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Radial diffusion modeling with empirical lifetimes: comparison with CRRES observations

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Abstract. A time dependent radial diffusion model is used to quantify the competing effects of inward radial diffusion and losses on the distribution of the outer zone relativistic electrons. The rate of radial diffusion is parameterized by K_p with the loss time as an adjustable parameter. Comparison with HEEF data taken over 500 Combined Release and Radiation Effects Satellite (CRRES) orbits indicates that 1-MeV electron lifetimes near the peak of the outer zone are less than a day during the storm main phase and few days under less disturbed conditions. These values are comparable to independent estimates of the storm time loss rate due to scattering by EMIC waves and chorus emission, and also provide an acceptable representation of electron decay rates following the storm time injection. Although our radial diffusion model, with data derived lifetimes, is able to simulate many features of the variability of outer zone fluxes and predicts fluxes within one order of magnitude accuracy for most of the storms and L values, it fails to reproduce the magnitude of flux changes and the gradual build up of fluxes observed during the recovery phase of many storms. To address these differences future modeling should include an additional local acceleration source and also attempt to simulate the pronounced loss of electrons during the main phase of certain storms.

Keywords. Magnetospheric physics (Energetic particles, trapped; Solar wind-magnetosphere interactions; Storms and substorms)

1 Introduction

The radiation belts consist of electrons and protons trapped by the Earth's magnetic field. Protons form a single radiation belt while electrons exhibit a two zone structure. The inner electron belt is located typically between 1.2 and 2.0 R_E, while the outer zone extends from 4 to 8 R_E. The quiet time region of lower electron fluxes is commonly referred to as a "slot" region. The inner belt is very stable and is formed by a slow, inward radial diffusion subjected to losses due to Coulomb scattering and whistler mode pitch angle diffusion (Lyons and Thorne, 1973; Abel and Thorne, 1998). The observed variability of electrons in the outer radiation belt is due to the competing effects of source and loss processes. Reeves et al. (2003) showed that approximately half of all geomagnetic storms result in a net depletion of the outer radiation belt or do not substantially change relativistic electron fluxes as compared to pre-storm conditions, while the remaining 50% result in a net flux enhancement. Non-adiabatic interactions with various plasma waves may result in acceleration of electrons while pitch-angle scattering causes diffusion of electrons into the loss cone where they are removed by collisions with atmospheric particles on the time scale of one quarter bounce period.

Leading mechanisms for acceleration to relativistic energies include radial diffusion driven by ULF waves (e.g. Elkington et al., 2003), local stochastic acceleration driven by VLF waves (Horne and Thorne, 1998; Summers et al., 1998; Horne et al., 2003, 2005), and shock induced acceleration (Li et al., 1993). The loss of relativistic electrons is mainly due to pitch-angle scattering cased by EMIC waves (Thorne and Kennel, 1971; Lyons and Thorne, 1972; Albert, 2003; Summers and Thorne, 2003; Meredith et al., 2003), chorus waves outside the plasmapause (O'Brien et al., 2004 and Thorne et al., 2005a) and plasmaspheric hiss (Abel and Thorne, 1998). In the present study we use a data-model comparison technique to estimate electron lifetimes. This is a first attempt to derive the physical parameters which could be used as a reference for theoretical estimates. In the Discussion section we speculate on the possible theoretical interpretation of the results.

2 Particle motion and diffusion

High energy electrons in the radiation belts undergo three types of periodic motion:

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1. Gyro motion around field lines (∼ms);
2. Bounce motion in the meridian plane between mirror points (∼s.);
3. Gradient and curvature drift around the Earth (∼10 min).

Each type of periodic motion has an associated adiabatic invariant, referred to as 1st, 2nd and 3rd adiabatic invariants (μ, J, and Φ or J_1, J_2, and J_3), respectively. By ignoring processes which result in jumps in phase space, and neglecting diffusion with respect to the phases of the adiabatic motion, the evolution of the phase space density f can be described in terms of the Fokker-Planck Eq. (1) (Schulz and Lanzerotti, 1974), which has a form of a diffusion equation when written in terms of canonical variables such as adiabatic invariants,

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial J_i} D_{ij} \frac{\partial f}{\partial J_j} \tag{1}$$

where we used Einstein's notations with summation over repeated indexes.

