1. INTRODUCTION TO RADIATION BELT VARIABILITY DURING STORMS

1.1. Energetic Electron Observations During Storms.

The Earth’s energetic (> a few hundred keV) electrons are distributed in two main belts separated by a pronounced quiet-time “slot” between $2 < L < 4$ (Figure 1). The inner belt, which tends to be very stable, is formed by slow inward radial diffusion [Lyons and Thorne, 1973] in the presence of loss to the atmosphere due to Coulomb scattering and whistler mode pitch-angle diffusion [Lyons et al., 1972; Abel and Thorne, 1998]. The outer belt is extremely variable, especially during geomagnetic storms. During the main phase of a storm (e.g., Figure 1, orbit 186) pronounced flux depletions are observed, which have been attributed to a combination of adiabatic change associated with the formation of a storm-time ring current (the so called Dst effect [e.g., Kim and Chan, 1997]) and to rapid pitch-angle scattering losses to the atmosphere [Albert et al., 2003; Summers and Thorne, 2003; O’Brien et al., 2004] and drift losses to the magnetopause. Reeves et al. [2003] have demonstrated that approximately 50% of the recently monitored magnetic storms leave the outer zone either essentially unaffected or with a net flux depletion at relativistic energies. The remaining 50% of storms cause a net flux enhancement in the outer belt. A small subset of the latter has been attributed to drift resonant acceleration due to penetration into the magnetosphere of a strong interplanetary shock [e.g., Li et al.,...
1993]. But the majority of storm-associated acceleration follows a temporal evolution similar to that of the October 1990 storm monitored on CRRES (figure 1). Usually, there is a rapid injection of medium energy (few 100 keV) electrons into both the slot region and outer zone following the main phase depletion. However, extremely energetic electrons (> 1 MeV) exhibit a more gradual build up over a period of several days during the storm recovery. Furthermore, during this gradual build up, pronounced peaks in phase space density develop [Brautigam and Albert, 2000; Green and Kivelson, 2004], indicative of local acceleration.

Here we attempt to quantify the competition between loss and acceleration processes throughout the main and recovery phases of storms and thereby address the distinction between storms that do or do not lead to enhanced outer zone flux [e.g., Summers et al., 2004a]. We will also consider the different dynamical behavior of medium energy and highly relativistic electrons, due to resonant interactions with different magnetospheric plasma waves.

1.2. Storm-time Distribution of Plasma Waves.

In Section 2 we review the basic concepts of resonant scattering of electrons by plasma waves capable of violating the first or second adiabatic invariant. Such wave-particle interactions can lead to pitch-angle scattering and ultimate

![Figure 1. Variation in energetic electron flux observed by the MEA instrument on CRRES during different phases of the October 10–13, 1991 magnetic storm.](image-url)
loss of particles to the atmosphere, or to energy diffusion associated with a net transfer of energy between particles and waves. The spatial distribution of three plasma waves capable of interacting with relativistic electrons during a storm is sketched in Figure 2.

Chorus emissions are intense whistler-mode waves, which are excited in the low-density region outside the plasmapause by the injection of plasmasheet electrons into the inner magnetosphere during enhanced storm-time convection. Chorus emissions are highly non-linear waves that occur in discrete micro-bursts at frequencies between 0.2–0.8 of the equatorial electron gyrofrequency [Tsurutani and Smith, 1977; Santolik et al., 2003]. These waves have been associated with intense microburst precipitation (with effective loss times ~ day for 1 MeV electrons) [Lorentzen et al., 2001; O'Brien et al., 2004] and stochastic energy diffusion [Horne and Thorne, 1998; Summers et al., 1998; 2002]. A statistical survey has been made of the spatial distribution of chorus emissions seen on CRRES and their dependence on magnetic activity [Meredith et al., 2003b]. Nightside chorus is strongly confined to the equatorial region (λ<15°), while dayside emissions are stronger at high latitudes (λ>20°). A significant correlation has been found between the storm-time acceleration of electrons to relativistic energies throughout the entire outer radiation belts and enhanced chorus emissions [Meredith et al., 2002, 2003c] or micro-burst precipitation [O'Brien et al., 2003], suggesting that chorus plays an important role in the acceleration process.

