How whistler mode hiss waves and the plasmasphere drive the quiet decay of radiation belts electrons following a geomagnetic storm

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Abstract. We show how an extended period of quiet solar wind conditions contributes to a quiet state of the plasmasphere that expands up to L ~ 5.5, which creates the perfect conditions for wave-particle interactions between the radiation belt electrons and whistler-mode hiss waves. The correlation between the hiss waves and the plasma density is direct with hiss wave power increasing with plasma density, while it was generally assumed that these quantities can be specified independently. Whistler-mode hiss waves pitch angle diffuse and ultimately scatter freshly injected electrons into the atmosphere until the slot region is formed between the inner and outer belt and the outer belt is drastically reduced. In this study, we use and combine Van Allen Probes observations and Fokker-Planck numerical simulations. The Fokker-Planck model uses consistent event-driven pitch angle diffusion coefficients from whistler-mode hiss waves. Observations and simulations allow us to reach a global understanding of the variations in the trapped electron population with time, space, energy, and pitch angle that is based on the
1. Introduction

Understanding and predicting the physical mechanisms that control the electron flux reduction in the heart of Earth’s radiation belts is critical to preserve orbital hardware that operates in this region. In this study, we analyze the evolution of the full three-dimensional structure of the radiation belts in L, E, and equatorial pitch-angle, $\alpha$, during quiescent days that follow a storm. We focus on a global characterization of the fast slot formation and the outer belt decay, which led to a drastic reduction in the flux level of the whole radiation belt system, spanning from above the ionosphere at 600 km up to geostationary orbit at 36000 km.

This study is based on the analysis of high-quality observations from NASA’s Van Allen Probes (RBSP) [1] that are the most comprehensive in-situ measurements ever taken in the near-Earth space radiation environment. Data analysis is supported by computations made with the Versatile Electron Radiation Belt (VERB-3D) code [e.g. 2, 3, 4], that is based on a full 3D quasi-linear Fokker-Planck formalism. We feed the VERB-3D code with event-specific pitch-angle diffusion coefficients [5, 6, 7] that are self-consistently computed from in-situ measurements of plasmaspheric waves and the plasma density from RBSP.

The analysis of the radiation belt observations (section 2), of the plasmasphere (section 3), and of the whistler-mode hiss waves (section 4) reveal strong correlations. When all wave and plasma observations are self consistently fed into a Fokker-Planck code (section 5), they lead to an accurate reproduction of the full radiation belt structure, showing the fundamental role of the plasmasphere and the whistler-mode hiss waves in the net removal of high-energy radiation belt electrons.

2. Van Allen Probes observations of the removal of slot and outer belt electrons

The Van Allen Probes (RBSP) consist of twin spacecraft on near-equatorial elliptic orbits. The orbital period is ~9 hr, the MLAT coverage $|\text{MLAT}| < 20^\circ$, and the orbital apogee is $\approx 6$ Earth radii. Full precession of the apogee through all MLTs occurs approximately every 2 years.

In this study we focus on the storm of March 1, 2013 [8], which is associated with a high-speed solar wind stream that created strong erosion of the plasmasphere during the first day of the storm, down to L=3. During the storm, the outer belt flux considerably dropped. The storm was followed by enhancements of relativistic electrons in the slot region and outer belt as well as an expansion of the plasmasphere back to a normal extended state. Three days after this storm, an extended period of 11 days of quiet solar wind conditions persisted, with the plasmasphere expanding outwards to L~5.5.

Figure 1 (left) shows flux observations on outbound orbits on March 4 and eleven days later on March 15 2013 from the MagEIS instrument [9] onboard RBSP-A. The Roederer L-shell value is computed using the T89 magnetic field model. The data grid is made of 800 available L-shells from L=1.6 to L=6.1, 20 available energies from 30 keV to 4.2 MeV, as well as 11 available pitch angles from 8 to 172 degrees. Data have been background-corrected [10] and interpolated onto a fixed (L, E) grid that matches the simulation grid used in section 4. The Level 3 omnidirectional flux (column 1 of Figure 1) is computed from the sampled background-corrected MagEIS Level 3 directional fluxes measured at local pitch-angle $\alpha=8, 25, 41, 57, 74, 90, 106, 123, 139, 155, 172^\circ$ that are symmetrized by direct averaging to be sampled at $\alpha=8, 25, 41, 57, 74, 90^\circ$ and integrated with respect to $\alpha$ and solid angle in order to provide a local omnidirectional flux at the RBSP latitude.