Losses in the inner magnetosphere create gradients in phase space density (usually directed away from the Earth). Radial diffusion driven by ULF waves acts to reduce such gradients by transporting particles radially inward, which violates the third adiabatic invariant. Since the period of ULF waves is much longer than the time scale associated with the first and second adiabatic invariants, only the third adiabatic invariant is violated. Conservation of the first and second adiabatic invariants consequently results in the acceleration of particles during the inward transport. If we ignore local acceleration and rewrite Eq. (1) in terms of L, assuming a dipole field, we obtain the radial diffusion equation in the form:

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left[D_{LL} L^{-2} \frac{\partial f}{\partial L}\right] - \frac{f}{\tau}, \tag{2}$$

where τ is the electron lifetime, and D_{LL} is the radial diffusion coefficient. In this formulation the first two adiabatic invariants μ and J are held constant and Eq. (2) can be solved numerically for $f(L, t)$.

While the equilibrium structure of high energy electron fluxes and the formation of the slot region have been accurately modeled under quiet conditions (Lyons and Thorne, 1973), the dynamics of relativistic electrons during geomagnetic disturbances is still poorly understood. In the present study we attempt to estimate the lifetime parameter by adopting an empirical relationship for the rate of radial diffusion due to magnetic fluctuations (Brautigam and Albert, 2000), which tends to dominate throughout the outer radiation zone

$$D^M_{LL}(Kp, L) \ = 10^{(0.506Kp-9.325)} L^{10}, \ Kp = 1 \ to \ 6 \tag{3}$$

Solutions of the time dependent code, ignoring the effects of local acceleration sources and only considering radial diffusion with losses, are compared to CRRES observations.

3 Model description

The inner boundary for our simulation $f(L{=}1){=}0$ is taken to represent loss to the atmosphere. The outer boundary condition on the phase space density is obtained from the fluxes at $L{=}7$. Even though fluxes near geosynchronous orbit vary significantly during the storm, CRRES measurements will be highly effected by adiabatic variations (Kim and Chan, 1997). Consequently, in this study we use constant boundary conditions based on averaged fluxes at $L{=}7$ obtained from CRRES and Polar measurements (N. Meredith, P. O'Brien personal communication). We model fluxes by an exponential fit $J{=}8222.6{}^{*}exp\ (-7.068\,K)\,\mathrm{cm^{-2}\,sr^{-1}\,keV^{-1}\,s^{-1}}$, where K is kinetic energy in (MeV) obtained from the time-averaged satellite flux measurements. Variations of the outer boundary conditions may create outward gradients in phase space density, which will drive inward radial diffusion and could result in significant electron losses during the main phase of the storm. Inclusion of L^* derived time dependent boundary conditions for various existing field models will be deferred for future research.

For simplicity we first assume that the diffusion coefficients and lifetimes are independent of energy and solve Eq. (2) for $f(L, t)$, normalized to unity at the outer boundary. This solution will be the same for all μ values. Consequently, to obtain $f(E, L)$ the normalized phase space density should be multiplied by $J(E^*)/p^{*2}$, where E^* and p^* are kinetic energy and momentum of the particles for any prescribed value of μ at the outer boundary and J is a differential flux at the outer boundary. Following (Shprits and Thorne, 2004) lifetimes are parameterized as a function of K_p.

4 Simulations of 500 CRRES orbits

We describe a numerical experiment which starts on 30 July, DOY 211 (the number of days since the start of 1990). We simulate MeV electron fluxes for 196 days which approximately corresponds to 500 orbits of the CRRES measurements. The second panel in Fig. 1 shows 1 MeV electron fluxes measured by the High Energy Electron Fluxmeter (HEEF) on CRRES satellite for the outer radiation belt. The 1 MeV electron fluxes show significant variability by three orders of magnitude with fluxes maximizing between 3.5 and 4.5 R_E. The periods of enhanced storm time electron fluxes vary in duration from a few days to two weeks. The substantial depletions of the outer radiation belt prior to the increases in fluxes is most likely associated with increased wave activity during the main phase of the storm, but might also be caused by variations of fluxes at the outer boundary which will not be taken into account in these simulations.

The third panel shows simulated electron fluxes with a constant lifetime parameter of 10 days at all L, which is comparable to expected loss times from plasmaspheric hiss (Lyons et al., 1972; Abel and Thorne, 1998). Model results with a 10-day lifetime globally overestimate fluxes at all L.

The unrealistic refilling of the slot at almost all times of the simulation, and duration of increased storm-time fluxes for up to a month indicate that a 10-day lifetime is unrealistically long.

The top panel of Fig. 1 shows simulations with empirical lifetimes parameterized as a function of K_p. The model is initiated with a quiet-time steady-state solution. In finding the best parameterizations we attempt to minimize the differences between model results and observations for the following parameters: location of the maximum in fluxes, variation in fluxes in the outer zone, and the demarcation line between high and low fluxes near the inner edge of the outer radiation belt. The best simple fit to the lifetime parameter that we visually found to minimize differences in the above parameters is τ=(3/K_p) outside the plasmapause which gives $\tau\approx$3 days during quiet times and less than a day during storms. Inside the plasmapause we set lifetimes to 10 days. The approximate plasmapause location is computed according to Carpenter and Anderson (1992).

