Inward radial diffusion and pitch angle scattering in the slot region

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The radial diffusion coefficient is calculated for electrons and protons of different energy in the slot region of the earth's radiation belt for various values of McIlwain parameter $L$ and time scale $T$. It is found that the diffusion coefficient increases with $L$ and decreases as the energy of the particle is increased. The pitch angle diffusion coefficient is also calculated. The lifetime of slot electrons calculated from the pitch angle diffusion coefficient agrees with the measured values.

1 Introduction

During geomagnetically quiet times, the inner zone electron flux peaks near $L = 1.2-1.8$ and outer zone flux peaks near $L = 4-6$ (where $L$ is the McIlwain parameter). The morphology of the slot and its transient behaviour during geomagnetic disturbance is described by Russel and Thorne. There is a rapid build-up of energetic electrons during strong magnetic storms followed by a rapid decay. This rapid decay is due to enhanced loss of electrons resulting from pitch angle scattering by broad band whistler mode emissions generated by the Doppler-shifted cyclotron resonance interaction with the energetic electrons. The slot-region electron precipitation associated with VLF chorus, plasmaspheric hiss and lightning are studied extensively by Imhof et al. They have suggested that most of the precipitating electrons injected into the drift loss-cone by wave particle interactions involve waves of lower frequencies and hence higher resonant electron energies, than do the waves associated with short duration lightning or chorus.

Based on the data acquired on S81-1 spacecraft and NOAA-6 satellite, Imhof et al. provided a basis for deriving the total loss rate of electrons from the radiation belts by short duration events. The general concepts on radial diffusion and pitch angle diffusion in the radiation belts are reviewed by Lyons and Williams. In this paper, the radial diffusion by a storm-like electric field variation and the pitch angle scattering in the slot region of the earth's radiation belt are studied.

2 Inward radial diffusion

Fluctuations in large scale magnetospheric magnetic and electric fields with frequencies of the order of particle drift frequency around the earth result in radial diffusion of the particles. In this study, the radial diffusion by fluctuations in magnetospheric electric field alone in the region $L = 1.5-5$ is considered. This is because the diffusion by magnetic field fluctuations becomes increasingly important with increasing $L$ relative to that from electric potential field fluctuations. The diffusion coefficient, $D_L$, for substorm-like electric field variations which rise rapidly and are followed by an exponential decay with a time constant $T/2$, is given by

$$D_L = 0.25 \frac{c^2 \langle A^2 \rangle (L^2/B_0)^2}{T(1 + 0.5 \omega_T T^2)} \ldots \quad (1)$$

where

$$\omega_T = \frac{3c \mu}{eL^2 R_e^2} \left[1 + \frac{2 \mu B_0}{mc^2 L^3}\right]^{-1/2} \ldots \quad (2)$$

and

$$\mu = mv_\perp^2 L^3/(2B_0) \ldots \quad (3)$$

In Eqs (1)-(3), $c$ is the speed of light, $\langle A^2 \rangle$ the mean square fluctuating electric field, $B_0$ the equatorial dipole field strength for $L = 1$, $\omega_T$ the azimuthal drift frequency, $e$ the electronic charge, $m$ the electron rest mass, $R_e$ the earth radius, $\mu$ the magnetic moment and $v_\perp$ the velocity component perpendicular to the magnetic field. Electric fields having amplitudes of 0.1-0.28 mV/m and periods in the range 0.25-0.75 hr have been taken from observations of the motion of whistler ducts within the plasmapause.

3 Results and discussion

Using Eq. (3) the values of $\mu$ are calculated for both electrons and protons of chosen energy, and $L$ values and the corresponding $\omega_T$ values are calculated using Eq. (2). Using the values of $\omega_T$ thus obtained, the $D_L$ values are calculated. The various parameters used are as follows:

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Amplitude of electric field \((A)\) = 0.1 mV/m
Period \((T)\) = 0.25, 0.5 and 0.75 hr
Electron energy \((E_e)\) = 40, 60, 100 and 500 keV, for \(L=2-5\)
Proton energy \((E_p)\) = 10 MeV, for \(L=1.5-5\)