Plasmaspheric hiss is an incoherent whistler-mode wave (in the frequency band between a few hundred Hz and a few kHz), which is generally confined within the plasmapause [Thorne et al., 1973]. Resonant electron interactions with hiss cause pitch-angle scattering and loss of energetic electrons from the slot region [Lyons and Thorne, 1973; Albert, 1994; Abel and Thorne, 1998]. The intensity of plasmaspheric hiss (and corresponding rate of loss) is strongly enhanced during the recovery phase of storms [Smith et al., 1974] and during substorm activity [Meredith et al., 2004]. Scattering by hiss can therefore contribute to the slow decay (over 5–10 days) of enhanced outer zone relativistic electrons flux, as the plasmapause expands outwards to higher L following a storm [Spjeldvik and Thorne, 1975].

Electromagnetic ion cyclotron (EMIC) waves are lower frequency (Pc1-2 band) waves (0.1–5 Hz), which are excited in bands below the proton gyrofrequency during the injection of energetic ions into the ring current [Horne and Thorne, 1994]. Wave amplification is enhanced by the increase in density along the dusk side plasmapause [Thorne and Horne, 1997; Jordanova et al., 1998] and within plasmaspheric drainage plumes that are formed in the afternoon sector during storm conditions [Spasojevic et al., 2003]. EMIC waves can cause rapid ion precipitation [Jordanova et al., 2001; Spasojevic et al., 2004], but can also scatter relativistic electrons [Thorne and Kennel, 1971; Lyons and Thorne, 1972; Lorentzen et al., 2000; Summers and Thorne, 2003; Meredith et al., 2003a].

2. RESONANT WAVE-PARTICLE INTERACTIONS

2.1. Resonant Interactions With Magnetospheric Waves.

As particles undergo their adiabatic gyro, bounce and drift motion in the radiation belts, they can interact with the plasma waves described above. The first invariant of the electron motion can be violated during interactions with plasma waves whose frequency ω is Doppler shifted to a multiple (n =0,±1,±2,...) of the relativistic electron gyrofrequency as expressed below:

\[ \omega - k_{\parallel} v_{\parallel} = n\Omega_e / \gamma \]  

(1)

where \( \gamma = (1 - (v/c)^2)^{-1/2} \) is the relativistic factor and \( k_{\parallel} \) and \( v_{\parallel} \) are components of the wave propagation vector and particle velocity along the direction of the ambient magnetic field. During wave-particle interactions, there can be a net exchange of momentum and energy leading to particle scattering in momentum space. An example of momentum space scattering of electrons by a typical band of field-aligned equatorial chorus [Horne and
When the waves propagation vector is oblique, the Landau (n=0) and higher order cyclotron resonances can also occur. This permits resonant scattering over a much broader region of momentum space [Lyons et al., 1971] and there is no unique resonant diffusion surface. For small angles of propagation first harmonic scattering will dominate, but higher order scattering (and the Landau resonance) becomes important for highly oblique waves (e.g., plasmaspheric hiss [Albert, 1994; Abel and Thorne, 1998] or ECH emissions [Horne and Thorne, 2000]). During the various permitted resonant interactions, particles will experience a random walk in momentum space, which can be treated by evaluating rates of pitch-angle and energy (or momentum) diffusion.

The efficiency of energy diffusion (compared to pitch-angle scattering) is largely controlled by the ratio between the resonant electron velocity and the wave phase velocity [Gendrin, 1981]. Since the wave phase speed is strongly influenced by the ambient plasma density, or more specifically the ratio $\omega_p/\Omega_e$, plasmaspheric hiss and EMIC waves mainly cause pitch-angle diffusion and precipitation loss to the atmosphere. Energy diffusion only becomes effective in the low-density region just outside the plasmapause [Horne et al., 2003a]. Consequently, when intense chorus emissions ($B_w \sim 100\text{pT}$) are sustained for a period of days they are able to provide substantial energy diffusion [Horne et al., 2004]. Local acceleration to relativistic energies becomes effective for magnetic storms with prolonged chorus activity in the recovery phase [e.g., Summers et al., 2002] and has even been observed during prolonged substorm activity [Meredith et al., 2003c; Summers et al., 2004b].

Radial diffusion, driven by drift resonance with enhanced ULF waves [Hudson et al., 2001; Elkingston et al., 2003], also leads to particle acceleration during inward radial transport, in locations where there is a positive radial gradient in particle PSD. The observed temporal variability of the outer zone reflects the competition between the acceleration and loss processes. The Fokker-Planck equation [e.g., Schulz and Lanzerotti, 1974] provides a convenient mathematical framework for treating the temporal evolution of particle phase space density. Processes that violate each adiabatic invariant may be described in terms of diffusion coefficients, which scale in proportion to the power spectral density of the relevant resonant waves. Radial diffusion requires ULF fluctuations with periods comparable to the particle azimuthal drift time (~ 10 mins), while pitch-angle and energy diffusion require higher-frequency waves that satisfy (1).

