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CYCLOTRON MODEL FOR QUASSI-STEADY PRECIPITATION OF ENERGETIC ELECTRONS AT THE PLASMAPAUSE

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1. Introduction

Satellite data show existence of regular zones of strong particle precipitation from the ion and electron radiation belts. Systematic precipitation of energetic electrons which correlate with ELF-VLF chorus generation are observed on the morning side of the magnetosphere ($3 < L < 6$). An extended precipitation zone of both ions and electrons is revealed on the night side, in the region of dipolar and tail-like magnetic fields. A specific precipitation zone of energetic electrons has been observed on the evening/afternoon side after sufficiently strong magnetic storms. This zone has some remarkable features investigated by *Yahnina et al.,* [1996] using the data from low-altitude ($h \sim 10^3$ km) NOAA satellites. In particular, the moderate pitch-angle diffusion regime is evident in this precipitation, and the precipitation exhibits a specific step-like latitudinal variation. These quasi-steady events are often accompanied by precipitation of protons located in the same LT sector but at higher latitudes. Here, a theoretical model based on cyclotron resonant interactions is suggested to explain observed phenomena.

2. Basic equations and their approximate solution

We consider that this electron precipitation zone is formed by energetic electrons which interact via the whistler wave cyclotron resonance instability with a region of relatively large cold plasma density. This region is caused by restructuring of the plasmasphere during the magnetic storm. The source of energetic electrons is on the night side and electrons enter the interaction region due to the process of magnetic drift. We take the simplest self-consistent model for stationary cyclotron interaction which includes the pitch-angle diffusion equation for the distribution function F of energetic electrons and the wave energy transfer equation for the spectral density E_ω of the whistler-mode waves in the form [*Bespalov and Trakhtengerts*, 1986]:

$$\frac{V_D}{R_0 L}\frac{\partial F}{\partial \varphi} = \frac{\partial}{\partial \mu}\mu D \frac{\partial F}{\partial \mu} - \delta F \qquad (1)$$

$$V_{g\perp}\frac{\partial E_\omega}{\partial r_\perp} = (\gamma - \nu) E_\omega \qquad (2)$$

where δ characterizes losses of particles into the loss cone:

$$\delta = \begin{cases} 0 & \mu \ge \mu_c \\ \delta_0 = 2v/l & 0 \le \mu \le \mu_c \end{cases} \qquad (3)$$

v is the electron velocity, l is the length of a magnetic flux tube, $\mu = \sin^2\theta_L$, where θ_L is the pitch-angle in the equatorial plane, $\mu_c \approx (2L)^{-3}$ is the loss cone boundary. ν is wave damping rate, γ is whistler growth rate:

$$\gamma = \gamma_0 \int_0^1 \left(\mu \frac{\partial F}{\partial \mu}\right) d\mu \qquad (4)$$

D is the diffusion coefficient

$$D = \int G E_\omega d\omega \qquad (5)$$

G is the known function [*Bespalov and Trakhtengerts*, 1986] which determines the effectiveness of the cyclotron interaction. V_D is the magnetic drift velocity of electrons in the equatorial plane, R_0 is the Earth radius, L is the geomagnetic shell parameter, φ is the azimuthal angle, and $v_{g\perp}$ is the whistler wave group velocity component across the geomagnetic field. This component exists when the whistler wave ducts are absent, and the waves are reflected by the plasmapause and/or in the magnetosphere. For simplicity, we suppose that $dr_\perp = LR_0 d\varphi$.

In the strict expressions for γ and D, the integration limits depend on μ and ω (see [*Bespalov and Trakhtengerts*, 1986]). Such a dependence is especially important in D and can lead, in some cases, to a new generation regime in a cyclotron maser [*Trakhtengerts*, 1995]. We suggest here that the oblique whistler waves exist, and they smooth over the *D* dependence on μ. In equation (4), the distribution function is normalized to unity:

$$\int_0^1 F d\mu = 1 \qquad \gamma_0 \approx a \frac{n_h}{n_{pL}} \omega_{BL} \tag{6}$$

where $a \approx 0.2$ is the numerical coefficient, n_h / n_{pL} is the ratio of hot and cold electron densities in the equatorial plane at that *L* value and ω_{BL} is the electron gyrofrequency there.