Figure 1 (left) shows a dynamic enlargement of the slot region and a decrease in the flux level in the outer belt. The omnidirectional flux level reduces by 1-2 orders of magnitude depending on the location and energy. The creation of the slot is quite fast and achieved in 10 days. In turn, the outer belt flux decays gradually and falls by a factor ~20. The decay creates an energy structure with an S-shaped edge of the outer belt [11, 5, 12, 6, 7], which is sketched in red in Figure 1 (panel 4 second column). The decay of the outer belt is quite uniform across pitch-angles, with only small differences in the structure at different pitch-angles. Outer belt directional fluxes turn out to be nearly isotropic.
(by a factor of ~2) at any given time. The quasi-invariance of the directional outer belt flux with pitch-angle is remarkable and occurs at all energies. It is consistent with the absence of local acceleration from whistler-mode chorus wave particle interactions. Likewise, the position of the inner edge of the outer belt is relatively independent of pitch-angle.

In contrast, the inner belt and the inner slot edge are strongly pitch-angle dependent. We observe a low-energy inner belt [13], with the flux of electrons dropping steeply above 800 keV. The inner belt is wider at large pitch-angle leading to a narrower slot and to an outer edge of the inner belt increasing in L as pitch-angle increases.

Figure 1 (right panel) shows 1D Fokker-Planck computations of the equilibrium 2D structure (L-shell, Energy) of the radiation belts computed prior to the first RBSP observations of the energy structure [11]. This computation uses statistical wave and plasma models. Models are described in [12]. This simulation shows a similar S-shape structure that is due to the removal of electrons by wave particle interaction by whistler-mode hiss waves. This figure raises 5 important questions that have motivated our studies; can the use of local wave and plasma measurements help us to recover the observed radiation belt structure, and if so, with what accuracy? Can we reproduce the decay time scale knowing that the equilibrium structure is by definition a steady structure requiring an infinite amount of time? Do we replicate a physical barrier [14] made of vanishing radial transport that prohibits fast transport of relativistic energy electron below L=2.8? What is the role and the importance of the plasmasphere? Are hiss waves alone capable of creating the observed structure?

Figure 1: MagEIS omnidirectional flux (n.cm⁻².s⁻¹.keV⁻¹) computed by integration of the Level 3 MagEIS local directional symmetrized flux (n.cm⁻².s⁻¹.keV⁻¹) measured from RBSP-A and shown here at α₀=25, 57, and 90°. The omnidirectional flux is shown on the fourth day of the storm on March 4 (first line, left panel) after the plasmasphere has recovered (cf. next section) and eleven days later (second line, left panel) after the gradual electron decay, illustrating the drastic removal of the electrons brought by the storm. The final outer belt structure has a S-shape for all α₀, which is drawn in red (panel 4 second column). 1D Fokker-Planck computations (right panel) of the equilibrium 2D structure (L-shell, Energy) of the radiation belts computed anteriorly to RBSP observations with statistical wave and plasma models.

3. On the importance of keeping the correlation between hiss waves and the plasmasphere

The plasma density enters directly in the dispersion relation that controls the strength of wave-particle interactions, and an accurate knowledge of its value is thus important for the computation of the electron diffusion and scattering. In addition, we show in this section that whistler mode hiss waves are also strongly dependent on the plasma composition, probably because either their transport within the plasmasphere or their local birth and growth is dependent on the plasma density conditions, if not because of both reasons.

3.1. Accurate determination of the plasmasphere

The plasma density associated with each magnetic wavefield observation is either derived directly from the upper hybrid resonance frequency [15] measured by the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) [16], or derived from spacecraft floating potential data, calibrated against plasma densities determined from the upper hybrid resonance frequency [17]. Spacecraft floating potential is measured by the Electric Fields and Waves (EFW) instrument [18]. A third alternative to derive the plasma density, though not used here, is to infer density from whistler wave measurement [19].