On a time scale of days we are able to approximately reproduce the location of the flux maxima, the radial extent of enhanced fluxes, and the post storm decay of fluxes in the outer zone. The sharp increases in fluxes during the main phase of the storm are probably due to unrealistic constant boundary conditions and our neglect of more intense wave scattering during the main phase of a storm when radial diffusion rates are the highest. The radial diffusion model also fails to reproduce the duration of flux enhancements of many storms, as well as the gradual build-up of fluxes during storms, which is described in more detail in Sect. 5.

Figure 2 shows the logarithm of the ratio of observed to modeled fluxes. During the first 15 days of the simulation there is a two orders of magnitude difference between the model and the observation due to inaccurate initial conditions. However after 20 days, the model reaches a dynamical state which is independent of the initial conditions. Prolonged orange and red areas show intervals where the radial diffusion model underestimates fluxes by an order of magnitude. We attribute this discrepancy to our neglect of a local acceleration source throughout the recovery phase of storms. Short lasting blue areas correspond to an overestimation of fluxes by the model which could be due to an underestimation of losses or unrealistic constant boundary conditions during the main phase of storms.

5 Simulations of October 1990 storm

We use our optimized loss time scale to model the 9 October 1990 storm (Brautigam and Albert, 2000; Meredith et al., 2002; Summers et al., 2002), (Fig. 3, top panel). Observations show a sudden drop in fluxes throughout the outer radiation belt during the main phase of the storm which starts on DOY 283 (top panel). However, since we have chosen constant boundary conditions, radial diffusion is unable to reproduce the main phase decrease of fluxes. The K_p index (bottom) reaches its maximum value of 6 on DOY 283, which induces a rapid increase in modeled 1-MeV fluxes (middle panel) during the storm main phase. The radial diffusion model also predicts a decay of fluxes right after the main phase of the storm, contrary to High Energy Electron Fluxmeter (HEEF) measurements on CRRES which indicate that fluxes maximize several days into the recovery phase and stay high for almost 10 days after the onset of the storm with peak fluxes above 10^7 (cm sr s MeV)$^{-1}$.

This discrepancy between the radial diffusion model and observations can be mostly explained by the influence of an additional local acceleration source which was not included in the model. Based on CRRES observations, Meredith et al. (2002) showed that this event contained prolonged substorm activity during the recovery phase of the storm with an AE index above 100 for 6 days. The VLF wave intensity was above 1000 pT^2 day over the range 3.5<L<6.5, with a peak value of more than 10^4 pT^2 day around L=5. Note that relatively high geomagnetic activity keeps the plasmapause compressed throughout the recovery phase. This combination of

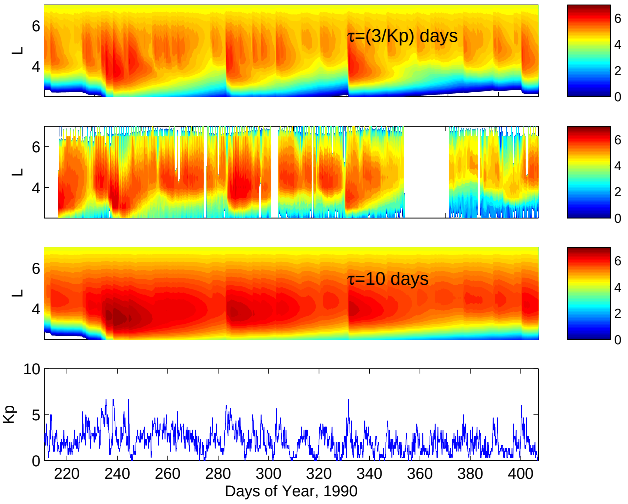

Fig. 1. Comparison between 0.95 MeV electron fluxes in $\log_{10}$ (cm^2 sr s MeV) computed by our radial diffusion model with empirical lifetimes (first panel), electron flux measurements on CRESS satellite (second panel). Model simulations with constant lifetimes of 10 days are shown (third panel). The fourth panel shows the evolution of the K_p index used for the calculation of the D_{LL} and τ.

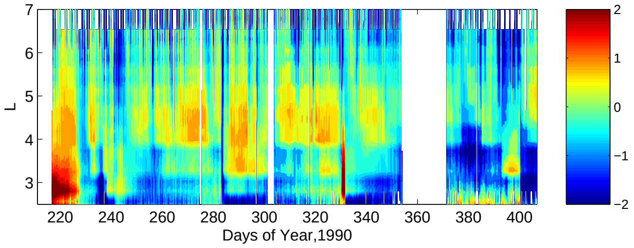

Fig. 2. Logarithm of ratio of 0.95 MeV HEEF CRRES electron fluxes to those produced by the optimized radial diffusion model.

