiation belt received little attention in the past decades due to the lack of quality measurements. Using the state-of-the-art pitch angle-resolved data from the Magnetic Electron Ion Spectrometer instrument onboard the Van Allen Probes, a detailed analysis of hundreds of keV electron PADs below L = 4 is performed, in which the PADs are categorized into three types: normal (flux peaking at 90°), cap (exceedingly peaking narrowly around 90°), and 90° minimum (lower flux at 90°) PADs. By examining the characteristics of the PADs of ~460 keV electrons for over a year, we find that the 90° minimum PADs are generally present in the inner belt (L < 2), while normal PADs dominate at L ~ 3.5–4. In the region between, 90° minimum PADs dominate during injection times and normal PADs dominate during quiet times. Cap PADs appear mostly at the decay phase of storms in the slot region and are likely caused by the pitch angle scattering of hiss waves. Fitting the normal PADs into sin^n α form, the parameter n is much higher below L = 3 than that in the outer belt and relatively constant in the inner belt but changes significantly in the slot region (2 < L < 3) during injection times. As for the 90° minimum PADs, by performing a detailed case study, we find in the slot region this type of PAD is likely caused by chorus wave heating, but this mechanism can hardly explain the formation of 90° minimum PADs at the center of inner belt.

1. Introduction

Relativistic electrons in the inner magnetosphere are distributed into two regions: inner radiation belt (L < 2) and outer radiation belt (L > 3), and the slot region (2 < L < 3) where the fluxes of electrons are typically low separates the two belts. In the inner radiation belt and slot region, though MeV electrons exhibit limited changes except during extremely active times, hundreds of keV electrons are subject to great variations, and various acceleration and loss processes are responsible for those variations [e.g., Li et al., 1993; Baker et al., 2004, 2007; Baker and Blake, 2012; Zhao and Li, 2013a, 2013b]. The electron pitch angle distribution (PAD) is an important characteristic of radiation belt electrons, since the evolution of PADs can give us important information on the source and loss processes in a specific region.

Many previous studies have focused on the characteristics and evolution of electron PADs in the outer radiation belt [e.g., West et al., 1973; Gannon et al., 2007; Chen et al., 2014]. Generally, the electron PADs in the outer radiation belt can be categorized into three types: the normal distribution, butterfly distribution, and flat top distribution. The normal distribution is the most general type of PAD in the outer belt, for which the electron flux peaks at 90° pitch angle (PA) and smoothly decreases at smaller PAs. It is thought to form as a result of the loss to the atmosphere combining with the pitch angle diffusion. Inward radial diffusion can also cause the flux peak around 90°. Due to the conservation of the first and second adiabatic invariant, when an electron moves inward, the perpendicular momentum increases more than the parallel component, which would increase the PA of electron and thus create a more 90° peaked PAD [e.g., Schulz and Lanzerotti, 1974]. The butterfly distribution has a minimum around 90°, which looks like a butterfly in the polar plot (in which PA is the polar angle and flux is the radius). The butterfly distribution is thought to be caused by the drift-shell-splitting effect combining with magnetopause shadowing or strong negative radial flux gradient [e.g., Sibeck et al., 1987; Selesnick and Blake, 2002]. Horne et al. [2005] have also suggested that chorus wave heating could cause butterfly distribution by preferentially heating off-equator electrons. For the flat top distribution the electron flux is approximately equal at a wide PA range centered around 90°.
It can be a transition between the normal distribution and butterfly distribution or can be due to strong wave-particle interactions [Horne et al., 2003]. Besides these three types of PADs, another PAD type, “cap” PAD (also called “head-and-shoulder” PAD), has also been recognized [e.g., Lyons and Williams, 1975a; Sibeck et al., 1987]. This type of PAD looks like a bump around 90° on top of a normal distribution. It is found to be present in the outer belt and slot region. As for the formation of cap distributions, Lyons and Williams [1975a] shows the comparison between the observation and modeling of wave-particle interaction, and the agreement between the two suggests that the cap distribution forms as a result of pitch angle scattering caused by the plasmaspheric whistler mode waves in the slot region. However, Sibeck et al. [1987] has also investigated the cap distribution in the outer belt and suggested that this type of PAD can be caused by a combination of the drift-shell-splitting effect and a substorm injection or a sudden magnetospheric compression. For tens to hundreds of keV electrons, “cigar” distribution with flux peaking along the direction of local magnetic field has also been found in the outer radiation belt, and it is thought to be related to the tail-like stretching of the nightside magnetic field prior to the substorms and thus could be used as an indicator of likely substorm onset [Baker et al., 1978].

Comparing to the PADs in the outer belt, PADs in the inner radiation belt and slot region received limited attention during the past decades. Lyons et al. [1972] calculated the pitch angle diffusion rate in the slot region, and the results showed that the interaction between electrons and plasmaspheric hiss waves can cause cap PADs in the slot region. Also, Lyons and Williams [1975a, 1975b] examined the PADs of 35–560 keV electrons in the outer belt and slot region using data from Explorer 45 and found that the PADs observed in the slot region during quiet time agree with the theoretical results of his wave scattering, while during storm time the PADs distort greatly. Most recently, Zhao et al. [2014] reported a new type of PAD of hundreds of keV electrons in the inner belt and slot region using Magnetic Electron Ion Spectrometer (MagEIS) measurements onboard Van Allen Probes. This PAD type, we call it 90° minimum PAD here, appears as a Gaussian distribution with a small bite out around 90°. It is generally present in the inner belt and occurs in the slot region during storm times.

