Bounce resonance scattering and proton precipitation

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Pitch angle scattering of energetic protons due to bounce resonance with fluctuating geomagnetic field is studied both at low and high latitudes. It is found that like electron diffusion, proton diffusion is also quite weak at low latitudes (L=1.1, 1.5), but the maximum contribution of bounce resonance scattering is ≈ 0.1% only in both cases. It is also seen that bounce resonance favours precipitation of protons of higher pitch angles (i.e. those mirroring near or at the equator), and low energy protons will easily be bounce-scattered at all shells in comparison to high energy ones. Further diffusion is found to increase with increase in L-value and decrease in proton energy.

1 Introduction

Wave-particle interactions in the ionosphere and magnetosphere represent an important loss mechanism for energetic particles. Lyons et al.1 have quantitatively investigated the pitch angle diffusion of energetic electrons resulting from resonant (cyclotron mode as well as Landau mode) interactions with the observed plasmaspheric whistler mode wave-band. Considering almost all the geomagnetic latitudes and pitch angle diffusion at all cyclotron-harmonics, they1 were able to explain the long term stability of the inner radiation zone (1.1 ≤ L ≤ 1.7), the location of its outer edge as a function of electron energy and the removal of electrons to the levels near zero throughout the slot (i.e. a region between inner radiation zone and outer radiation zone). Pitch angle diffusion of energetic particles may cause their precipitation into the lower ionosphere causing D- and E-region perturbations, X-ray emission, aurorae production and light/heating2.

While studying particle precipitation phenomena in the South Atlantic magnetic anomaly, Pinto and Gonzalez3 found that electron and proton precipitation can be caused by lightning discharges, coulomb scattering, magnetospheric wave-particle interaction, magnetospheric/ionspheric electric field as well as bounce resonance and fluctuating magnetic field4.5. Like electron precipitation by whistler mode (ELF, VLF waves, lightning discharges) interactions and other processes, proton precipitation, too, plays an important role in the ionosphere and magnetosphere. Hultquist6 and Hultquist et al.7 have studied the precipitation of energetic proton and its relation with ring current position, location of plasmapause, geomagnetic activity, etc. Cornwall et al.8,9 have suggested that ion cyclotron waves generated by the ring current protons and absorbed by the thermal electrons which are heated so much that they can excite the 6300Å OI line, are the cause of stable auroral red (SAR) arcs. This process has been the subject of studies on the relation between the plasmapause and SAR arcs10-12. The theory suggested by Cornwall et al.8,9 for production of SAR arcs by precipitating protons was verified later on through direct observation and studies by Hultquist6 and Hultquist et al.7. Precipitated protons (1-50 keV) have been observed aboard OGO-3, whereas ESRO-1A,B recorded them with energy (peak flux) of 6 keV and 80° pitch angle. The ATS-5, Explorer-45 and OGO-5 have recorded proton flux events with pitch angles as low as 10° and energy up to 1 MeV (lower limit being at 80 eV) (Refs 10,11). Pizella and Frank13 and Winningham14 have also reported such events.

Does bounce resonance scattering play any role in the precipitation of these energetic protons? Roberts and Schulz15 have studied the role of bounce reso-
nance in electron precipitation and hinted that, whereas small pitch angle electrons can be dragged into loss cone by whistler mode waves, large pitch angle electrons can be pitch-angle-scattered by bounce resonance by fluctuating electric or magnetic fields (plasma turbulence). Roberts and Schulz\textsuperscript{15}, Dragt et al.\textsuperscript{16} and Fillius\textsuperscript{17} have indicated that some type of wave-particle interactions must be operating on trapped protons and bounce resonance may be a contributor to it. The bounce frequencies of protons in the magnetosphere are significantly lower than those for electrons, and power spectral density of magnetic fluctuations may increase with decreasing frequency below 1 Hz causing strong bounce interaction of protons. Let us recall here that a trapped proton may gain or lose energy due to bounce resonant interaction with waves in plasma. Since total energy of protons and fields must be conserved, a gain in proton energy must be accompanied by a decrease in wave energy and vice versa. Thus, bounce resonance may not be only a proton precipitation event but also a wave damping/amplification process\textsuperscript{18}.

In this paper bounce resonant interaction between trapped energetic protons and fluctuating magnetic field has been studied. The study is made at $L=1.1-4.0$, giving emphasis at low latitudes. The method provided by Roberts and Schulz\textsuperscript{15} has been followed with its slight modifications keeping in mind the recent works in the field and incorporating recent studies in the field of wave-particle interaction and particle precipitation.