Figure 2(left) shows the plasma density in March 2013 with both measurements combined together and complemented by the statistical model of [20] when a measurement is lacking. Figure 2(center) shows the limit of the plasmasphere, i.e. the plasmapause defined for a limiting minimal density, ρlim,
computed with the 2 previous manners and for $\rho_{\text{lim}}$=100 /cc and $\rho_{\text{lim}}$=30 /cc for March 2013. The two storms of March 2013 (March 1 and March 17) are clearly visible through the deep compression of the plasmasphere (center), with the plasmapause reaching almost $L=2.5$ for the second storm. Histograms in Figure 2(right) made on the datasets from 09/2012 to 04/2016 show the variability of the plasmapause location according to the method. In the bottom histogram, the mean difference is 0.18, the median is 0.10, and the standard deviation of the distribution of differences is 0.24. The absolute value of the difference is less than 0.5$L$ for 92% of cases. This means it is difficult to accurately determine the plasmasphere within 0.5$L$ and, therefore, the separation between whistler hiss mode waves and whistler mode chorus waves. A $+0.1L$ arises on top from the choice of $\rho_{\text{lim}}$ (Figure 2 left, top). This argues against most common radiation belt models that use a plasmapause for delimiting the hiss and the chorus waves influence. On the contrary, models, as here, that directly use the density are likely to be more accurate since $\rho_{\text{lim}}$ is never used as a separator of the wave domains.

![Plasmasphere location](image)

Figure 2: (Left) the electron density in March 2013 measured from EMFISIS and EFW, with the limit of the plasmasphere, i.e. the plasmapause, sketched in red. Dense filamentary structures show the complexity of this medium. (Center) The plasmapause ($\rho_{\text{lim}}$) as a function of time in March 2013 deduced from the upper hybrid resonance frequency and $\rho_{\text{lim}}$=100 /cc (blue), from spacecraft potential with $\rho_{\text{lim}}$=100 /cc (red) and $\rho_{\text{lim}}$=30 /cc (black). (Right) Histogram of the differences between the 3 methods made from 09/2012 to 04/2016.

3.2. Dependence of whistler mode hiss waves with the plasma density

Plasmaspheric hiss describes an incoherent collection of R-mode electromagnetic plasma waves (whistler-mode waves), largely confined to the Earth’s plasmasphere. This wave type has long been recognized as important to inner magnetospheric dynamics for its role in scattering electrons, to the point of modifying the morphology of the radiation belts through the creation of the slot region [e.g., 21, 11, 5].

We identify wave measurements from the EMFISIS instrument, restricting the measurements to right-hand polarized waves with ellipticity above 0.2 [22], and to a frequency range typical for plasmaspheric hiss from 50 Hz to 2 kHz [23]. The hiss wave power spectral density is plotted in Figure 3(left) in March 2013. A filamentary temporal structure of the wave amplitude is very apparent. Structures are changing in time and space dynamically in a complex way as the satellite orbits around the Earth. Amplitudes vary by orders of magnitude. The stronger waves are located in the middle of the plasmasphere interior, varying between $L = 2$ and $L = 4$. The wave normal direction of plasmaspheric hiss is predominantly field aligned, although a small oblique component is apparent for higher frequencies in the inner plasmasphere [24].

Figure 3(right) reveals the apparent correlation found between whistler-mode hiss wave power and the plasma density for various substorm conditions indicative of the magnetic activity; hiss power increases with density [25]. On the contrary, there is no pattern found between the hiss power and L-shell and variations in density create jumps in the wave power (last column). Density and hiss power are thus coupled and the good knowledge of their value at both every location and time is critical to obtain the best accuracy.
understanding the decay of outer belt electrons from hiss waves. This absence of pitch angle diffusion explains why electrons of energy below ~800 keV and for MLT=10-12 where hiss are powerful. Sorting with density reveals the hiss power is strongly correlated with density.

4. Wave-particle interactions

In this study, bounce and drift averaged diffusion coefficients $D_{\alpha_0, t}(E, \alpha_0, t)$ are computed following the method and equations in [26], which account for a sum over all harmonics [-n,...,0,...,n], a wave normal integration, and bounce averaging between the mirror points. Equations are not recalled here for the sake of conciseness [20]. Both the low-frequency and high-density approximations [20, 27 26] are adapted for this problem [6] and used. We made use of the mean wave normal angle width, $\Delta \theta_m(t, L)$, which is derived from the EMFISIS data [28]. The mean frequency, the frequency width, the wave normal angle, and the mean wave normal angle width of plasmaspheric hiss are all used synchronously at every L in the computation of the diffusion coefficients. The plasma density varies with latitude $\lambda$ according to a $\cos^2(\lambda)$ law which is applicable in the plasmasphere [29]. Variation of the wave properties with latitude is not accounted for (cf. discussion in [6]). Magnetic Local Time (MLT) dependence of the wave amplitude is accounted for [30].

Massively parallel simulations are required to compute the diffusion coefficients for 60 energies (E varying from 0.07 MeV to 6 MeV) at every node (t, L), i.e., a quarter million times (43L x 93t x 60E). We use a grid of 256 pitch angles in [0, 90°] and 50 cyclotron harmonics. Such a resolution leads to ~61.5 million diffusion coefficients computed on a supercomputer, using 4000 processors during ~20 hr.