In this paper, we further investigate and provide a comprehensive description of the PADs of hundreds of keV electrons below \( L = 4 \) using over a year’s data from MagEIS [Blake et al., 2013] onboard Van Allen Probes [Kessel et al., 2013], focusing on \( \sim 460 \) keV electron PADs as a function of L shell in the slot region and inner belt. In addition to the 90° minimum PAD reported by Zhao et al. [2014], we also identify normal and cap PAD in the low L region and show the characteristics and distribution of these three types of PADs in the low L region. Using the PADs observed in the slot region and inner belt, we can thus infer the source and loss processes in the low L region. More specifically, we focus on the 90° peaked PADs and 90° minimum PADs in the low L region, respectively. For the normal PADs, by fitting them into \( \sin^2 \alpha \) form, the parameter \( n \) is calculated and results are discussed. For the 90° minimum PAD, we perform more detailed statistical analysis as well as the case study and discuss the possible mechanisms responsible for the formation.

2. Data

The Van Allen Probes, launched on 30 August 2012, were designed to study the radiation belt dynamics through measurement of the thermal plasma, energetic particles, fields, and waves [Kessel et al., 2013]. The Van Allen Probes operate in an elliptical orbit, with the inclination of 10° and altitude of \( \sim 600 \) km at perigee and geocentric distance of 5.8 \( R_E \) at apogee. With the spin axis approximately pointing to the Sun, the spacecraft is spinning with a period of \( \sim 12 \) s. The MagEIS instrument, as part of the Energetic Particle Composition and Thermal Plasma Suite (ECT) [Spence et al., 2013], provides high-resolution energetic electron flux measurement with energy range of \( \sim 30–4000 \) keV. It contains four independent magnetic electron spectrometers on each spacecraft, one low-energy spectrometer (LOW), two medium energy spectrometers (M75 and M35), and a high-energy spectrometer (HIGH). The low unit, high unit, and one of the medium units (M75) are mounted with the field of view centered at 75° to the spin axis, while the field of view of another medium unit (M35) is centered at 35° to provide larger PA coverage. In this study, we mainly use the PA-resolved electron data from M75 of MagEIS, which provides \( \sim 200 \) keV–1 MeV electron flux measurement with good PA coverage. It is worth mentioning that the energy of each channel of MagEIS was changing during the mission, so for the statistical analysis presented in this study we use the electron data of energy channel closest to 460 keV.
3. Energetic Electron Equatorial PADs in the Slot Region and Inner Belt: Survey Plots

Though many studies have investigated the PADs in the outer radiation belt, the PADs in the inner radiation belt and slot region received little attention in past decades due to the lack of quality data, which was then due to the unforgiving contamination from the very energetic inner belt protons (e.g., Selesnick et al., 2014) and also from sometimes newly formed very energetic electrons and protons in the slot region (Blake et al., 1992; Li et al., 1993; Hudson et al., 1995; Baker et al., 2004). The clean measurements of hundreds of keV electrons from MagEIS onboard Van Allen Probes provide us an unprecedented opportunity to study the PADs in the low L region (L < 4). In this section, we focus on the PADs of ∼460 keV electrons in the low L region, show different types of PADs as a function of L for over a year, and discuss about the possible physical processes behind them.

Based on MagEIS PA-resolved data, the PADs of hundreds of keV electrons in the slot region and inner radiation belt are most similar to Gaussian distributions combined with some modifications around 90° PA. The PADs in the low L region can be roughly divided into two categories: 90° peaked PADs and 90° minimum PADs, while 90° peaked PADs can again be categorized into the normal distribution and cap distribution. Figure 1 shows examples of normal PAD, cap PAD, and 90° minimum PAD observed in the low L region using data from MagEIS onboard Van Allen Probe-A. For over a year, we found that most equatorial PADs in the slot region and inner belt can be described as one of these three categories, provided that the flux level is higher than the background noise. Thus, for the statistical analysis in this paper, we exclude all PADs with the total square root of counts (summed over all pitch angles) less than 50. However, there is still a situation where the counts are high but the PAD is almost flat, indicating high background noises with small signal-to-noise ratio. This kind of situation occurs mostly at the inner edge of outer belt as well as the inner part of inner belt. As for the inner edge of outer belt, the high flux level of background is likely caused by the bremsstrahlung radiation produced by very energetic electrons; while for the inner belt, it is more likely caused by the inner belt proton contamination. We call this type of PAD the “undefined” PAD since it cannot be categorized into any of the three well-defined PAD types and is likely formed due to contamination.