In the following section we describe how the quasi-linear formulation [Kennel and Engelmann, 1966] can be applied to quantify the bounce-averaged rates of pitch-angle and energy diffusion during resonant wave-particle interactions, which violate the first invariant.

For a prescribed band of waves at any given location, resonance (for any harmonic) with a given energy electron will only occur for a limited range of pitch-angles (e.g., Figure 3). Furthermore, as particles move along their bounce orbit from the equator to their mirror point, the condition for resonance (1) varies substantially, due to changes in magnetic field strength, plasma density and the particle parallel velocity. Latitudinal variations in the local pitch-angle diffusion rate $D_{\alpha\alpha} = \langle (\Delta \alpha)^2 \rangle / 2 \Delta t$ for first harmonic scattering by a field-aligned band of chorus at $L=4$ are shown in the lower panels of Figure 4, as a function of equatorial pitch-angle. The net diffusion rates when bounce-averaged over the orbit of the electron are shown in the upper panels. For 100 keV electrons, first order cyclotron resonant scattering near the edge of the loss cone ($\alpha_0 \sim 5.4^\circ$) peaks for interactions near $15^\circ$ latitude, while at 500 keV substantial scattering near the loss cone only occurs above $25^\circ$ latitude. As a consequence, 100 keV electrons can be scattered into the loss cone by night-side chorus emissions, with a loss time comparable to an hour (D$_{\alpha\alpha}(\alpha_0) \sim 3 \times 10^{-4}$ s$^{-1}$). In contrast, precipitation loss of relativistic (>500 keV) electrons requires the presence of high latitude chorus emissions. Such waves are only found on the dayside [Meredith et al., 2003b], thus explaining the MLT location of relativistic electron microbursts seen on SAMPEX [O’Brien et al., 2004]. Note also that the scattering loss times for relativistic electrons are comparable to a day (D$_{\alpha\alpha}(\alpha_0) \sim 10^{-5}$ s$^{-1}$), so that microbursts can cause substantial flux depletion during a storm.

The intensity of plasmaspheric hiss [Meredith et al., 2004] and EMIC waves [Braysy et al., 1998; Erlandson and Ukhorskiy, 2001] are also substantially enhanced during a storm. Both emissions will therefore contribute to storm-time relativistic electron loss. Hiss is predominantly found on the dayside inside the plasmapause or within drainage plumes. Typical storm-time amplitudes of hiss are 100 pT, and relativistic electrons will be subject to scattering by such waves for about 50% of their drift orbit. To be scattered by left-hand polarized EMIC waves, electrons must overtake the wave (to reverse the effective sense of polarization in the electron frame) with sufficient velocity for the Doppler shift term in (1) to satisfy resonance. Scattering at energies near 1 MeV can only occur in regions where $\omega_p/\Omega_e > 10^{-30}$ (namely inside the plasmasphere) and also requires the presence of EMIC waves at frequencies just below an ion gyrofrequency.

![Figure 4](image.png)

**Figure 4.** Comparison between the local pitch-angle diffusion rates (lower panels) at specified latitudes and the bounce-averaged values (upper curve) for first order cyclotron resonance between 100 keV and 500 keV electrons and field-aligned chorus.
As a consequence of the restricted conditions for resonance, relativistic electron scattering by storm-time EMIC waves probably only occurs for 1% of the particle drift orbit. These properties have been used by Albert [2003] to evaluate the net bounce-averaged diffusion rate of MeV electrons by a combination of hiss and EMIC waves during a storm. The results (Figure 5) indicate an electron lifetime ~ 0.8 days compared to 3.5 days for hiss alone. Since EMIC waves during the main phase of a storm can be more intense than the amplitudes (B\textsubscript{w} = 1 nT) adopted by Albert, EMIC scattering could be a dominant mechanism to account for the rapid loss of relativistic electrons during the onset of a storm (Figure 1). EMIC scattering could also cause the rapid electron flux depletions reported by Onsager et al. [2002] and Green et al. [2004], and the intense hard X-ray events observed on balloons [Millan et al., 2002].

