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# Review of modeling of losses and sources of relativistic electrons in the outer radiation belt I: Radial transport

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ABSTRACT

In this paper, we focus on the modeling of radial transport in the Earth's outer radiation belt. A historical overview of the first observations of the radiation belts is presented, followed by a brief description of radial diffusion. We describe how resonant interactions with poloidal and toroidal components of the ULF waves can change the electron's energy and provide radial displacements. We also present radial diffusion and guiding center simulations that show the importance of radial transport in redistributing relativistic electron fluxes and also in accelerating and decelerating radiation belt electrons. We conclude by presenting guiding center simulations of the coupled particle tracing and magnetohydrodynamic (MHD) codes and by discussing the origin of relativistic electrons at geosynchronous orbit. Local acceleration and losses and 3D simulations of the dynamics of the radiation belt fluxes are discussed in the companion paper [Shprits, Y.Y., Subbotin, D.A., Meredith, N.P., Elkington, S.R., 2008. Review of modeling of losses and sources of relativistic electrons in the outer radiation belt II: Local acceleration and loss. Journal of Atmospheric and Solar-Terrestrial Physics, this issue. doi:10.1016/j.jastp.2008.06.014].



## 1. Introduction

Energetic electron radiation belts consist of electrons with energies from 100 keV to several MeV that are trapped by the Earth's magnetic field. Early observations of the radiation belt electrons (Van Allen and Frank, 1959; Vernov and Chudakov, 1960) suggested the existence of two distinct radiation belts, with the outer zone located at distances greater than 3–4$R_E$ and the inner zone below 2$R_E$. The region between the two zones is commonly referred to as the slot region (e.g., Vernov et al., 1969; Russell and Thorne, 1970) and is more pronounced during quiet times. Within a decade of the discovery of the radiation belts, it was realized that electron fluxes in the outer zone are highly variable (Rothwell and McIlwain, 1960; Craven, 1966) and correlated with geomagnetic activity (e.g., Arnoldy et al., 1960; Jelly and Brice, 1967; Tverskoy, 1967), while fluxes in the inner region are quite stable, with significant variations occurring only during the most intense magnetic storms (Williams and Smith, 1965; Pfitzer and Winckler, 1968).

The development of quasi-liner theory (Drummond and Pines, 1962; Vedenov et al., 1961) and its subsequent application to the radiation belts (Andronov and Trakhtengerts, 1964; Kennel and Petschek, 1966; Kennel and Engelman, 1966; Lerche, 1969) resulted in the realization that wave–particle interactions play an important role in the dynamics of the radiation belts.

Observations from the OGO-5 spacecraft provided more detailed information on the spectral properties of whistler mode waves (Thorne et al., 1973), which allowed quantitative estimates of the losses due to wave–particle interactions (Lyons et al., 1972) and an explanation of the two-zone structure of the radiation belts (Lyons and

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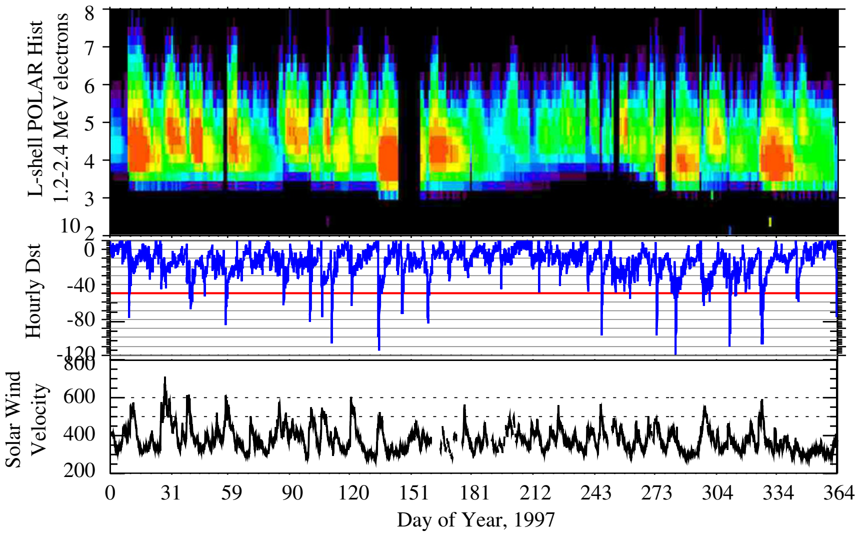


**Fig. 1.** (Top) 1.2–2.4 MeV radiation belt electron fluxes as a function of L-shell and time observed on Polar; (middle) the hourly Dst index (with −50 nT marked in red); and (bottom) solar wind velocity (reproduced from Reeves et al., 2003; Copyright 2003 American Geophysical Union).

