CHAPTER - V
PRECIPITATION OF LOW ENERGY (eV and keV) ELECTRONS NEAR THE LOWER EDGE OF INNER RADIATION BELT
5.1 INTRODUCTION

Wave-particle interactions in the ionosphere and magnetosphere represent an important loss mechanism for radiation belt electrons. During quiet periods, the loss of electrons has been explained in terms of Coulomb collisions with atmospheric constituents (Walt, 1964, 1966; Imhof and Smith, 1966; Imhof et al., 1973). On the other hand, stormtime loss of electrons has been explained by wave-particle interactions involving cyclotron resonance (Tsurutani et al., 1975 and references therein). Tsurutani et al. (1975) have found that the possibility of wave-particle interactions and precipitation of energetic electrons in the inner radiation belt is highly enhanced during the periods of geomagnetic disturbances when the region is intensified with ELF hiss emissions. Voss and Smith (1977,1980) have also associated ELF hiss with the low latitude precipitation zone. Recently, Jain and Singh (1990) have studied the pitch angle scattering and diffusion of energetic electrons during geomagnetic storms at the lower edge of the inner radiation belt in terms of cyclotron resonance involving whistler-mode waves of natural origin as well as radiated from ground based transmitters. L-dependent peaks observed in the energy spectra of quasi-trapped inner belt electrons have also been interpreted in terms of cyclotron resonance involving whistler-mode waves radiated from ground based transmitters (Imhof et al., 1974,1981a; Vampola and Kuck, 1978; Koons et al., 1981; Jain and Singh, 1992; Datlowe and
Imhof, 1993). However, cyclotron resonances are limited to electrons with energies greater than a few MeV at the lower edge of inner belt, while most of the electrons have energies in eV and keV range (Teague et al., 1976). The precipitation mechanism of such low energy electrons in the inner radiation belt particularly near its lower edge is not very clear. Pinto and Gonzalez (1989a) have, however, suggested Landau resonance involving natural ELF hiss emissions as a possible loss mechanism for these low energy inner belt electrons.

In the present chapter, we extend the work of Pinto and Gonzalez (1989a) to study the precipitation of eV and keV electrons near the lower edge of inner radiation belt by considering Landau resonance interaction of such electrons with plasmaspheric ELF hiss of natural origin (Thorne et al., 1973; Smith et al., 1974; Tsurutani et al., 1975; Larkina and Likhter, 1982) at an altitude of 400 km near the mirror point of the energetic electrons. Our results show that Landau resonance interaction causes significant flux of precipitated electrons towards lower L-shells in the inner radiation belt.

5.2 Expressions Used

The resonance energy of the energetic electrons is given by

$$E_R = (\gamma - 1) m_0 c^2$$  ....(5.1)
in which $\gamma_r$ is the relativistic factor, $m_0$, the rest mass of electron and $c$ is the speed of light in vacuum. The relativistic factor for cyclotron resonance is calculated using the relation (Pinto and Gonzalez, 1989a; Tsurutani et al., 1975):

$$\left(\frac{\gamma_r}{\gamma_r - 1}\right)_{\text{cyclotron}} = \left(\frac{\Omega_e}{w_p}\right)^2 \left(1 + \frac{\Omega_p}{w}\right) \frac{1}{\cos^2 \alpha} \quad \text{......(5.2)}$$

where $\Omega_e$, $\Omega_p$, $w_p$ and $w$ are electron gyrofrequency, proton gyrofrequency, plasma frequency and wave frequency respectively in rad. s$^{-1}$, and $\alpha$ is the local pitch angle of the energetic electrons. The relativistic factor for Landau resonance can be written as (Pinto and Gonzalez, 1989a)

$$\left(\frac{\gamma_r}{\gamma_r - 1}\right)_{\text{Landau}} = \left(\frac{w}{\Omega_e}\right)^2 \frac{\gamma_r^2}{\left(\gamma_r - 1\right)_{\text{cyclotron}}} \quad \text{......(5.3)}$$

In order to calculate cyclotron resonance diffusion coefficient $D$, we follow equation (9) of Prakash and Singh (1992) which for $w \ll \Omega_e$ (ELF hiss), $\Omega_e = \frac{eB}{mA}$. $w_p = \sqrt{\frac{9n_0}{2\pi}}$

is simplified as

$$D = 3.2801 \times 10^{11} \left(\frac{\Omega_e}{n_0}\right)^2 \frac{B_f^2}{4\pi V_R} \quad \text{......(5.4)}$$

where $m$ and $e$ are electronic mass and charge respectively, $B$, the ambient magnetic field strength, $n_0$, the cold plasma density, $B_f^2$, the power spectral density of ELF hiss in $\gamma^2$ Hz$^{-1}$ and $V_R$ is the resonance velocity of energetic electrons.