2 Method of calculation and ionospheric model

We compute pitch angle diffusion coefficient $D(\alpha)$ due to bounce resonance from the following equations\textsuperscript{18}:

\begin{equation}
D(\alpha) = 0.25 \frac{D_{br}}{[E_0 E_1 (1+E_0/E_1)^2]} \quad \text{(1)}
\end{equation}

\begin{equation}
D_{br} = 6.28 E_1^2 \cdot P(f) \cdot H(f) \cdot f^2 \quad \text{(2)}
\end{equation}

\begin{equation}
H(f) = 0.2542 \ln x / x \quad \text{(3)}
\end{equation}

Here, $D_{br}$ is called bounce resonance diffusion coefficient, $E_1$ and $E_0$ are the perpendicular and parallel energy of resonant proton, $P(f)$ the normalized power of fluctuating field, $f$ the bounce frequency of resonant proton and $x$ the ratio of mirror point distance from equatorial top of field line ($Z_m$) and correlation distance $Z_c$. The parameters $Z_m$ and $Z_c$ are calculated from the following equations:

\begin{equation}
Z_c = (C_s / 400) f \quad \text{(4)}
\end{equation}

\begin{equation}
Z_m = 0.47 LR_0 \cot \alpha \quad \text{(5)}
\end{equation}

where, $L$ is the McIlwain parameter, $R_0$ the earth radius (6370 km) and $C_s$ the Alfvén speed of energetic particle.

The cold proton densities ($N_p$, cm$^{-3}$) at the considered $L$-values of 1.1, 1.5, 4.0 are taken to be 25% of electron density at $L=1.1$ ($N_e=5000$, $N_p=20000$), 40% of electron density at $L=1.5$ ($N_e=1084$, $N_p=2710$) and 100% of electron density at $L=4$ ($N_e=N_p=400$). The values of cold electron density ($N_e$) correspond to diffusive equilibrium model\textsuperscript{18,20} and have been used earlier successfully by many workers\textsuperscript{2}. The proton concentration at $L=4$ is in agreement with that obtained from the following expression given by Carpenter and Anderson\textsuperscript{21}.

\begin{equation}
\Log(N_p) = 3.9043 - 0.3145L \quad \text{(6)}
\end{equation}

Equation (6) is in agreement with the FLIP plasma-sphere refilling model of Richards and Torr\textsuperscript{22} in which ionospheric plasma densities and temperatures are used\textsuperscript{23}.

3 Results and discussion

The study is made at $L$-value of 1.1, 1.5 and 4 which correspond to inner edge of inner belt, low latitudes and high latitudes, respectively. Energetic proton which is in bounce resonance with geomagnetic fluctuations has energies 100 keV, 1 MeV and 10 MeV. Resonant proton velocities ($V_R = V \cos \alpha$) after relativistic corrections come out to be 4374, 13920 and 43410 km/s, respectively. Time period of bounce resonant proton ($T_b$) is calculated using the following expression\textsuperscript{24}:

\begin{equation}
T_b = 4LR_0 / V_R f(\alpha) \quad \text{(7)}
\end{equation}

such that

\begin{align}
f(\alpha) &= 0.75, \text{ for } \alpha=90^\circ \\
&= 1.30 - 0.56, \text{ for } 40^\circ \leq \alpha \leq 90^\circ \\
&= 1.4, \text{ for } \alpha=0^\circ 
\end{align}

(8)

In the present case, the expression for $T_b$ is different from that of Roberts and Schulz\textsuperscript{15} who computed it using the expression $T_b = 4LR_0 / V_R$. The pitch angles ($\alpha$) considered in this study are those lying above 40°, as $D(\alpha)$ values are quite low at $\alpha<40^\circ$. 

The variation of pitch angle diffusion coefficient due to bounce resonance needs fluctuating normalized field $P(f)$ which is expressed as:

$$P(f) = \frac{B^2}{B_0^2}$$  \(\cdots (9)\)

where, $B^2$ is the spectral density of fluctuating field and $B_0$ the geomagnetic field ($31400 \, \text{nT}/L^2$). We have taken $B^2$ to be $1 \, \text{γ}^2/\text{Hz}$ as this spectral density of electromagnetic ion cyclotron waves (for $f=0.1 \, \text{Hz}$) has been observed in a wide $L$ range$^{21-25}$. It is considered that this intensity peaked at $f_0=0.1 \, \text{Hz}$ and spectral density is calculated at other frequencies from the following dependence:

$$B^2 = B_0^2 \left(\frac{f_0}{f}\right)^2$$  \(\cdots (10)\)

Equation (10) shows linear dependence of $B^2$ with bounce frequency ($f$). The present frequencies lie in Pc1-Pc3 range. Lanzerotti et al.$^{35,36}$ have reported magnetic fluctuations falling in a wide Pc range, and their results are in agreement with the present considerations.

Variations of $D(\alpha)$ with energies of energetic protons and $L$-values have been depicted in Fig. 1. The graphs are somewhat different from those given by Roberts and Schulz$^{15}$. Their results (Fig. 4, Ref. 15) show that $D(\alpha)$ peaks at certain pitch angle ($\alpha=89-89.7\,^\circ$) and then decreases, whereas the present result shows an increase in $D(\alpha)$ values with the increase in proton pitch angle, because here the bounce period expression used is different from that of Roberts and Schulz$^{15}$.

Figure 1 clearly shows that with the increase in proton energy, $D(\alpha)$ decreases at a given $L$ shell. Moreover, for a given energy of bounce resonant proton, diffusion coefficient $D(\alpha)$ increases with the increase in $L$-value and pitch angle. Thus it is inferred that:

(i) Pitch angle scattering of energetic protons due to bounce resonance is very weak at low $L$ shells (or low latitudes).