We plot in Figure 4 temporally averaged pitch angle diffusion coefficients from 5 to 15 March. This period is noteworthy due to the quiet and stable magnetospheric conditions that persisted for 15 days after the 1 March storm, as shown in the previous figures. Pitch angle diffusion occurs at lower energy as L increases, which creates a main diagonal line of diffusion. That maximal diffusion region shifts up in energy as $\alpha$ increases. At L = 2 and E below ~800 keV, we see a wide region of negligible diffusion. This absence of pitch angle diffusion explains why electrons of energy below ~800 keV and located at the inner belt edge (and below inside the inner belt) are not scattered out by hiss waves and remain trapped [13]. As L exceeds 4.5, hiss waves diffuse dominantly electrons of energy below 300 keV. For quiet times with a greatly extended plasmasphere, effects on low-energy electrons (≤300 keV) extend in the outer belt to L = 5.5. Such a plasmasphere configuration is essential to understanding the decay of outer belt electrons from hiss waves.

An important property that will be discussed later should be noticed in Figure 4; the pitch angle diffusion coefficients are homogeneous with respect to pitch angle for $L > \sim 3.5$, $E > \sim 100$ keV, and $\alpha_0$...
increases (for \( R \) values of 20, 50, 70, 80, 90° (from left to right) in the \( \alpha \) plane). Maximal pitch angle diffusion occurs along a main diagonal (red line) that shifts up in energy as \( \alpha \) increases and matches the location of the slot region (cf. next section).

5. How hiss drives the quiet decay of slot and outer belt electrons

We use the event driven diffusion coefficient previously derived from the dynamic wave properties and plasma density in section 4 within a full 3D Fokker-Planck code in order to test our capability to reproduce the flux evolution shown in Figure 1(left).

5.1. Full Fokker-Planck model

The time evolution of the gyro, bounce, and drift phase-averaged phase space density, \( f(t, L, \mu, K) \), in the presence of radial and pitch-angle diffusion can be described by [31]:

\[
\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L} \left( \frac{D_{LL} \partial f}{L^2 \partial L} \right) + \frac{1}{G} \frac{\partial}{\partial \alpha_0} \left( G D_{\alpha_0} \frac{\partial f}{\partial \alpha_0} \right) + \frac{1}{p^2} \frac{\partial}{\partial p} \left( p^2 D_{pp} \frac{\partial f}{\partial p} \right)
\]

with \( G = T(\alpha_0) \sin(2\alpha_0) \), \( \mu \) the first adiabatic invariant, \( K \) proportional to the second adiabatic invariant, with \( B_m \) the magnetic field at the mirror point and \( p \) the electron momentum, and the Roederer \( L \) value. \( D_{LL} \) is the radial diffusion coefficient. Here, we use a statistical radial diffusion coefficient driven by ultra low frequency (ULF) waves [32]. \( T(\alpha_0) \) is proportional to the bounce period evaluated at the equatorial pitch-angle, \( \alpha_0 \). Equation (1) neglects off-diagonal terms in the diffusion tensor. The VERB-3D is used to solve Equation (1) [e.g. 2, 3, 4]. VERB-3D uses an implicit finite differences method and an operator-splitting technique between radial and local processes. A dipole magnetic field is used in Equation (1) to compute the magnetic invariants at which the phase-space density (PSD) is evaluated when converting from flux to PSD.

The grid is composed of 45 uniformly distributed bins in \( L \)-shell, from 1.6 to 5.5. The grid at \( L = 5.5 \) is composed of 100 uniformly distributed pitch angles, from 0.3° to 89.7°, and 100 uniformly distributed in \( \log_{10} \) space bins in energy from 0.5 keV to 4.5 MeV. The radial diffusion term is solved on the adiabatic invariant (\( \mu, J, L \)) grid, while local diffusion terms are solved on the physical (energy, \( \alpha, L \)) grid.