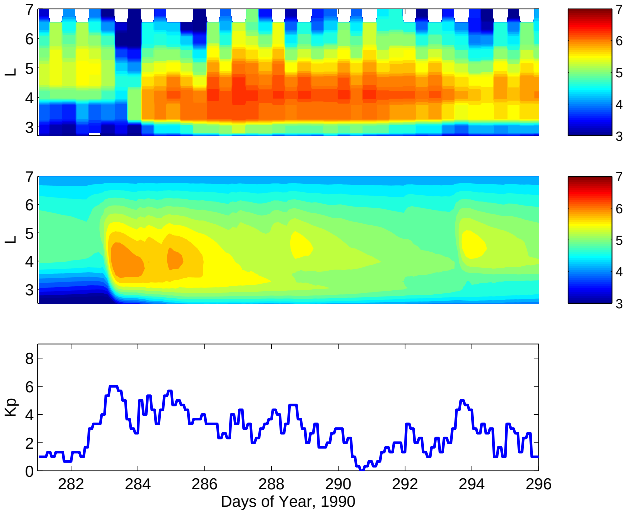

Fig. 3. Comparison of electron fluxes in $\log_{10}$ (cm^2 sr s MeV) measured by CRRESS at 0.95 MeV (top), and our radial diffusion model simulations with empirical lifetimes (middle). Evolution of the K_p index (bottom).

a compressed plasmapause and increased VLF activity creates favorable conditions for local acceleration (Horne et al., 2003) throughout the recovery phase of the storm, in a broad spatial region outside the plasmapause.

6 Discussion

The study reported here presents the first attempt of a data-model derived empirical estimation of the lifetime parameter. The radial diffusion model with simplified data derived lifetimes is capable of predicting the radial extent of high energy fluxes and locations of peak fluxes for many storms, and predicts MeV fluxes within one order of magnitude accuracy for most of the time of the simulation and most L values. Our results indicate that lifetimes range from less than a day during active conditions to a few days under less disturbed conditions.

The simulation described above indicates that pitch-angle scattering (perhaps due to chorus waves) provides a dominant loss of high-energy electrons during the recovery phase of storms. Theoretical estimates of pitch-angle diffusion coefficients, as well as combined SAMPEX-Polar measurements (Thorne et al., 2005a), also suggests that losses due to chorus waves could be dominant in the outer radiation belt and result in loss time scales comparable to a day.

Our radial diffusion model fails to reproduce the gradual build-up of fluxes observed during many storms and this suggests that local acceleration is required to accurately model the dynamics of electron fluxes during storms. A combination of inward radial diffusion driven by ULF waves and local stochastic acceleration and loss, resulting from interactions with whistler mode and other waves, as well as outward radial diffusion caused by variations near geosynchronous orbit, is responsible for the formation and variability of the outer radiation belt. Pitch-angle scattering outside the plasmasphere provides an effective loss mechanism which operates on a similar time scale as radial diffusion or local acceleration. Main phase losses due to chorus emissions are greatly enhanced with loss times falling to less than a day outside the plasmapause. Even more rapid pitch-angle scattering by EMIC waves may provide local loss on the scale of a few hours during the main phase of a storm (Albert, 2003; Summers and Thorne, 2003). The effect of losses at high L-values and outward radial diffusion will be a subject of future studies. As a consequence, losses can dominate over sources during the main phase of the storm and create a net depletion of the radiation belts. During the extended storm recovery, losses become less important (e.g. O'Brien et al., 2004) and the combined effect of a local acceleration source, together with radial diffusion can lead to an enhancement of radiation belt fluxes for a period of up to 10 days after the main phase of the storm.

Various feedback mechanisms become important in regions where local acceleration, losses and radial diffusion act simultaneously and on similar time scales. Radial diffusion driven by local stochastic loss at lower L shells may be an important source of relativistic electrons. On the other hand, localized acceleration may create peaks in the phase space density which will be smoothed out by the radial diffusion. In this situation outward radial diffusion may work as a local loss process. To account for various feedback mechanisms between loss and source processes, a full 3-D model of the radiation belts, solving the Fokker-Planck Eq. (1) should be used. This model should account for major loss and source processes at all L values. The results of the model should be compared to fluxes as a function of $L*$, so that adiabatic variations are filtered out. Future modeling should also include automated parameter estimation tools which could be applied to various source and loss mechanisms.

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