During particularly strong geomagnetic storms, the intensification of the convection electric field causes the plasmapause to be compressed inwards to very low L values. Drainage plumes of high density also develop in the afternoon or dusk sector [Spasojevic et al., 2003]. Such extreme conditions allow chorus emissions to be excited at much lower L (<3) on the dawn side and for EMIC (and hiss) waves to be excited along the dusk side drainage plumes (Figure 2). Recently, a new PADIE code has been developed at the British Antarctic Survey, which is capable of evaluating pitch-angle and energy diffusion rates for multiple-harmonic resonance with any prescribed distribution of waves. Bounce-averaged pitch-angle diffusion rates for a realistic distribution of chorus at L=3 are shown in the left-hand panel of Figure 6. The corresponding bounce-averaged energy diffusion rates D\textsubscript{Ek} = \langle (\Delta E)^2 \rangle/2E^2\Delta t are shown in the left panel of Figure 7. To compute these rates of diffusion, we adopt a Gaussian distribution of wave frequency peaked at \omega/\Omega = 0.35 with width \delta\omega/\Omega = 0.15 based on the equatorial gyrofrequency \Omega. Following the formalism of Lyons et al. [1972], the wave energy is distributed over a 30° Gaussian distribution of wave normal directions (consistent with observations). We further assume that the chorus wide-band wave intensity is 100 pT within 30° of the equator, and only present on the dawn side (Figure 2). The oblique distribution of waves allows us to include the effect of Landau resonance and the multiple-harmonic cyclotron resonances (for these calculations we include the first five positive and negative harmonics). We assume that the plasma density is 100/cc at L=3 (based on the trough model of Sheeley et al., [2001]), and independent of latitude over the region of interaction.

The bounced-averaged results indicate that both pitch-angle scattering and energy diffusion are extremely dependent on energy and equatorial pitch-angle. Low energy electrons are subject to the most rapid pitch-angle scattering in the vicinity of the loss cone. At energies between 10–30 keV (not shown here) scattering loss times (~ an hour) are shorter than the azimuthal gradient drift time. As a consequence of scattering by chorus and ECH waves [Horne and Thorne, 2000], low-energy plasmasheet electrons should develop strong azimuthal gradients as they are injected into the inner magnetosphere during the storm [e.g., Meredith et al., 2004]. Since such particles contribute to the diffuse aurora, the latter should be far more intense at night than on the day side, as typically observed [Petrinec et al., 1999]. Conversely, above 100 keV the computed loss times exceed the electron azimuthal drift times and an azimuthally symmetric distribution should develop. Interestingly, the bounce-averaged diffusion rates near the edge of the loss cone for 100 keV electrons are comparable to those computed from an approximate analytic treatment based on first order cyclotron resonance with field-aligned waves (e.g., Figure 4). This indicates the dominance of first harmonic scattering for the adopted wave characteristics. For energies >1 MeV, first order scattering can only occur at latitudes above the assumed wave cut off at 30°. Consequently, the relativistic electrons require higher harmonic scattering to be precipitated into the atmosphere and the modeled lifetimes from chorus scattering become much longer than a day. The sharp change in the gradient of D\textsubscript{ao} near \alpha\textsubscript{o} ~ 30–35° is a model-dependent consequence of our adopted cutoff in the wave power above 30° latitude. Better information on the spatial distribution of chorus intensities will be needed to obtain accurate lifetimes at these relativistic energies.

For E>100 keV, energy diffusion rates tend to maximize over a broad range of equatorial pitch-angles well away from the loss cone, so accelerated particles remain trapped.
Interestingly, relativistic electrons are only subject to the dominant first harmonic scattering at high latitudes, where the ratio of $\omega_p/\Omega_e$ is reduced. Since energy diffusion becomes far more effective at lower values of $\omega_p/\Omega_e$, the values of $D_{EE}$ for highly relativistic electrons tend to increase at lower equatorial pitch-angles, in sharp contrast to their rate of pitch-angle diffusion. The sharp decrease near $\alpha_o \sim 30-35^\circ$ is again a consequence of our adopted cutoff in the wave power above $30^\circ$ latitude. Nonetheless, although better information on the latitudinal distribution of waves is needed to compute acceleration rates accurately, it is clear that chorus can induce substantial stochastic acceleration over the duration of a storm.