To show the categorization of PADs in the low L region, we use some criteria to identify different types of PADs. First, in order to identify those undefined PADs, we fit a PAD into a Gaussian function and calculate the correlation coefficient between the data and the Gaussian function. All PADs with correlation coefficients less than 0.8 are identified as undefined PADs. Using this criterion, we found between L = 1.5 and 3 only ∼2% PADs are undefined. Then, we identify the 90° minimum PADs using the same criteria as used by Zhao et al. [2014]: $f_{\text{avg}}(85° : 95°) < 0.95 \times f_{\text{avg}}(90° - \alpha : 90° + \alpha)$, where $f_{\text{avg}}(a : b)$ is the averaged flux of electrons with pitch angle between a and b, and $\alpha$ is chosen from 5° to 45° to give the maximum value of $f_{\text{avg}}(90° - \alpha : 90° + \alpha)$. If a PAD cannot meet the criteria of 90° minimum PAD, we then separate data into two parts according to the PA (PA = [60°, 120°] and PA = [0°, 60°] ∪ [120°, 180°]) and fit them into two Gaussian functions respectively. If the full width at half maximum of the second Gaussian function (using data for PA = [0°, 60°] ∪ [120°, 180°]) is at least twice of the first Gaussian function (using data for PA = [60°, 120°]), we identify this PAD as a cap PAD. The rest of the PADs are characterized as normal PADs. However, at very low L (< 1.4), the loss cone is very large (up to ∼ 40° at L = 1.4 and even higher at lower L), and the background noise from inner belt proton contamination is getting comparable with or higher than the electron
Figure 2. (top) Classification of pitch angle distributions of ∼460 keV electrons during 7 September 2012 to 24 March 2014 using data from MagEIS onboard Van Allen Probe-A. Different colors represent different types of PADs: blue denotes the 90° minimum PAD, green represents the normal PAD, and red represents the cap PAD, while grey indicates the undefined PAD. White regions are where the counts are too low to show clear PAD pattern or the satellite is away from the magnetic equator (with corresponding equatorial pitch angle of locally mirroring particle less than 80°). (bottom) Spin-averaged flux of ∼460 keV electrons during 7 September 2012 to 24 March 2014 using data from MagEIS onboard Van Allen Probe-A, when the equatorial pitch angle of locally mirroring particle is greater than 80°. The spin-averaged flux with PA close to the loss cone, which makes some normal PADs at L ∼ 1.3 as cap PADs. Thus, we simply mark all cap PADs detected below L = 1.4 as undefined PADs.

Figure 2 (top) shows the distribution of different PAD types of ∼460 keV electrons between L = 1 and 4 during 7 September 2012 to 24 March 2014 using the data from Van Allen Probe-A, with the corresponding equatorial pitch angle of locally mirroring electrons (α_eq) greater than 80°. Different colors represent different types of PADs: blue represents 90° minimum PAD, green is the normal PAD, and red is the cap PAD. The undefined PADs are marked as grey. Note that the occasional white gaps between L ∼ 1.2 and 2.5 are where Van Allen Probe-A is away from the magnetic equator (α_eq < 80°), while the gaps above L ∼ 2.5 are most likely where the data were rejected because the counts are low (total square root of counts < 50). The spin-averaged flux of ∼460 keV electrons during this time period is also provided for reference (Figure 2, bottom). The L parameter used in this study is the McIlwain L of locally mirroring particles with the T89 dynamic magnetic field model [Tsyganenko, 1989] using International Radiation Belt Environment Modeling library [Boscher et al., 2010], while L* parameter used in section 5, where the phase space density is calculated, is the Roederer L with the T89 model.

As Figure 2 (top) shows, the 90° minimum PADs dominate at L ∼ 1.4–1.8 almost all the time, while the normal PADs dominate at high L mostly (L > 3.5). In the region between, the PADs are subject to the influence of storm time injections. During storm times, as the plasmasphere shrinks while the radial diffusion and wave heating enhances, hundreds of keV electrons can penetrate into the slot region and sometimes even inner belt. Along with the injections, 90° minimum PADs dominate in both the slot region and inner belt. After the formation, 90° minimum PADs gradually disappear in the slot region, which is likely due to the pitch angle scattering caused by whistler mode waves, and the normal distribution becomes the dominant PAD type again between L = 1.8 and 2.5. After the injections, as the electron flux decreases, the cap distributions gradually appear between L ∼ 2.5 and 3.5, until the flux is too low to show a clear PAD pattern. As the modeling results from Lyons et al. [1972] predict, the resonance interaction between electrons and plasmaspheric hiss waves can produce PAD with a bump near 90°. Thus, the formation of the cap distribution in the slot region is likely due to the pitch angle scattering caused by plasmaspheric hiss waves. Grey regions, which represent the “undefined” PADs, are located near the inner edge of the outer belt after storms as well.
Figure 3. (top) The $n$ values of normal PADs of $\sim 460$ keV electrons calculated from Vampola’s equation as a function of $L$ shell during 7 September 2012 to 24 March 2014. The grey region represents where the $n$ value cannot be accurately calculated due to the contamination from inner belt protons. (middle) The corresponding equatorial pitch angle at the flux peak of $90^\circ$ minimum PADs of $\sim 460$ keV electrons during the same time period. (bottom) Spin-averaged flux of $\sim 460$ keV electrons, the same as in Figure 2.

as $L \sim 1.2$–1.3 and indicate the presence of high background noise from bremsstrahlung radiation or inner proton contamination.

To summarize, in this section we showed the equatorial PADs of $\sim 460$ keV electrons in the slot region and inner belt and identified three types of PADs: normal, cap, and $90^\circ$ minimum PAD. Below $L \sim 1.8$, $90^\circ$ minimum PADs dominate, while between $L \sim 3.5$ and 4 normal PADs dominate. In the region between, $90^\circ$ minimum PADs become dominant during storms and normal PADs dominate during quiet times. The cap distribution appears mostly during the decay periods in the slot region and thus is likely caused by the wave-particle interaction with plasmaspheric hiss waves. In the next two sections, we will discuss the $90^\circ$ peaked and $90^\circ$ minimum PADs in detail and suggest the physical processes responsible for the formation of those PADs.