The Landau resonance diffusion coefficient $D_L$ is related with the cyclotron resonance diffusion coefficient $D$ at a point
along the field line under consideration (Pinto and Gonzalez, 1989a):

$$D_L = (\frac{\Omega}{\gamma W \sin^4 \alpha}) D_L \quad \ldots \ldots (5.5)$$

The precipitated flux $J_p$ is given by the relation (Coroniti and Kennel, 1970)

$$J_p = (\frac{T_{L_{\text{min}}}}{T_L}) J_T \quad \ldots \ldots (5.6)$$

in which $J_T$ is the trapped flux, $T_L$, the electron life time and $T_{L_{\text{min}}}$ is the minimum life time corresponding to strong diffusion. The life time $T_L$ is calculated by taking the inverse of the diffusion coefficient (Kennel and Petschek, 1966).

5.3 RESULTS AND DISCUSSION

In order to study the pitch angle diffusion and precipitation of resonant electrons at the lower edge of the inner radiation belt, we calculate the resonance energy of these electrons and their pitch angle diffusion coefficients at the $L$-shells of 1.1 and 1.2 considering both equatorial and off-equatorial cyclotron and Landau resonance interactions of the energetic electrons with the plasmaspheric ELF hiss of natural origin. Plasmaspheric ELF hiss emissions are unstructured emissions characterised by continuous bandlimited white noise, which are characteristically found to peak at 550 Hz, have an approximate band width of 300 Hz and to have a magnetic field intensity highly dependent on geomagnetic activity. Their
intensity is found to vary from $10^{-7} \gamma^2 \text{ Hz}^{-1}$ during quiet periods to $10^{-7} - 10^{-6} \gamma^2 \text{ Hz}^{-1}$ during recovery phase of storms (Tsurutani et al., 1975). The values of electron density $n_0$ at the $L$-shells of 1.1 and 1.2 are considered to be $3.01 \times 10^{10}$ and $8.13 \times 10^9 \text{ el.m}^{-3}$ respectively in the equatorial plane and $1.5 \times 10^{11} \text{ el.m}^{-3}$ at an altitude of 400 km in the ionosphere. These values have been obtained from a diffusive equilibrium model of the ionosphere (angerami and Thomas, 1963) which has been used earlier by several other workers also at low latitudes (Prakash et al., 1979; Singh et al., 1992; Prakash and Singh, 1994). The values of the plasma density are estimated using the relation $\omega_p^2 = \frac{n_0 e^2}{m \varepsilon_0}$, $\varepsilon_0$ being electric permittivity of free space. To obtain the resonance energy $E_R$, we calculate the values of relativistic factor $\gamma$, for both cyclotron and Landau resonances employing equations (5.2) and (5.3) of section 5.2. Since the values of loss cone angle at the $L$-values of 1.1 and 1.2 are 57.4° and 45.1° respectively, we consider the pitch angles of the electrons outside the loss cone between 60° and 85° at $L = 1.1$ and between 50° and 85° at $L = 1.2$. The calculated values of $\gamma$ are then substituted in equation (5.1) to obtain the values of $E_R$ at the different values of pitch angle $\alpha$.

Fig.5.1 shows the variation of calculated resonance energy $E_R$ with pitch angle $\alpha$ at a wave frequency of 550 Hz for cyclotron resonance. The resonance energy is found to increase both with
FIG. 5.1 - VARIATION OF CYCLOTRON RESONANCE ENERGY WITH PITCH ANGLE.
the increase in pitch angle and L-value. Equatorial values of $E_R$ are slightly higher than the off-equatorial values for cyclotron resonance at the same L-shell. The calculated values of $E_R$ are greater than 10 MeV at both the L-shells.

Fig.5.2 shows the variation of resonance energy $E_R$ with pitch angle $\alpha$ for Landau resonance at an altitude of 400 km. Like $E_R$ for cyclotron resonance, the value of $E_R$ for Landau resonance is also found to increase with pitch angle $\alpha$ and L-value. The calculated values of $E_R$ are found to lie between 44 eV and 2.4keV. Thus, off-equatorial Landau resonance acts on much lower energies than the first order equatorial cyclotron resonance.

Recently, Jasna et al. (1992) have investigated the precipitation of suprathermal electrons (10 - 100 eV) induced by oblique whistler-mode waves at higher latitudes. They have shown that the precipitated energy fluxes resulting from the interaction of ~100 eV electrons with oblique waves can be upto 30 times larger than that due to the precipitation of 100 keV electrons by parallel propagating waves at $L = 3$.