Even with these simplifications, the system of equations (1)-(2) is difficult to solve. Further we take into account that, for the step-like precipitation events which are of our interest, the initial isotropization of *F* by switching on the cyclotron instability is faster than the electron losses due to precipitation into the loss cone. In this case, the loss term δF in equation (1) can be taken into account by the multiplier:

$$F(\mu, \varphi) = \Phi(\mu, \varphi) \exp\left(-\frac{R_0 L}{V_D} \mu_c \varphi \right) \tag{7}$$

where $\Phi(\mu,\varphi)$ meets the equation:

$$\frac{V_D}{R_0 L} \frac{\partial \Phi}{\partial \varphi} = \frac{\partial}{\partial \mu} \mu D \frac{\partial \Phi}{\partial \mu} \tag{8}$$

with the following initial and boundary conditions:

$$\varphi = 0 \qquad \Phi = \Phi_0(\mu) \tag{9}$$

$$\mu = \{0;1\} \qquad \mu D \frac{\partial \Phi}{\partial \mu} = 0 \tag{10}$$

The solution of the system of equations (8)-(10) is written as

$$\Phi = \sum_{i=0}^{\infty} b_i J_0\left(2 p_i \sqrt{\mu}\right) \exp\left(-p_i^2 \xi\right) \tag{11}$$

where J_0 is the zeroth order Bessel function, and the eigennumbers p_i are the roots of the equation

$$J_1(2p_i) = 0 \tag{12}$$

($p_0 = 0$, $p_1 = 1.9$, $p_2 = 3.5$, …). The coefficients b_i are determined by Φ_0:

$$b_i = q_i^{-1} \int_0^1 d\mu \Phi_0(\mu) J_0\left(2 p_i \sqrt{\mu}\right) \tag{13}$$

$$q_i = J_0^2(2p_i) \tag{14}$$

and the variable ξ is equal to

$$\xi = \frac{R_0 L}{V_D} \int_0^{\varphi} D(\varphi') d\varphi' \tag{15}$$

From (2) we have the equation for *D*:

$$\frac{v_{g\perp}}{R_0 L} \frac{\partial D}{\partial \varphi} \cong (\gamma - \nu)_{max} D \tag{16}$$

where, in the case of the sufficiently dense cold plasma,

$$(\gamma - \nu)_{max} \approx \gamma_0 \int_0^1 \mu \frac{\partial F}{\partial \mu} d\mu - \nu_0 \tag{17}$$

where $\nu_0 = \nu_{(\omega = \omega_m)}$, $\omega_m = \beta_0^2 \omega_{BL}^3 / \omega_{pL}^2$ is the characteristic frequency of cyclotron waves, $\beta_0 = v_0 / c$, and $\omega_{pL}^2 = 4\pi e^2 n_{pL} / m$ is the square of the plasma frequency in the equatorial plane.

The initial stage of isotropization of the distribution function *F* can be roughly described by the relation

$$(\gamma - \nu)_m \approx \bar{\gamma}_0 e^{-p_1^2 \xi} - \nu_0 \tag{18}$$

Using (18) we can transform (16) to the form

$$\frac{v_{g\perp}}{R_0 L} \frac{\partial D}{\partial \xi} \cong \bar{\gamma}_0 e^{-p_1^2 \xi} - \nu_0 \quad \text{where } \bar{\gamma}_0 = \frac{5}{6} \gamma_0 \tag{19}$$