4. Ninety Degrees Peaked PADs in the Slot Region and Inner Belt

Ninety degrees peaked PADs can be categorized into two types: the normal PAD and cap PAD. The normal PAD can also be fitted into a $\sin^{n} \alpha$ form, where $n$ represents the steepness of the normal PAD, with high $n$ number indicating a highly $90^\circ$ peaked distribution. To show more detailed features of the normal PADs, we fit the normal PADs into $\sin^{n} \alpha$ according to the equation given by Vampola [1998]: $n = (\log(l_{90/45}) + 0.004105)/0.14303$, where $l_{90/45}$ is the ratio of the flux at $90^\circ$ to that at $45^\circ$. In this study, we average the electron flux between PA = 85° and 95° and divide it by the averaged flux of electrons with PA of 40°–50° and 130°–140° and use this result as $l_{90/45}$ in Vampola's equation. Figure 3 (top) shows the $n$ values calculated by this method for normal PADs of $\sim 460$ keV electrons at $L < 4$, with $\alpha_{eq}$ greater than 80° and total square root of counts greater than 50. The grey region ($L < 1.8$) represents where the $n$ values cannot be
accurately calculated by this method due to the inner belt proton contamination to the electron fluxes with PA of 40°–50° and 130°–140°. Similar to Figure 2, only data from Van Allen Probe-A are used. It is clear that below \( L \sim 3 \), the \( n \) values are much higher than that at the inner edge of the outer belt, which is consistent with previous studies [e.g., Gannon et al., 2007]. This could be caused by the wave-particle interaction between electrons and plasmaspheric hiss waves, which only exist inside the plasmasphere. The inward radial diffusion could also play a role. In the inner belt, the value of \( n \) is relatively uniform, while in the slot region the \( n \) parameter changes frequently during injections. If we focus on the electron injections into the low \( L \) region, e.g., during the 17 March 2013 storm, we can find that the \( n \) parameter in the slot region is very high at the beginning of the injection, indicating a steep normal distribution. Afterward \( n \) becomes a little smaller, while as the flux decays, \( n \) becomes larger again. We will discuss this phenomenon in the rest of this section by showing detailed PAD evolution. Note that at \( L < 1.8 \), the background flux level is high due to the contamination from inner belt protons, which may elevate the flux at PA = 45° significantly; thus, in this region the parameter \( n \) cannot be accurately calculated using the Vampola’s equation. However, the peak flux of the electrons, around PA = 90°, is still significantly above the background at \( L > 1.3 \). Not shown here, we also examined the magnetic local time (MLT) and longitude dependence of the \( n \) parameter for \( L < 4 \) and found no significant variations. Figure 3 (middle) is discussed in section 5, and Figure 3 (bottom) shows the spin-averaged flux of \( \sim 460 \) keV electrons for reference.

To examine the evolution of 90° peaked PADS in the slot region during the injection, we also plotted the detailed PADS of \( \sim 460 \) keV electrons at \( L = 2.7 \) during 17–23 March 2013 (Figure 4). Here we use both inbound and outbound passes since there is no significant MLT dependence on \( n \) values, and only plot PADS with \( \alpha_{eq} > 80° \). The time of each plot is shown on the top and labeled as inbound or outbound pass in the top left corner. On 17 March, electron flux began to increase in the slot region, while the flux of electrons with PA \( \sim 90° \) increased first, forming a highly 90° peaked PAD. This is a general feature in the slot region during injections. One possible reason that the flux of electrons with PA \( \sim 90° \) enhances first is the inward radial diffusion. As an electron diffuses inward, to conserve the first adiabatic invariant, the perpendicular momentum increases, and the PA of the electron becomes closer to 90°; thus, a more 90° peaked PAD forms. As the injection went on, the fluxes of electrons with lower PAs also increased and the \( n \) value became smaller. During the flux decay time, the fluxes of electrons with low PAs decreased faster than that of high PAs, which results in high \( n \) PADS again.

At the end of the time period shown here, the cap PAD appeared. Since it appeared along with the flux decaying, it was very likely caused by wave scattering. According to the modeling results from Lyons et al. [1972], the edge of the “cap” in a PAD of 500 keV electrons caused by pitch angle scattering of plasmaspheric whistler mode waves should appear around 80° at \( L = 3 \). This is consistent with our observations.

On the other hand, the 90° minima in PADS also appeared during the injection shown here and gradually disappeared afterward at this \( L \) shell. We will discuss the 90° minimum PAD in detail in the next section.
In this section, we mainly examined the 90° peaked PADs in the low L. By fitting the normal PADs into $\sin^n \alpha$, we found that $n$ values in the inner belt and slot region are much higher than those in the outer belt, and the $n$ parameter is almost constant in the inner belt, while it changes considerably in the slot region during injections. By investigating an event in detail, we found that the formation of the highly 90° peaked PAD at the beginning of the injection is likely caused by inward radial diffusion, while during the decay time, due to the hiss wave scattering, low PA electrons are scattered into the loss cone more efficiently and steep normal PADs form again. Gradually, cap PADs occur due to the hiss wave scattering. Overall, plasmaspheric hiss wave scattering is an important mechanism which can lead to the steep normal PADs and cap PADs in the slot region and inner belt, while inward radial diffusion can also create highly 90° peaked PADs at the beginning of injection.

5. Ninety Degrees Minimum Pitch Angle Distributions in the Slot Region and Inner Belt
5.1. Observations During an Injection Event
In this section, we mainly focus on the 90° minimum PADs in the low L region. Zhao et al. [2014] reported on this new type of PAD in the low L region. They found such kind of PAD is persistent in the inner belt and appears in the slot region during storm time, which can also be inferred from Figure 2. To investigate the possible mechanisms leading to the formation of 90° minimum PADs, we will start with the observations of a specific injection event then investigate the possible causes in detail.