5.2. The quasi-isotropic decay of the quiet outer belt

Our analysis starts on 4 March when calm conditions prevail. The plasmasphere extends to \( L \approx 5.5 \) from 4 to 16 March and justifies the use of only plasmaspheric hiss waves to compute the pitch angle diffusion coefficient as whistler-mode chorus waves are typically only observed outside the plasmasphere. Lightning-generated waves and very low frequency (VLF) transmitter waves that can have some effects in the plasmasphere are neglected based on their low mean amplitude observed from RBSP and relative to the hiss wave power shown in Figure 3(left). Nevertheless the question of the global effects of lightning-generated whistlers remain today open as it is difficult to assess all lightning flashes occurring and transmitted to the trapped electron as it drift round the Earth [e.g. 32].
Both initial and boundary conditions are taken from MagEIS L3 unidirectional fluxes, respectively at \( t = 0 \) at all L-shells and at \( L = 1.6 \) and \( L = 5.5 \). Boundary conditions are supplied when RBSP A is at \( L = 5.5 \) (each \( \sim 9 \) hr), interpolated between two passes, and updated every 3 hr in the codes. Simulated omnidirectional fluxes are computed with respect to equatorial pitch angle similarly to the MagEIS omnidirectional flux. Electrons with pitch angles that are too large to allow them to reach the spacecraft are not counted in the omnidirectional flux. The latter is indeed calculated, for each day of the simulation, at the local latitude of RBSP A, which is \( L \) dependent.

In Figure 5, we found the simulated omnidirectional flux (second line, first and third panels) agrees with the observed omnidirectional flux (first line, first and third panels). As the electron decay occurs, a characteristic boundary to the outer belt that has been described as “S-shaped” in energy and \( L \) forms in the simulation and agrees with the observations. The time for the slot to form and the outer belt to decay is 11 days in both observations and simulations. The outer belt flux decays gradually by a factor \( \sim 20 \) in both observations and simulations. The coincident location of the observed slot and the diagonal of maximal pitch angle diffusion is evident. The upper part of the S-shaped outer belt is a remarkably dense pocket of core electrons located at \( L \) in \([4, 5.2]\) and \( E \) in \([0.7, 2]\) MeV that is preserved due to weaker pitch angle diffusion from whistler mode hiss waves.

The lower-energy (<200 keV) electrons in the outer belt have been described as the radiation belt “seed population” and the higher energies as the “core” radiation belt [34]. Here we see that the seed population and the core population are distinct and frequently separated by a bite-out of low fluxes at intermediate energies (~200–500 keV), particularly at L-shells from 4.7 to 5.2. This bite-out for \( L \) in \([4.7, 5.2]\) and \( E \) in \([200, 500]\) keV is present in both simulations and observations. It creates a 1D energy spectrum at fixed \( L \) with two maxima.

The greatest inaccuracies occur below 100 keV due to the absence of modeling of the low-energy injections as well as in the so-called pocket of core electrons (700 keV to 2 MeV) in the outer belt where fluxes are overestimated. The overall accuracy of these simulations was quantified in [7] with dedicated metrics; we found this proposed event-driven method has an accuracy (within a factor of 2) to predict the electron flux decay after storms.

![Figure 5](image-url)

Figure 5: (top to bottom) Panels showing the evolution of the flux (first to fourth columns) in the (L,E) plane on the 4 and 15 of March 2013. (first column) The omnidirectional flux (in \#·cm\(^{-2}\)·s\(^{-1}\)·keV\(^{-1}\)) is the integral of the directional flux with respect to pitch angle and solid angle, shown here at (second to fourth columns) \( \alpha_0=25^\circ, 57^\circ, 90^\circ \) (in \#·cm\(^{-2}\)·sr\(^{-1}\)·keV\(^{-1}\)). In each panel we compare (first line) the Magnetic Electron and Ion Spectrometer (MagEIS) data, (second line) the Versatile Electron Radiation Belt (VERB-3D) results (3D). The VERB-3D results are plotted at the latitude of the spacecraft. The agreement of the simulations with observations is quite good. Notable results relative to the radiation belt structure in these figures are the pitch angle-dependent inner belt flux decay, a flux decay in the outer belt which is quasi-homogeneous in pitch angle, and an outer flux with two distinct (L, E) regions (seed electrons below ~100 keV and a core radiation belt population for \( L \sim [4.5, 5.5] \) and \( E \sim [0.7, 2] \) MeV.)
Outward radial diffusion causes significant flux decay only above L ~ 5.2, based on the gradual flux decay occurring for energies that are too high for significant hiss loss in ~10 days. Pitch angle diffusion from whistler mode hiss waves is thus only mostly responsible for the whole radiation belt structure.