Employing equations (5.4) and (5.5) of previous section we have calculated the values of the cyclotron resonance diffusion coefficient $D$ in the equatorial plane and Landau resonance diffusion coefficient $D_L$ at an altitude of 400 km in the ionosphere along the field lines of $L = 1.1$ and 1.2. Table 5.1 shows the variation of $D$ and $D_L$ with pitch angle $\alpha$. 
FIG. 5.2 VARIATION OF LANDAU RESONANCE ENERGY WITH PITCH ANGLE.
<table>
<thead>
<tr>
<th>Pitch angle $\alpha$ (degree)</th>
<th>$L = 1.1$</th>
<th>$L = 1.2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$ (rad$^2$/s)</td>
<td>$D_L$ (rad$^2$/s)</td>
<td>$D$ (rad$^2$/s)</td>
</tr>
<tr>
<td>50</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>$7.60 \times 10^{-4}$</td>
<td>$4.16 \times 10^{-3}$</td>
</tr>
<tr>
<td>70</td>
<td>$1.11 \times 10^{-3}$</td>
<td>$5.76 \times 10^{-3}$</td>
</tr>
<tr>
<td>80</td>
<td>$2.19 \times 10^{-3}$</td>
<td>$6.95 \times 10^{-3}$</td>
</tr>
<tr>
<td>85</td>
<td>$4.36 \times 10^{-3}$</td>
<td>$7.28 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

In the calculations of $D$ and $D_L$, we have used wave magnetic field intensities of $1 \times 10^{-6} \gamma^2 \text{Hz}^{-1}$ and $4 \times 10^{-7} \gamma^2 \text{Hz}^{-1}$ at the $L$-shells of 1.1 and 1.2 respectively at an altitude of 400km in the ionosphere (Tsurutani et al., 1975; Jain and Singh, 1990) for 550 Hz ELF hiss. The equatorial magnetic field intensities are estimated assuming 5 dB enhancement (Jain and Singh, 1990) which have been found to be $3.16 \times 10^{-6} \gamma^2 \text{Hz}^{-1}$ and $1.26 \times 10^{-6} \gamma^2 \text{Hz}^{-1}$ at the $L$-values of 1.1 and 1.2 respectively. Table 5.1 shows that both $D$ and $D_L$ increase with the increase in pitch angle and decrease with increase in $L$. Similar trend for the variation of cyclotron resonance diffusion coefficients with the pitch angle $\alpha$ has been found by Jain and Singh (1990, 1991) at $L = 1.2$. However, the value of $D_L$ is slightly higher than the value of $D$ for the same pitch angle $\alpha$ and $L$-value. The average values of $D$ at the
L-values of 1.1 and 1.2 are found to be $2.11 \times 10^{-3}$ and $3.81 \times 10^{-3}$ \text{rad}^2 \text{s}^{-1} respectively and the corresponding average life times of the resonant particles (energy $> 10$ MeV) are estimated to be 7.92 minute and 4.37 minute respectively. These life times are lower than those calculated by Jain and Singh (1990) at $L = 1.2$ in the equatorial plane. They have estimated the resonance energies of the mega-electron volt electrons resonant at 550 Hz and 3.2 kHz to be 4.40 MeV and 1.53 MeV at $L = 1.2$ and the corresponding life times were found to be 2 hour and 4 days respectively. Taking $T_L \min \approx 0.1$ sec. (i.e. of the order of bounce period), $J_T = 4 \times 10^6$ at $L = 1.1$ and $J_T = 1 \times 10^6$ el., cm$^{-2}$ s$^{-1}$ sterad$^{-1}$ at $L = 1.2$ (Katz, 1966) for energetic electrons (energy $> 1$ MeV) we get from equation (5.6) of sec 5.2 that $J_p = 1.06 \times 10^4$ el., cm$^{-2}$ s$^{-1}$ at $L = 1.1$ and $J_p = 4.79 \times 10^3$ el., cm$^{-2}$ s$^{-1}$ at $L = 1.2$ respectively, which in terms of energy flux become $1.70 \times 10^{-1}$ erg. cm$^{-2}$ s$^{-1}$ and $7.66 \times 10^{-2}$ erg. cm$^{-2}$ s$^{-1}$ respectively assuming $E_R = 10$ MeV. These fluxes are comparable with energy fluxes deposited in the lower ionosphere in the low latitude precipitation zone (Voss and Smith, 1980) and at $L \sim 2.4$ (Inan and Carpenter, 1987). Thus the equatorial first order cyclotron resonance seems to contribute significantly to total daily global energy deposition of $\sim 5 \times 10^{19}$ ergs (deg. latitude)$^{-1}$ (Imhof and Gaines, 1993) or $4 \times 10^{20}$ ergs (Baker et al., 1987). Hence, we find the first order equatorial cyclotron resonance quite capable of
explaining the loss of higher energy electrons \((E_R > 10 \text{ MeV})\) near the lower edge of inner radiation belt. In order to explain the loss of eV and keV electrons in this region, we invoke off-equatorial Landau resonance (Pinto and Gonzalez, 1989a). From Table 5.1, we find the average values of \(D_L\) at the \(L\)-shells of 1.1 and 1.2 to be \(6.04 \times 10^{-3} \text{ rad}^2 \text{ s}^{-1}\) and \(2.08 \times 10^{-3} \text{ rad}^2 \text{ s}^{-1}\) respectively. These values give average life times of 2.76 minute and 8 minute at \(L = 1.1\) and \(1.2\) respectively. These small life times indicate that off-equatorial resonance can cause significant diffusion and precipitation of eV and keV electrons at the lower edge of the inner belt. Again considering \(T_{\text{lim}} \sim 0.1 \text{ sec.}\), we obtain \(J_p = 6.04 \times 10^{-4} J_T\) at \(L = 1.1\) and \(J_p = 2.08 \times 10^{-4} J_T\) at \(L = 1.2\). These values of \(J_p\) are consistent with the precipitating energetic electron spectrum in the South Atlantic Magnetic Anomaly (SAMA) region computed from X-ray enhanced flux measurement on 14th April 1981 (see figure 6 of Pinto and Gonzalez, 1989b) for keV electrons. Thus off equatorial Landau resonance may satisfactorily explain the loss of low energy (eV and keV) electrons near the lower edge of inner radiation belt.