Figure 5 shows the PADs of $\sim$460 keV electrons at $L = 3.5$, 3.0, 2.5, and 2.0, respectively, during 28 June to 2 July 2013, which is a geomagnetic active time period with minimum $Dst$ index $\sim -100$ nT and maximum $AE$ index $\sim 1200$ nT. The magnetic latitude (Mlat) and the corresponding equatorial pitch angle of locally
Figure 6. Pitch angle distributions of electrons of (top) 231 keV, (middle) 464 keV, and (bottom) 593 keV, respectively at \( L = 3.0 \) during 28 June to 2 July 2013. The time of each panel is the same with Figure 5b.

mirroring electrons (\( \alpha_{eq} \)) are shown in the top right corner of each panel. Here we use outbound passes of Van Allen Probe-A to exclude any possible dependence on MLT. Note that only the passes close enough to the magnetic equator during this time period are shown here (with \( \alpha_{eq} \) at all four L shells greater than 75°). On 29 June, electron fluxes were enhanced significantly at \( L = 2.5 \) and above, while the flux at \( L = 2 \) almost did not change. Along with the flux enhancement, the minima at 90° PA appeared at all four L shells shown here. Afterward, the electron fluxes began to decay at \( L = 3 \) and 3.5, while at \( L = 2.0 \) and 2.5 the flux level did not change significantly during this time period. At \( L = 3.5 \), the 90° minimum PAD disappeared around 1 July 2013, while at \( L = 3.0 \) we can still see a hint of 90° minimum at this time and then the cap PAD appeared, indicating that the plasmaspheric hiss scattering was taking effect. At \( L = 2.5 \) and 2.0, the 90° minimum PAD developed on 29 June persisted during this time period. The differences in the disappearance rates of minima at 90° at different L shells indicate the presence of plasmaspheric hiss wave scattering, since according to the modeling results from Lyons et al. [1972], inside the plasmasphere the pitch angle diffusion coefficient of 500 keV electrons due to the hiss wave scattering is smaller in the lower L. Also note that at the beginning of injection, the flux peaks at different L shells occurred at similar pitch angles. During the decay period, the flux peaks at \( L = 3 \) and 3.5 moved to higher PAs gradually, which is also expected from the pitch angle scattering, while the flux peaks at \( L = 2.5 \) and 2.0 almost did not change during this time period.

PADs of electrons with different energies are also investigated. PADs of 231 keV, 464 keV, and 593 keV electrons at \( L = 3.0 \) are shown in Figure 6, and the time of each panel is the same with that of Figure 5b. It can be seen that the 90° minimum PADs appeared at all three energy channels at the beginning of the injection, and the PA of the flux peak of each energy channel is about the same. As the electron fluxes decayed, the minima at 90° gradually disappeared, while at higher-energy channels, minima at 90° disappeared faster, indicating a more efficient pitch angle scattering. This is also consistent with the theoretical results from Lyons et al. [1972] that the pitch angle diffusion coefficient due to the hiss wave scattering of 500 keV electrons is higher than that of 200 keV electrons at \( L = 3 \). Though we did not show here, this is true for \( L \sim 2.5-3.5 \) also. Above \( L \sim 3.5 \), the difference is too small, and between \( L \sim 2 \) and 2.5, the flux of 593 keV electrons is too low to show valid PAD patterns.

From Figures 5 and 6 it is evident that the 90° minimum PAD of hundreds of keV electrons exists in the inner belt and the slot region during the injection. Such kind of PAD appears at the beginning of the injection, while the flux peaks form at similar PAs at different L shells and for electrons with different energies. After the formation, this PAD pattern gradually disappears in the slot region and disappears faster at higher...
Figure 7. The occurrence rate of $90^\circ$ minimum PADs as a function of (top) $L$ shell and longitude or (bottom) MLT. The number of PADs in each bin is color coded and shown on the top right corner of each plot, with the corresponding color bar showing on the top right corner of each row.

$L$ and for higher-energy electrons. Thus, we conclude that the disappearance of $90^\circ$ minima in PADs is very likely due to the plasmaspheric hiss wave scattering inside the plasmasphere. In the next subsection, we will focus on the formation of the $90^\circ$ minimum PAD and discuss the possible mechanisms leading to it in the low $L$ region.

5.2. Possible Mechanisms

5.2.1. Drift-Shell-Splitting/Multipole-Drift-Shell-Splitting Effect

Figure 7 shows the occurrence rate of $90^\circ$ minimum PADs as a function of $L$ shell and longitude (Figure 7, top) or MLT (Figure 7, bottom) for different levels of geomagnetic activity, represented by $Dst$ index. Figure 7 (left, middle, and right columns) shows the results during quiet ($Dst > -20$ nT), moderate ($-50 < Dst < -20$ nT), and intense ($Dst < -50$ nT) geomagnetic activity, respectively. The number of PADs, or sample size, in each bin is color coded and shown in the top right corner of each plot (the corresponding color bar is shown on the top right corner of each row). Comparing the situation under different levels of geomagnetic activity, it is clear that during quiet time, $90^\circ$-minimum PADs exist in the inner radiation belt only; when the geomagnetic activity becomes moderate or intense, the occurrence rate of $90^\circ$ minimum PADs enhances significantly in the slot region. However, there is no significant longitudinal dependence or MLT dependence in the occurrence rate of $90^\circ$ minimum PAD. This indicates the formation of such kind of PAD is not due to the drift-shell-splitting or multipole-drift-shell-splitting effect. This is easy to understand since the drift-shell-splitting effect is expected to be very limited in the low $L$ region, while the multipole-drift-shell-splitting effect is only significant at $L$ close to 1 [e.g., Roederer et al., 1973].

