Resonant enhancement of relativistic electron fluxes during geomagnetically active periods

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Abstract. The strong increase in the flux of relativistic electrons during the recovery phase of magnetic storms and during other active periods is investigated with the help of Hamiltonian formalism and simulations of test electrons which interact with whistler waves. The intensity of the whistler waves is enhanced significantly due to injection of 10–100 keV electrons during the substorm. Electrons which drift in the gradient and curvature of the magnetic field generate the rising tones of VLF whistler chorus. The seed population of relativistic electrons which bounce along the inhomogeneous magnetic field, interacts resonantly with the whistler waves. Whistler wave propagating obliquely to the magnetic field can interact with energetic electrons through Landau, cyclotron, and higher harmonic resonant interactions when the Doppler-shifted wave frequency equals any (positive or negative) integer multiple of the local relativistic gyrofrequency. Because the gyroradius of a relativistic electron may be the order of or greater than the perpendicular wavelength, numerous cyclotron, harmonics can contribute to the resonant interaction which breaks down the adiabatic invariant. A similar process diffuses the pitch angle leading to electron precipitation. The irreversible changes in the adiabatic invariant depend on the relative phase between the wave and the electron, and successive resonant interactions result in electrons undergoing a random walk in energy and pitch angle. This resonant process may contribute to the 10–100 fold increase of the relativistic electron flux in the outer radiation belt, and constitute an interesting relation between substorm-generated waves and enhancements in fluxes of relativistic electrons during geomagnetic storms and other active periods.

Key words. Magnetospheric physics (energetic particles, trapped; plasma waves and instabilities; storms and substorms).

1 Introduction

Magnetic storms cause some of the largest geomagnetic field deformations. The source of these strong perturbations originates at the Sun and they are believed to be triggered by a persistent southward interplanetary magnetic field. Generally, a magnetic storm is characterised by an enhancement in the ring current, due to the injection of ions by strong convective electric field. An additional important storm characteristic is the behaviour of energetic electrons during different phases of the storm. The evolution of relativistic electrons in the outer radiation belt depends on the time scale of magnetic perturbations and on the different characteristic frequencies of electron dynamics. If the perturbation time scale is much longer than that of the quasiperiodic motion of a particle in geomagnetic field, the corresponding adiabatic invariant is conserved. Conservation of the three invariants during the main phase of the storm together with Liouville’s theorem requires that the enhanced ring current, which decreases the inner magnetospheric magnetic field, causes a decrease in relativistic electron flux as the electrons move to higher L shells. The resulting decrease in relativistic electron fluxes at this phase has been observed by numerous satellites like SAMPEX, WIND and POLAR (Baker et al., 1997; Reeves et al., 1998). At the recovery phase one observes an increase up to two orders of magnitude in the flux of relativistic electrons (Li et al., 1998; Reeves et al., 1998). During active times the flux increase of very energetic electrons (>3 MeV) at lower L shells often precede the increase of electrons with the same first and second adiabatic invariant at higher L and results in a peak of the distribution f(L) around L = 4.5 (Selesnick and Blake, 1997). The decay phase is characterised partly by adiabatic behaviour, as well as by radial diffusion (which violates the third invariant) and by pitch angle scattering (which violates the first two adiabatic invariants) (e.g., McIlwain 1996; Li et al., 1998). The increase in the relativistic electron flux during active times and in the storm recovery phase is
the least understood process and is addressed in the present investigation.

Large flux enhancements above quiet-time levels at $L \sim 4$–5 have been observed during geomagnetic storms, as well as during active periods following the arrival of high speed solar wind streams at 1 AU. GPS data show increase in the flux of $\geq 1$ MeV electrons at $L = 4.5$ during the January 1997 coronal mass ejection (CME) January 1997 event, without significant flux increase initially at higher $L$ values. The HIST instrument on the POLAR satellite (Blake et al., 1996) measured numerous large enhancements in $f(L)$ at low $L$ shells during active periods, including the January CME event (Selesnick and Blake 1997, 1998). In other active periods the enhanced fluxes of energetic electrons (0.7–3.0 MeV) at $L \sim 4$–5 probably are not a result of diffusion from higher $L$ shells (Selesnick and Blake, 1998), which determines the spatial distribution during quiet periods. Additionally, an analysis of the November 3–4, 1993 high-speed solar wind stream event showed that the phase space density in the solar wind is insufficient to explain the increase of relativistic outer radiation belt electrons (Li et al., 1997). Therefore, enhancement in the high energy electron fluxes at lower L-Shells (Paulikas and Blake, 1979) indicates a possible existence of additional processes which operate at this region where a local heating mechanism may be operative for relativistic electrons.