Table 5.1 indicates enhancing diffusion of electrons as pitch angle increases. This is contrary to the well known fact that higher the pitch angles as compared with the loss cone angle, slower will be the electron diffusion into the loss cone and that the electrons having large pitch angles near 90° are stably trapped in the inner radiation belt (Vaculov et al., 1975).
However, this problem can be resolved by considering the fact that at higher pitch angles close to 90°, the values of resonance energy $E_R$ are tremendously very high (Chang and Inan, 1983; Prakash, 1991) and hence the electrons with energies less than $E_R$ close to 90° will not resonantly interact with the whistler-mode waves and will remain stably trapped. The same fact emerges from non-linear theory (Villalon, 1989) of gyroresonant interaction of energetic trapped electrons and protons in the earth's radiation zones with the ducted electromagnetic cyclotron waves. They have shown that for a given paritcle velocity $V$ (and hence energy), the equatorial range of pitch angles ($\alpha_m - \alpha_o$) which resonantly interact with the waves is given by

$$\sin^2 \alpha_m \sin^2 \alpha_o = 2 \left( \frac{kV}{\Omega_e} - 1 \right) \quad \ldots \ldots (5.7)$$

in which $\alpha_o$ is the loss cone angle, $k$, the equatorial wave number and $\Omega_e$, the equatorial electron gyrofrequency. Thus particles having pitch angles $\alpha > \alpha_m$ close to 90° will be stably trapped. Only the electrons having pitch angles $\alpha_o < \alpha < \alpha_m$ will diffuse into the loss cone and will finally be precipitated.

Chang and Inan (1983) have shown that for cyclotron resonance, the relativistic factor $\gamma$ approaches $\frac{\Omega_e}{\omega}$ as $\alpha$ approaches 90° indicating very high resonance energy near 90° for cyclotron resonance. If we neglect 1 on right hand side of equation (5.3) as $\gamma_r \gg 1$, we get for Landau resonance near 90° pitch angle,
\[ (\gamma - 1)^2 \text{Landau} = 1 \]

which gives Landau resonance energy, on using equation (5.1),

\[ E_R = \left( \sqrt{2} - 1 \right) m_0 c^2 = 209.5 \text{ keV near } \alpha = 90^\circ. \]

Thus Landau resonance acts on electron energies up to \( \sim 200 \) keV only. Electrons of energies greater than \( \sim 200 \) keV cannot be precipitated by this mechanism.

5.4 CONCLUSION

In this chapter, we have studied the precipitation of eV and keV electrons near the lower edge of the inner radiation belt in terms of off-equatorial Landau resonance interaction between energetic electrons and plasmaspheric hiss of natural origin. Off-equatorial Landau resonance is found to act on much lower energies (\( \sim 45 \text{ eV} - 2.5 \text{ keV} \)) than the first order equatorial cyclotron resonance (energy \( > 10 \text{ MeV} \)). The loss of low energy electrons is satisfactorily explained in terms of off-equatorial Landau resonance near the lower edge of the inner radiation belt. The maximum energy and flux of precipitating electrons in this region by Landau resonance are found to be \( \sim 200 \text{ keV} \) and \( 10^{-3} \) times the trapped flux respectively which are consistent with the precipitating energetic electron spectrum in the SAMA region for keV electrons.