5.2.2. Wave Heating

Wave heating is believed to be one of the most important acceleration processes for radiation belt electrons. However, most previous studies focus on the wave heating in the outer radiation belt since most waves capable of accelerating electrons, such as chorus waves, were observed there. As for the inner belt and slot region, many studies suggest radial diffusion to be the main source for energetic electrons and very
Figure 8. The phase space density data for electrons with $\mu = 12, 15, \text{ and } 18 \pm 10\%$ MeV/G, $K < 0.005 G^{1/2} Re$, during 28 June to 2 July 2013, using data from MagEIS LOW and M75 units of both Van Allen Probes.

instrument [Wygant et al., 2013] onboard Van Allen Probes during this injection event. During this event, chorus waves were observed by both probes. On 28 June 2013 and early 29 June 2013, which is just before the occurrence of 90° minimum PAD, Van Allen Probe-A, locating at the midnight sector during that time, observed that chorus waves extended to $L \sim 3$. It is well known that chorus waves only exist outside the plasmasphere. During this event, the plasmapause location reached $L \sim 2.56$ when judging from the sharp change in spacecraft potential along with the abrupt onset of hiss emission using data from EFW [Zhao et al., 2014]. Since mostly Van Allen Probes only crosses the plasmapause twice per 9 h, the plasmapause location could move even closer to the Earth between spacecraft passes. Thus, during this event chorus waves could have extended into even lower $L$ region, so they are likely responsible for the formation of 90° minimum PADs in the slot region. Also, we calculated and plotted out the equatorial PA of the flux peak for 90° minimum PADs of $\sim 460$ keV electrons from September 2012 to March 2014 (Figure 3, middle). It shows clearly that during this injection event the flux peaks in PADs formed at $\sim 65°$–70°. Thus, the observed PA of the flux peak is consistent with the theoretical results of nightside chorus wave heating derived by Horne et al. [2005].

However, chorus waves only exist outside the plasmasphere, and the plasmapause location can barely reach $L < 2$. It is still hard to explain the formation of PADs in even lower $L$ by chorus wave heating. On the other hand, fast magnetosonic waves, which exist both inside and outside the plasmasphere, could create 90° minimum PADs by preferentially heating up off-equator electrons in a wider $L$ range. However, based on Figure 3 (middle), the PA of flux peak below $L = 2$ is generally at $\sim 70°$ and sometimes even lower, which does not agree with the theoretical results derived by Horne et al. [2007] which predicts that the flux peak inside the plasmasphere caused by fast magnetosonic waves will appear at $\sim 80°$.

5.2.3. Wave Heating Combining With Inward Radial Diffusion

We have discussed the possibility of chorus waves creating 90° minimum PADs and concluded that chorus waves can play an important role in the formation of such type of PADs outside the plasmasphere. However, limited studies show the influence of wave heating. Here we examined detailed wave data to show the possibility of wave heating creating 90° minimum PADs.

Existing outside the plasmasphere, chorus waves accelerate off-equator electrons more efficiently. Horne et al. [2005] calculated the bounce-averaged energy diffusion rate of chorus waves in different sectors and found that nightside chorus waves preferentially heat up hundreds of keV electrons with PA of $60°$–80°. Fast magnetosonic waves could also be a potential mechanism causing 90° minimum PAD. Magnetosonic waves exist both inside and outside the plasmasphere, while outside the plasmasphere magnetosonic waves preferentially heat up hundreds of keV with PA of $\sim 60°$, and inside the plasmasphere they are more efficient for electrons with even higher PAs ($\sim 80°$) [Horne et al., 2007].

To investigate the possibility of wave heating, we examined the data from the Electric Field and Wave (EFW)
the 90° minimum PAD generally exists in the center of the inner belt, where the plasmapause can rarely get to. Thus, we also considered the possibility of wave heating combining with inward radial diffusion causing such type of PADS. It is possible that the 90° minimum PADS are created by chorus waves outside the plasmapause, and then the electrons diffuse inward while the minima at 90° in PADS is conserved. Figure 8 shows the phase space density data of $\mu = 12$, 15, and 18 (±10%) MeV/G, $K < 0.005 G^{1/2}/R_E$ equatorially trapped electrons, where electrons with $\mu = 18$ MeV/G, $K < 0.005 G^{1/2}/R_E$ approximately correspond to an energy of 460 keV at $L = 2.0$. The phase space densities are calculated using flux data from the LOW and M75 units of MagEIS on both Probes. Figure 8 shows that the radial gradient in phase space density is always positive during this injection event, which indicates the presence of inward radial diffusion. It is well accepted that inward radial diffusion preferably energizes electrons with larger pitch angle. In this situation, if the 90° minimum PAD is created at larger L and then the electrons diffuse inward, we would expect the flux peak moves toward 90° as the electrons move to lower L. However, as Figures 3 (middle) and 6 show, during the injection the flux peak appeared at similar PAs at different L and for electrons with different energies, almost occurring at the same time (within the time resolution of the spacecraft traversing the region). These facts indicate that inward diffusion is present during injections but does not play a significant role in causing 90° minimum PADS in the inner belt.

Figure 9 shows the detailed phase space density data of electrons with $\mu = 18$ MeV/G and $K < 0.005 G^{1/2}/R_E$ at $L = 3.5, 3.0, 2.5, 2.0$, and $1.5 (\pm 0.05)$, respectively, during 28 June to 2 July 2013. Red dots are the data from Van Allen Probe-A, while black points are the data from Van Allen Probe-B.