Unidirectional outer belt fluxes (column 2 to 4) are remarkably quasi-isotropic in pitch-angle, with slightly lower flux at small pitch-angles in both simulations and observations. This is explained by the diffusion coefficients that are quasi-homogeneous with respect to pitch-angle for L>3.5, E>100 keV, and $\alpha_0$~<60° (Figure 4). Thus, the 3-D structure of the quiet state of the outer belt is quasi-isotropic. The main differences between the small pitch angle ($\alpha_0$~<60°) and the large pitch angle ($\alpha_0$~>60°) appear through the slot width, which is larger at low pitch angle (ΔL ~2) and smaller otherwise (ΔL ~1.5). That difference is only due to the pitch angle dependence of the inner belt. In the inner belt, the diffusion coefficients (at all $\alpha_0$) is too small for L ~ [1.5, 2.2] and E ~ [50, 900] to produce changes in 11 days. This preserves the inner belt core from fast hiss effects that occur at higher L-shell and/or energy. Only at the scale of months and years can these waves have an effect, resulting in a stable pitch angle-dependent low-energy inner belt core dominated by a large pitch angle population.

5.3. The anisotropic decay of the low energy quiet slot region

Bottleneck-shaped distributions are indicative of distinct dynamics for low/high pitch angles. These distributions have only been found in our simulation in the slot region for L ~ [3, 3.5] and E ~ [100, 300] keV, with E increasing as L-shell diminishes. Both simulations and observations are plotted in Figure 6 for a 100 keV electron at L=3.5. They show a 1 order of magnitude difference between the flux decay at small pitch angle (x1/100) and the flux decay at large pitch angles (x1/10) in 11 days. Only the simulation has the typical and theoretical smooth bottleneck-shaped distributions. In turn, the equivalent bottleneck shape of the observation corresponds to a steep gradient of the PSD (Figure 6 dashed line) that forms in 10-12 days. The existence of the observed bottleneck shape at these energies and L-shell as well as the isotropic shape of the outer belt at higher L-shell proves the dominant mechanism is pitch angle diffusion due to hiss waves and the ability of quasi-linear theory to describe it accurately. Other waves with other resonant/dispersion relations would interact at other energy and locations.

Disagreement between observations and simulations is in turn uniformly distributed in pitch angles and is explained by the lack of daily injections of low energy electrons at higher L-shell (L~4-6).

6. Conclusions

In this work we show the importance of the plasmasphere environment for the gradual removal of high-energy electrons that are injected by solar magnetic storms. The plasmasphere recovers from the storm compression in expands back to almost geostationary orbit, which provides a quiet and stable nest for the whistler-mode hiss waves to develop and pitch angle diffuse until scattering of the electrons occurs. The correlation between the hiss waves and the density is direct: hiss wave power increases with plasma density for low, medium, and high substorm activity (cf. [25] to known more).
Only weak variations with respect to L value are observed for a given density range. Hiss wave amplitudes are thus dependent upon plasmaspheric density. This implies that one important timescale for hiss wave power birth, growth, and variability in L-MLT space is the timescale of plasmasphere evolution, while it was generally assumed that these quantities can be specified independently.

In the quiet environment of the recovering plasmasphere, whistler-mode hiss waves contribute to a massive removal of both the slot electrons and the outer belt electrons in 10-12 days. The electron flux in the outer belt decays, for instance, by a factor 20. The remaining (L, E, $\alpha_0$) structure of the radiation belts is made of a pitch-angle dependent inner belt of electrons below 900 keV preserved from hiss wave scattering in its core and with its dynamic outer edge eroded by hiss waves. The slot and outer belt electrons are quite homogeneous in equatorial pitch-angle for $\alpha_0$~<60° above L~3.5 due to the homogeneity of the diffusion coefficients, itself inherited from the hiss wave properties. Only the low energy electrons of the slot (L~[3, 3.5] and E~[100, 300] keV) decay in an anisotropic manner and form the well known bottleneck shaped distribution indicative of distinct dynamics for low and high pitch angles. The remaining trapped outer belt electrons are located within a two-region structure in (L, E) with a fading region in-between (L~[4.5, 5.5] and E~[200, 500] keV) appearing in the process of the slot formation. This leads to a 1D energy spectrum at fixed L with two maxima. The first region of the outer belt is a low energy seed population (<100 keV) centered at L~5, with local hourly/daily injections often filling all the L-shells down to the inner belt. The second region is a core radiation belt population of high-energy trapped electrons (L~[4.5, 5.5] and E~[0.7, 2] MeV) with edges fading with the hiss duration and intensity (cf. [7] to known more). This core region decays slowly from hiss waves and is also preserved from electromagnetic ion cyclotron (EMIC) wave scattering due to the rather low energy (<2 MeV).

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