(ii) Bounce resonance scatters higher pitch angle protons easily. It is pointed out here that lower pitch angles are prone to fall in loss cone ($\alpha$ is not much greater than $\alpha_0$, the loss cone pitch angle) to be precipitated out of radiation belts/ring current due to cyclotron/Cerenkov, etc. resonance.

(iii) Lower the proton energy, higher is the probability of the particle to be pitch-angle scattered due to bounce resonance.

(iv) Role of bounce scattering in precipitating low energy protons becomes more important as $L$-value increases. At higher ($L \geq 4$) shells it becomes quite significant.

To what extent does bounce resonance scattering contribute in precipitation of energetic protons? To reply this question we make a comparative study of pitch angle diffusion coefficients of 100 keV protons due to bounce resonance and cyclotron resonance.
environment. In addition to the large amplitude of anomalous conditions in the magnetospheric plasma, ions are certainly unusual in amplitude and said that reported events of supports our assumption. Lanzerotti et al. have reported very large amplitude oscillations in the Pc2 frequency band (0.1-0.5 Hz) which were recorded at Plano (Illinois, USA, 41.66°N, 88.43°W) and Cascade (Iowa, USA, 42.3°N, 91.02°W). These large amplitude (30 nT, \( f_0 = 0.14 \text{Hz} \)) geomagnetic field oscillations were observed superimposed on lower frequency ones (0.008 Hz) at \( L = 3 \) during a large magnetic storm. These oscillations, which have such amplitudes at the reported stations were found to be consistent with a wave excited by the bounce motion of protons with a peak in the energy distribution at 100 keV. In the present case fluctuating field amplitude at 0.1 Hz is 0.33 nT only. Why have we not considered these values of magnetic fluctuations in the Pc2 range when all other parameters are consistent with experimental observations? Indeed, in his review Rostoker proposed the hydromagnetic wave phenomena of Pc2 band to possess wave amplitude not greater than 0.5 nT (which supports our assumption). Lanzerotti et al. have said that reported events of Plano and Cascade stations are certainly unusual in amplitude and location of occurrence, and definitely indicate anomalous conditions in the magnetospheric plasma environment. In addition to the large amplitude of these oscillations (Pc1, Pc2 band), they were superimposed on longer period (~100 s) geomagnetic variation which were highly non-uniform azimuthally. We have taken correlation distance, in the present case, to be four hundredth part of a wavelength, i.e. some 100 times smaller than that considered by Roberts and Schulz. Actually, we get \( x \) values smaller at low latitudes than at \( L = 4 \). Roberts and Schulz have given two formulas for parameter \( H(f) \) — one is given as Eq. (3) in Sec. 2 and is applicable for \( x > 1 \) and second formula for \( H(f) \) computation is used for \( x < 1 \). The two formulas give conflicting values at \( x = 1 \). To avoid this problem we have taken \( Z_0 = \lambda/400 \). This is analogous to full wave treatment done at low altitudes (50-200 km) to study electromagnetic wave propagation, whereas ray tracing treatment is given for wave propagation studies at high altitudes (above 200 km). Roberts and Schulz have shown (Fig. 4, Ref. 15) that change of correlation distance (from \( \lambda \) to \( \lambda/4 \)) produces insignificant difference in \( D(\alpha) \) values for \( 40 \leq \alpha \leq 85^\circ \) [\( 7 \times 10^{-3} \leq \cot^2 \alpha \leq 1.4 \)].

![Fig. 2—Plots showing variation of \( D(\alpha) \) with pitch angles (70-85°) at different \( L \) shells for 100 keV proton energy and 20%, 40% and 60% proton concentrations.](image)
Is there any experimental evidence to support the present result? Actually, any precipitation event cannot occur due to a single cause and various processes may have their major/minor contributions in precipitating the energetic particles out of radiation belts/ring current. Two questions further arise: (i) how do different proton concentrations affect the diffusion process? and (ii) bounce frequency (or velocity) being same, which kind of particles are more easily scattered — electrons or protons? For this purpose, we have considered 20%, 40% and 60% proton concentrations (N_p) at L=1.1 and L=1.5, and computed diffusion coefficients for electrons and protons. The D(α) values for different proton concentrations are shown in Fig. 2 which shows that as proton concentration increases, D(α) value also increases. It is also clear from Fig. 2 that D(α) for protons is always higher than D(α) for electrons, suggesting that at still higher L shells (e.g. L=6.6) strong proton diffusion may be due to bounce resonance scattering. Hultquist has shown that strong proton diffusion at L=6.6 is not due to wave-particle interactions (cyclotron/Cerenkov resonances). We infer that this may be due to bounce resonant scattering.

4 Conclusion

The contribution of bounce resonance scattering has been found to be quite low in comparison to that of cyclotron resonance. The results show that the protons with higher pitch angles mirroring at or near the equator can be efficiently pitch-angle scattered by bounce resonance. Also, during the bounce resonance, pitch angle scattering is found to be increased with the decrease in proton energy.

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