Figure 9 shows the detailed phase space density data of electrons with $\mu = 18$ MeV/G and $K < 0.005 G^{1/2}/R_E$ at $L = 3.5, 3.0, 2.5, 2.0$, and $1.5 (\pm 0.05)$, respectively. It is clear that the phase space density increased at larger L shells first then gradually increased at lower L, which shows the presence of inward radial diffusion. However, note that the phase space density at $L = 2.0$ decreased first as shown in Figure 9, and we can also find in Figure 5d that the flux of locally mirroring electrons at $L = 2$ decreased during this injection event, which is actually responsible for the formation of minimum at 90°. This can hardly be explained by wave heating or radial diffusion. Though whistler mode wave scattering can scatter electrons close to 90° at this L shell, it can only smooth the PAD without creating a minimum at 90° [e.g., Abel and Thorne, 1998]. Thus, the formation of 90° minimum PAD in the inner belt still can hardly be explained by the mechanisms discussed here.

To summarize so far, in this section we showed the 90° minimum PADS of electrons with different energies and at different L shells during an injection event, and then we discussed about the possible mechanisms which could be responsible causing such type of PADS. From Figure 7, we know that there is no longitude or MLT dependence of occurrence rate of 90° minimum PADS; thus, we can rule out the possibility of drift-shell-splitting or multipole-drift-shell-splitting effect. Wave heating by chorus waves is still the most likely explanation for the formation of 90°-minimum PADS outside the plasmapause, while the inward radial diffusion is present during the injection but does not play an important role in the formation of such type of PADS.
PADs in the inner belt. Though chorus wave heating works well for the formation of 90° minimum PADs in the slot region, the formation of 90° minimum PADs at $L^* \sim 2$ and lower is still a mystery and cannot be well explained by any known mechanisms examined here.

6. Discussion

In this study, we examined the PADs in the slot region and inner belt using data from MagEIS onboard Van Allen Probes. The high-quality data from Van Allen Probes give us an unprecedented opportunity to investigate the detailed PADs in the low $L$ region. Using these data, we categorized the PADs below $L = 4$ into three types: normal, cap, and 90° minimum. Based on our categorization, during September 2012 to March 2014, about 98% of equatorial PADs ($\alpha_{eq} > 80^\circ$) of ~460 keV electrons between $L = 1.5$ and 3 can be classified into one of these three types, provided the total square root of counts (summed over all pitch angles) is greater than 50. We also found, between $L = 1.5$ and 3, 61% of equatorial PADs are categorized as 90° minimum PADs, 36% of them are normal PADs, and 1% of them are cap PADs. While in the whole region below $L = 4$, about 32% of equatorial PADs are categorized into the normal PAD, 2% of them are cap PADs, 49% of them are 90° minimum PADs, and 17% of them are undefined. These values show that the 90° minimum PAD is the most prevalent PAD type which is generally present in the low $L$ region.

Recently, Zhao et al. [2014] reported that 90° minimum PADs are generally present in the inner belt and appear in the slot region during storm time, and once created, such kind of PAD disappears faster at higher $L$ shells, while in the center of inner belt this type of PAD can last for over a year. In this paper, we present a more comprehensive characterization of the PADs in the region of $L < 4$ by categorizing PADs into three different types: normal, cap, and 90° minimum PADs. We show the characteristics of three types of PADs and discuss the possibly responsible mechanisms for the formation of each type of PADs through detailed analysis. We also focus on the formation of 90° minimum PAD. Zhao et al. [2014] suggested that chorus wave/fast magnetosonic wave heating could be the mechanism which caused 90° minimum PADs in the low $L$ region. In this paper, we examined more possibilities. By performing statistical analysis as well as analyzing an injection event in detail, we excluded the possibility of drift-shell-splitting/multipole-drift-shell-splitting and showed that the effect of radial diffusion on the formation of 90° minimum PADs is limited, whereas since the chorus waves were observed at low $L$ region just before the formation of 90° minimum PADs, they are likely responsible for the occurrence of 90° minimum PADs in the slot region. However, it is still hard to explain the formation of 90° minimum PADs in the inner belt by wave heating or any other mechanism we examined here. Future work is still needed to understand the formation of 90° minimum PADs in the inner belt.

Previously, a few studies also investigated the PADs in the low $L$ region. Lyons and Williams [1975b] studied 35–560 keV electron PADs throughout the slot region and outer belt during some storm and post storm time and found that the PADs are subject to the influence from storm injections. For 240–560 keV electrons, they found that normal PADs form during injections, while the PADs with the bumps surrounding 90° (cap PADs) gradually appear during the post storm period. This is consistent with our observations between $L \sim 2.5$ and 3.5, though we also identified the appearance of highly 90° peaked PADs at the beginning of injections, which are likely caused by enhanced inward radial diffusion. Lyons and Williams [1975b] also observed that 90° minimum PADs occasionally occur and disappear in the slot region with time scales from 8 to 24 h. However, we found this could be because they did not take magnetic latitude into consideration. Figure 2 (top) shows in the equatorial region the 90° minimum PADs almost always form during injections and afterward gradually disappear due to pitch angle scattering, while Figure 5 shows for ~460 keV electrons, minima at 90° disappear in about 2 days at $L = 3$ and 3.5 and persist even longer at lower $L$ shells.