2 Energization mechanisms

Enhancements in energetic radiation belt electron fluxes at invariant shells $L \sim 4$–5 may be the result of several processes; (a) direct injection by a strong electromagnetic pulse which abruptly deforms the magnetic configuration and energises electrons and protons by breaking their third invariant when a subset of particles is in a phase with a single “coherent” wave (Li et al., 1993) or when they are subjected to a large-amplitude ULF waves (Hudson et al., in press, 1999); (b) radial diffusion of a distribution function with a positive gradient in $L$ which violates the flux invariant by a random walk due to broad-band, small-amplitude, low-frequency electromagnetic perturbations (Schults and Lancerotti, 1974; Selesnick et al., 1997); (c) resonant interaction with higher frequency waves on the order of gyration or bounce time scales, with violation of the first two invariants. Mechanism (a) occurs infrequently and requires a large sudden commencement pulse excited by a fast interplanetary shock wave or intense ULF waves excited by a strong coronal mass ejection perturbation. Mechanism (b) tends to flatten the distribution $f(L)$ and cannot describe separately the increase in the lower $L$ shells and the formation of maxima at these $L$ values. Mechanism (c) requires recurrent increase in the power of waves which interact with a seed population of energetic electrons and diffuse them in energy and pitch angle. This mechanism involves resonant interaction with electrons bouncing and gyrating along the inhomogeneous dipole magnetic field, $\omega - k_{\parallel}v_{\parallel} - n\Omega/\gamma \sim 0$, where the wave is characterized by its frequency $\omega$ and parallel wave number $k_{\parallel}$ and the resonating electron by its parallel velocity $v_{\parallel}$, local gyrofrequency $\Omega$ and the relativistic factor $\gamma$, while the integer $n$ denotes the harmonic of the cyclotron interaction. In the next sections we focus on the interaction of these waves with relativistic electrons.

3 Flux enhancement scenario

A possible mechanism for energization of the relativistic electrons in the outer radiation belt is due to interaction with whistler waves. Whistler waves play an important role in the theory of trapped magnetospheric electrons but they are usually invoked as a loss mechanism. Resonant interaction with whistler waves, which occurs when the cyclotron resonance condition is satisfied, is considered as viable mechanism for the formation of the slot region in the inner magnetosphere by electron precipitation (Lyons and Thorne, 1973). Pitch angle scattering of electrons into the loss cone by whistler waves leads to a decay of the outer electron belt during quiet periods. These waves were also shown to be a source of heating of $\leq 1$ keV electrons by fundamental cyclotron ($n = -1$) and Landau ($n = 0$) interactions (Thorne and Horne, 1994, 1996). If the wave is propagating parallel to the magnetic field only the lowest order resonant interaction, where the electron and wave are moving in opposite directions along the magnetic field, produces changes in the electron pitch angle and energy. There exists an inverse correlation between the energy change and the pitch angle change: a decrease in the pitch angle leads to an increase in the energy. For typical plasma parameters around the dense plasmasphere, the dominant effect of the interaction is pitch angle scattering and while it is acknowledged that pitch angle scattering necessarily involves some energy change, it can be shown that this change is small (e.g., Hasegawa, 1975). Thus, any large change in energy involves a larger relative change in pitch angle, which will scatter electrons into the loss cone. However, if the whistler wave is not propagating exactly parallel to the magnetic field, higher order resonant interactions can occur when the Doppler-shifted wave frequency equals any (positive or negative) integer multiple of the gyrofrequency. Interaction of suprathermal (100 eV) electrons with oblique whistler waves was used for the study of electron precipitation (Jasna et al., 1992). For relativistic electrons moving along an inhomogeneous field there exist typically several harmonic interactions corresponding to the first few positive and negative integers where the resonant condition is satisfied, and since at these energies the gyroradius of the electron may be on the order of or greater than the perpendicular wavelength, the strength of the interaction at the higher harmonics is of the same order as at the fundamental. Since now the energy and pitch angle changes are no longer correlated, the electrons undergo more or less independent random walks in energy and pitch angle (and in the adiabatic invariant). Thus, the mechanism operates mainly for