3. TEMPORAL EVOLUTION OF PARTICLE FLUXES DURING A STORM

The temporal evolution of the particle phase space density $f(p, \alpha, L, t)$ can, in principle, be obtained by a numerical integration of the Fokker-Planck equation once all relevant diffusion rates have been specified. Codes such as Salammbô [Bourdarie et al., 1996] and RAM [Jordanova et al., 2001] have been developed to accomplish this, but currently they have not been able to incorporate all relevant physical processes. Because of the greatly different timescales involved in the violation of the first and third adiabatic invariant, one may analyze the consequences of radial diffusion at a rate $D_{LL} = \langle (\Delta L)^2 \rangle / 2 \Delta t$ with a simplified radial diffusion equation in which effects of local energy diffusion are treated as an effective source $S$, while loss from pitch-angle scattering is represented by a loss time $\tau_L$

$$\frac{\partial f}{\partial t} = \nabla^2 f - \frac{\partial}{\partial L} D_{LL} \nabla f + S - \frac{f}{\tau_L} \tag{2}$$

Conversely, although radial diffusion can act as a source of PSD at a given L shell, and also modify the pitch-angle distribution, it is convenient to ignore such effects (to first order) in order to assess the effectiveness of processes that violate the first invariant. We will adopt an even simpler approach here: using the diffusion rates obtained from the BAS code to evaluate first the temporal evolution of the resonant particle pitch-angle distribution (and thus obtain lifetimes due to precipitation). We subsequently use this rate of precipitation loss to quantify the post-storm buildup of the high-energy tail population due to energy diffusion. This will allow us to specify the net source rate $S(E)$ for relativistic electron acceleration by magnetospheric chorus emissions, which can subsequently be incorporated into the radial diffusion equation (2). Pitch-angle scattering by other waves can also be included in the loss term.

Under pure pitch-angle diffusion the temporal evolution of the particle PDS $f(\alpha_o, t)$ can be treated by the bounce-averaged pitch-angle diffusion equation:

$$\frac{\partial f}{\partial t} = \frac{1}{s(\alpha_o)y} \frac{\partial}{\partial y} s(\alpha_o)y D_{yy} \frac{\partial f}{\partial y} - \frac{f}{\tau_L}$$

(3)

where $D_{yy}(\alpha_o)$ is the bounce-averaged pitch-angle diffusion rate, $y = \cos \alpha_o$, and $s(\alpha_o) \approx 1.3 - 0.56 \sin \alpha_o$ reflects the change in bounce time with equatorial pitch-angle $\alpha_o$. The results from the PADIE diffusion code (Figure 6) have been used to follow the temporal evolution of $f(\alpha_o, t)$ by numerically integrating (3) assuming that $\tau_L$ is infinite for $\alpha_o > \alpha_L$ and equal to the quarter bounce time for $\alpha_o < \alpha_L$. For the initial state we assume that $f(\alpha_o, t=0) \sim \sin \alpha_o$. Solutions for 1 MeV electrons are shown in the right-hand panels of Figure 6 every 1/2 day. After one day the pitch-angle distributions are already beginning to approach their equilibrium flat-topped shape due to resonant interactions with chorus. The approach to this equilibrium shape occurs first at larger pitch-angles, where the rate of diffusion is highest. Subsequently, the fluxes simply decay in time while retaining their flat-topped shape. From the decay rate we obtain a lifetime comparable to 3 days, which is similar to that estimated from SAMPEX micro-bursts [O’Brien et al., 2004]. It is also worth noting that the predicted flat-topped shape is a characteristic feature of relativistic outer zone electrons observed on CRRES during the recovery phase of storms [Horne et al., 2003b]. This agreement substantiates the important role of chorus in scattering relativistic electrons during storms.

3.2. Hardening of High-Energy Tail by Stochastic Acceleration During Interaction With Chorus.

The approach described above can be used to quantify the scattering lifetimes $\tau_L(E)$ due to chorus for all relevant energies. Assuming that the particle phase space density is essentially independent of pitch-angle, the Fokker-Planck equation can be reduced to a one-dimensional form, which can be solved numerically to follow the temporal evolution of the particle phase space density $f(p)$ subject to momentum (or energy) diffusion and precipitation loss:

$$\frac{\partial f}{\partial t} = \frac{1}{p^2} \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial f}{\partial p} - \frac{f}{\tau_L}$$

(4)

where $D_{pp}$ is the bounce-averaged rate of momentum diffusion. Using average values of the energy diffusion rates shown in Figure 7, we have solved (4) numerically for a 3 day period to simulate the recovery phase of the Halloween magnetic storm when the plasmapause remained compressed inside $L=3$. As an initial condition we adopted a very depleted relativistic population. We also assumed...
that the flux at 200 keV remained fixed during the storm due to a balance between acceleration and loss processes. The results of the modeling are shown in the right-hand panel of Figure 7. The significant energy diffusion rate, together with the steep initial energy spectrum, causes a rapid enhancement of the high-energy tail population. Fluxes at 1 MeV increase to substantial levels within the first 12 hours of the storm recovery. Hardening of the spectrum continues throughout the recovery and 2–3 MeV electrons become apparent after 1–3 days. This timescale is comparable to the build up of relativistic electron fluxes observed on SAMPEX and HEO during the Halloween storm recovery [Baker et al., 2004].