Also, Horne et al. [2003] and Gannon et al. [2007] reported on the hundreds of keV electron PADs in the slot region. Using CRRES data, Gannon et al. [2007] found that between $L = 2$ and 3, the PADs of 510 keV electrons are mostly 90° peaked. However, this could be because they identified the 90° peaked PADs as distributions where the flux of 90° PA electrons is higher than that of 45° PA. Based on this criterion, 90° minimum PADs we observed in the slot region and inner belt cannot be identified because the bite out around 90° is small in pitch angle extent. Also, by using CRRES data, Horne et al. [2003] found the distributions at $L \sim 2$ are rounded and dominated by Coulomb collisions. This could also be due to high magnetic latitudes since CRRES was operating in an orbit with inclination of 18° and was away from the magnetic equator more often than Van Allen Probes.
Some previous studies also identified butterfly PADs in the outer radiation belt or the slot region, which have minima at 90° PA, but the flux peaks in PADs are at much lower PA (∼ 45° or even lower). Several possible mechanisms were also suggested in those studies. Adiabatic effect (or ring current effect) is one of the suggested mechanism which can cause the development of minima at 90° PA in electron PADs in the outer radiation belt [Lyons, 1977; Ebihara et al., 2008]. As a geomagnetic storm develops, the ring current builds up and decreases the geomagnetic field magnitude significantly near the equator in the outer belt. As a result of conservation of the first two adiabatic invariants of electrons and the decrease in the electron flux with increasing energy, minima at 90° PA in electron PADs develop in the outer radiation belt near the equator. However, the ring current effect is not significant enough in the slot region and inner radiation belt to cause 90° minimum PAD, since the magnetic field strength in the low L region does not change much during geomagnetic storms. For example, comparing the magnitude of magnetic field at the time of first two columns in Figure 5, using T89 model, we found that the magnetic field strength changed only 3% at L = 2, 1% at L = 2.5, and < 1% at L = 3 near the magnetic equator. Such a subtle difference in magnetic field magnitude is not able to produce minima at 90° PA through adiabatic effect. Another proposed mechanism is the recirculation process, which was initially identified as a possible mechanism for the energetic particles in the Jovian outer magnetosphere [Nishida, 1976] and then was used to explain the butterfly pitch angle distributions in the Earth’s outer radiation belt [Baker et al., 1989; Fujimoto and Nishida, 1990]. The recirculation process assumes there exists an energy-conserving cross-L outward transport of energetic electrons at low L region near the mirror point combining with the conventional inward radial diffusion and pitch angle diffusion, and thus, the energetic electrons can get energized by going through this process repeatedly. The cross-L transport near the mirror point results in butterfly distributions. However, since the cross-L transport occurs at low altitude near the mirror point, the resulting PAD should have peaks at very small PAs. For example, Fujimoto and Nishida [1990] simulated the recirculation process and found it can cause the butterfly distributions which have flux peaks at ∼ 10°–20° PA at L=6.6. But the 90° minimum PADs found in the slot region and inner belt show flux peaks at ∼ 70° or even higher. Also, it is hard to explain the 90° minimum PAD formation in the very low L by the recirculation process. Thus, the recirculation process is not likely to be associated with the 90° minimum PAD in the slot region and inner belt. On the other hand, Morioka et al. [2001] reported butterfly pitch angle distribution of MeV electrons in the inner belt and slot region using observations of Akebono and proposed a possible mechanism of UHR mode waves. However, their observation showed there is no significant 90° minimum in the PAD of 0.3–0.95 MeV electrons. This could be due to the limitation of the instrument, or the high magnetic latitude since Akebono was operating in a high-inclination orbit and was mostly away from the magnetic equator.

7. Conclusion

We investigated the PADs of hundreds of keV electrons in the region of L < 4 using data from MagEIS onboard Van Allen Probes, categorized them into different types, and examined the possible physical processes responsible for the formation of different types of PADs. The main conclusions are as follows:

1. Equatorial PADs in the slot region and inner belt can be divided into three types: normal, cap, and 90° minimum PAD. For ∼460 keV electrons, 90° minimum PADs dominate at L ∼ 1.4–1.8, while normal PADs dominate at L ∼ 3.5–4; in between, 90° minimum PADs dominate during injections, while afterward minima at 90° in PADs gradually disappear and normal PADs become dominant. Cap PADs generally appear at L = 2.5–3.5 during the flux decay period following an injection.

2. Based on the equatorial PADs of ∼460 keV electrons during September 2012 to March 2014, between L = 1.5 and 3, 98% of PADs can be categorized as one of these three PAD types. While 61% of PADs are categorized as 90° minimum PADs, 36% of them are normal PADs and 1% of them are cap PADs, which shows the 90° minimum PAD is the most prevalent PAD type in the low L region.

3. Fitting the normal PADs into sin^n α form based on Vampola’s equation, we found that below L = 3 the n parameter is much higher than that of the outer belt. The n parameter is almost constant in the inner belt; but in the slot region, it is generally higher at the beginning of injections and during the decay period, which is likely due to inward radial diffusion and plasmaspheric hiss wave scattering, respectively.

4. By performing a detailed case study, we showed that 90° minimum PADs of hundreds of keV electrons occur in the slot region during injections and gradually disappear afterward, while the flux peak forms at similar PAs for electrons with different energies. While the disappearance of 90° minimum PADs can be attributed to pitch angle scattering caused by hss waves, the formation of this type of PAD in the slot
region is likely caused by the chorus wave heating. However, the mechanisms examined in this study can hardly explain the formation of 90° minimum PADs in the center of inner belt.

Once again, the clean measurements of hundreds of keV electrons from MagEIS onboard Van Allen Probes enabled us for a detailed characterization of the PADs of hundreds of keV in the inner part of the outer belt, the slot region, and the inner belt, which is new and compelling.

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