Thorne, 1973). They showed that, in the slot region at $L$ between 2 and 3, where the background plasma density is on the scale of $10^3\,\mathrm{cm}^{-3}$, relativistic electrons are lost due to scattering by plasmaspheric hiss on time scales shorter than characteristic radial diffusion time scales, while lower energy electrons (~100 keV) can diffuse through the slot region without being lost to the atmosphere and will be accelerated to MeV energies at $L<2$. Fig. 1 shows observations of relativistic electrons in the outer radiation belt by the Polar spacecraft (Reeves et al., 2003). The strongest enhancements of the outer radiation belts usually occur following geomagnetic storms, indicated by a decrease in Dst and an increase in solar wind velocity. Strong geomagnetic storms often lead to the inward motion of the inner boundary of the outer radiation belts or refilling of the slot region (e.g., Thorne et al., 2007) or, as was recently observed during the October–November 2003 storms, even the formation of a new radiation belt in the slot region (Baker et al., 2004; Horne et al., 2005b; Shprits et al., 2006a). Strong enhancements of the radiation belts may be hazardous to satellites operating in the inner magnetosphere and dangerous for humans in space (Baker et al., 1996).

This review is presented in two papers. The first paper describes radial transport simulations, and the second paper describes the modeling of local acceleration and loss processes (Shprits et al., 2008). We first review the guiding center and radial diffusion simulations that indicate that fast losses and additional acceleration processes operate in the inner magnetosphere, while inward and outward radial diffusion can effectively redistribute relativistic electrons.

## 2. Fokker–Planck equation and the radial diffusion approximation

If electrons undergo quasi-periodic motion, we can define adiabatic invariants corresponding to particular types of the periodic motion. Each of the adiabatic invariants of the system is conserved as long as the parameters of the system change slowly compared to the time scale of each of the periodic motions. The geometrical interpretation of the adiabatic invariant is the area covered by the trajectory of the particle in phase space. If the parameters of motion are changing slowly compared to the period of the motion, the area covered by the trajectory in phase space will remain relatively constant (Landau and Lifshits, 1973).

Relativistic electrons in the radiation belts undergo three types of periodic motion: gyromotion, bounce motion between mirror points, and gradient and curvature drift around the Earth. The corresponding invariants are usually referred to as the first, second, and third adiabatic invariants, and they are denoted by ($\mu$, $J$, $\Phi$) or ($J_1, J_2, J_3$). Definitions of the adiabatic invariants are given in Appendix A; for more details, see Walt (1994). Since the adiabatic invariants and their phases form a set of canonical variables, the Fokker–Planck equation may be written in a form that is independent of the adiabatic changes. By ignoring diffusion in terms of the phases of the adiabatic invariants, the Fokker–Planck equation for the diffusive evolution of the phase-averaged 6D phase space density of the relativistic electrons may be written by specifying the phase-averaged phase space density $f$ in terms of the three adiabatic invariants (Schulz and Lanzerotti, 1974):

$$\frac{\partial f}{\partial t}=\frac{\partial}{\partial J_i}D_{ij}\frac{\partial f}{\partial J_j},\quad i,j=1,2,3, \tag{1}$$

where we use Einstein notation with summation over repeated indices. If we also ignore the violation of the first and the second adiabatic invariants, Eq. (1) may be written in the form of a radial diffusion equation (Fälthammar, 1965; Schulz and Eviatar, 1969):

$$\frac{\partial f}{\partial t}=L^{*2}\frac{\partial}{\partial L^*}\bigg|_{\mu,J}\left(D_{L*L*}L^{*-2}\frac{\partial f}{\partial L^*}\bigg|_{\mu,J}\right)-\frac{f}{\tau}+S, \tag{2}$$