The computed values of the radial diffusion coefficient are plotted in Figs 1-4. In Fig. 1, \(D_{LL}\) is plotted against \(L\) for electron energies of 40, 60 and 100 keV and \(T=0.5\) hr. It is clear from Fig. 1 that the radial diffusion coefficient increases with \(L\) which is in agreement with the results reported by Schulz and Lanzerotti. All the curves in Fig. 1 show a peculiar behaviour around \(L=2.5-3.5\). A sharp increase in electron lifetime is noted at low \(L\) values and this predicts the location of the slot's inner edge. It is also clear from Fig. 1 that the diffusion coefficient decreases as the energy of the particle is increased. This energy dependence of \(D_{LL}\) can be explained by Eqs (1)-(3). As we increase the energy of the particle, the magnetic moment and azimuthal drift frequency increase and correspondingly the \(D_{LL}\) value decreases. The decrease of \(D_{LL}\) with increase of energy is also reported by Lyons and Williams.

The nature of variation of \(D_{LL}\) with \(T\) for 500 keV electrons at \(L=3\) and 4.5 is depicted in Fig. 2. The diffusion coefficient is found to be high for \(L=4.5\) and low for \(L=3\). This is due to the fact that at higher \(L\) values, the 500 keV electrons are rapidly depleted as they diffuse inward through the slot region.

In Fig. 3, \(D_{LL}\) is plotted against \(L\) for 10 MeV protons for \(T=0.5\) and 0.75 hr. For \(L<1.5\), there is no variation of the diffusion coefficient for both \(T=0.5\) and 0.75 hr, but the change occurs for \(L>3.5\). This is due to the rapid loss by precipitation of the injected particles and it predicts that the outer edge of the slot should occur at higher \(L\) values.

The variation of \(D_{LL}\) with \(T\) for 10 MeV protons at \(L=2-3.5\) is shown in Fig. 4.

4 Pitch angle scattering

The whistler turbulent precipitation theories suggest that precipitating electrons must generate the pitch angle scattering. The pitch angle scattering of
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Table 1—Numerical values of the pitch angle diffusion coefficient and electron lifetime

<table>
<thead>
<tr>
<th>$B(f_0)$</th>
<th>$D(\alpha_0)$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma^2$/Hz</td>
<td>$s^{-1}$</td>
<td>$s$</td>
</tr>
<tr>
<td>$10^{-10}$</td>
<td>$1.03 \times 10^{-6}$</td>
<td>$9.7087 \times 10^5$</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>$1.03 \times 10^{-2}$</td>
<td>$9.7087 \times 10^1$</td>
</tr>
</tbody>
</table>

the trapped energetic particles is due to wave particle interactions occurring in the magnetosphere. Lyons et al.\(^9\) showed that the pitch angle distributions of electrons in the slot region during quiet times were consistent with pitch angle diffusion by bandlimited ELF hiss. Slot electrons with energy > 100 keV diffuse into the loss-cone, and they\(^9\) calculated the pitch angle diffusion coefficient averaged over the electron bounce period and summed up for all possible resonant interactions. The diffusion coefficient for bounce-resonance scattering by micropulsations has been evaluated by Viswanathan and Renuka\(^10\) by including the anharmonicity term in the expansion of the magnetic field equation around the equator.

The Fokker-Planck diffusion coefficient of trapped electrons with whistler mode turbulence is calculated using the following well-known relation\(^11\)

$$D(\alpha_0) = (1/3)(e/mc)^2 B(f_0)$$

where $\alpha_0$ is the electrons’ equatorial pitch angle cosine and $B(f_0)$ the power spectral density function of one magnetic field component of the whistler mode waves evaluated at the resonant frequency $f_0$. The calculated values of $D(\alpha_0)$ and the corresponding lifetimes are given in Table 1 for $B(f_0) = 10^{-10} \gamma^2$/Hz and $10^{-6} \gamma^2$/Hz ($\gamma = 10^{-5}$ gauss). The lifetime $\tau = 1/D(\alpha_0)$ of electrons found from the calculated diffusion coefficient agrees with the measured lifetimes in the slot\(^12\).

Thus, it can be concluded that the equilibrium structure of radiation belt slot electrons is maintained by a balance between the average rates of inward diffusion and pitch angle scattering loss.

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References