4. CONCLUDING REMARKS

Substantial progress has been made over the last few years in understanding the non-adiabatic dynamics of outer-zone radiation belt electrons. Observed variability during storms results from a competition between dramatically enhanced source and loss processes. Losses generally dominate during the storm main phase, whereas net acceleration can occur during the extended recovery. Two dominant source processes have been identified: radial diffusion driven by drift resonance with long period ULF waves and local stochastic acceleration resulting from cyclotron resonance with higher frequency waves. Observational evidence indicates that both mechanisms contribute to the enhancement of radiation belt flux [Mathie and Mann, 2000; O’Brien et al., 2003]. The rate of radial diffusion increases at higher L, while local acceleration becomes most effective at lower L just outside the storm-time plasmapause. Losses due to pitch-angle scattering into the atmospheric loss cone, and to a lesser extent drift loss into the magnetopause, are also greatly enhanced during storms.

Outer zone radiation belt electrons can interact with several distinct magnetospheric waves, which become enhanced during geomagnetic storms. As a consequence of the interaction, electrons are either scattered in pitch-angle or experience energy diffusion. EMIC waves, excited along the dusk side plasmapause or within storm-time plumes, can induce precipitation loss at MeV energies on timescales less than a day. Such scattering is a potential candidate to account for the rapid depletion of relativistic flux during the storm main phase when EMIC waves are most intense. Storm-time plasmaspheric hiss can also contribute to loss but typical scattering times are longer (several days) and such waves are probably more effective during the extended storm recovery as the plasmapause expands outwards to higher L. High latitude chorus emissions observed outside the plasmapause in the prenoon sector can cause MeV micro-burst precipitation with effective loss times comparable to a day [Thorne et al., 2004]. Such waves also cause energy diffusion, which leads to a net flux increase at relativistic energies even in the presence of micro-burst loss. Substantial acceleration, to energies greater that 1 MeV, can occur over a period of days, during the recovery phase of a magnetic storm.

For particularly strong magnetic storms, when the plasmapause is compressed well inside the normal location of the slot (L<3), local acceleration by chorus emissions can cause the reformation of the relativistic outer belt on L shells normally associated with the quiet-time slot. Following such intense storms, this new belt decays relatively slowly (over several days probably due to scattering by hiss). In the absence of rapid loss, inward radial diffusion should cause subsequent flux enhancements in the inner zone. For more moderate storms, the average intensity of chorus is probably smaller than 100 pT and the plasmapause generally expands outwards past L=3 within 12 hours of the main phase. Consequently, there is insufficient time to allow local acceleration to relativistic energies near L=3. But local acceleration to several hundred keV can occur within 5–10 hours, causing the observed rapid filling of the slot at lower energies (Figure 1). This is probably why the slot is generally only well defined for E> 1 MeV.

Our current theoretical understanding of radiation belt electron dynamics has evolved through the efforts of several research groups who have quantified different aspects of this intriguing puzzle. The important progress achieved to date has required a concentrated effort on each specific physical process, whereas in practice each processes is coupled. For example radial diffusion will modify the pitch-angle distribution and provide a source of particles for the excitation of plasma waves. Losses, due to those waves, will decrease the PSD [Shprits and Thorne, 2004] and thus create radial gradients, which enhance the inward radial diffusive flux. Future modeling efforts should be directed towards simultaneous inclusion of each important process. This will require multi-dimensional diffusion codes in which all diffusion coefficients are well specified. It will also involve coupling such kinetic codes that treat the microphysics (including non-linear scattering) with large-scale MHD and transport codes that can specify the injection of the source population. Aside from the numerical stability issues of such complex codes, the major obstacle in achieving such an holistic approach is our current limited knowledge of the spatial distribution and temporal variability of the power spectral intensity of each important wave mode. Future satellite missions, such as the Geosciences LWS radiation belt probes and the proposed ORBITALS mission, should carry instrumentation to address this important issue.
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