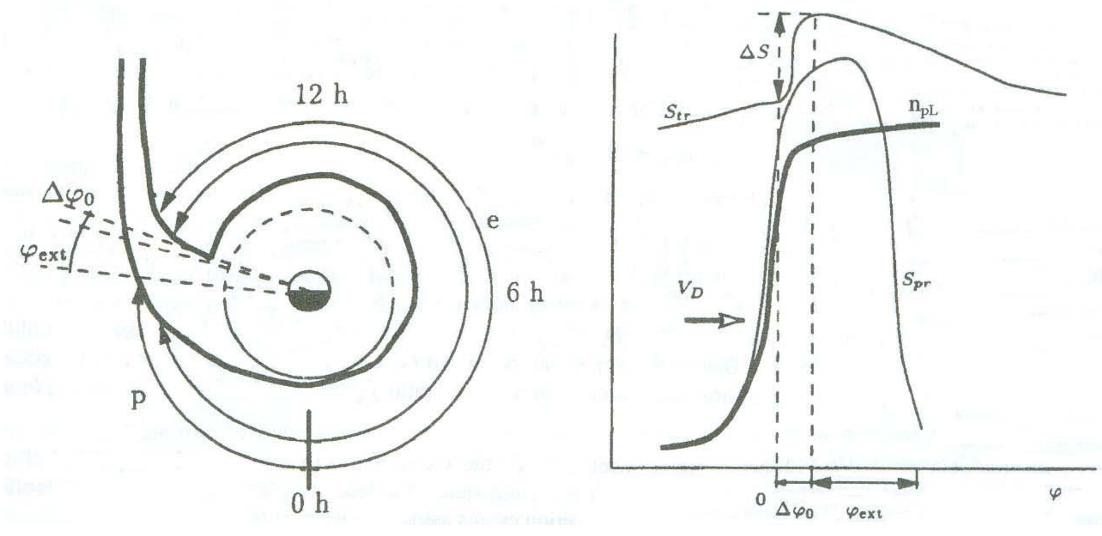

Figure 1. Qualitative picture of the energetic particle precipitation pattern during the recovery phase of a magnetic storm. This scheme qualitatively corresponds to the events observed by the NOAA satellites [1]. The solid line corresponds to the example observed by the NOAA satellites. S_{pr} is the precipitated electron fluxes, S_{tr} is the trapped electron fluxes. n_{pL} is the cold electron densities in the equatorial plane.

The solution of (19) with (15) taken into account has the form

$$D = D_m\left[1-\exp\left(-p_1^2\xi\right)\right]-\frac{V_D}{v_{g\perp}}\nu\xi + D_0 \tag{20}$$

$$\int_0^{\xi}\frac{dx}{D_m\left[1-\exp\left(-p_1^2 x\right)\right]-\frac{V_D}{v_{g\perp}}\nu x + D_0} = \frac{R_0 L}{V_D}\varphi \tag{21}$$

where

$$D_m = \frac{V_D\overline{\gamma}_0}{v_{g\perp}p_1^2} \tag{22}$$

and D_0 is the value of D at $\varphi = \xi = 0$. We can estimate the width $\Delta\varphi_0$ of the precipitation front using the solution (21) under $p_1^2\xi \le 1$. In the case $\gamma_0/p_1^2 >> \nu$, we have

$$\Delta\varphi_0 \sim \frac{v_{g\perp}}{\overline{\gamma}_0 R_0 L}\ln\left(D_m/D_0\right) \tag{23}$$

The extent φ_{ext} of the precipitation pattern in the strong diffusion regime is determined by the equation

$$\frac{4v_0}{\pi R_0 L^4 D(\varphi_{ext})} \approx 1 \tag{24}$$

where the dependence $D(\varphi_{ext})$ is determined from (20)-(21). In the approximation $D_m >> D_0$ and $p_1^2\xi >> 1$, we have

$$D(\varphi) \approx D_m \exp\left(-\frac{R_0 L\nu}{v_{g\perp}}\varphi\right) \tag{25}$$

$$\varphi_{ext} \approx -\frac{v_{g\perp}}{R_0 L\nu}\ln q \approx -\frac{\overline{\gamma}_0}{\nu}\ln q >> \Delta\varphi_0 \tag{26}$$

where

$$q = \frac{4v_0}{\pi R_0 L^4 D_m} \tag{27}$$

3. Discussion

The isotropization of the distribution function during the process of pitch-angle diffusion is accompanied by the redistribution of the energetic electrons along the magnetic flux tube. If the initial distribution is described by the power law ($F_\alpha = A\mu^\alpha$), the dependence of the energetic electron density along the magnetic field line *s* is

$$n_\alpha(s)/n_{L\alpha} = (B/B_L)^{-\alpha} \tag{28}$$

where $n_{L\alpha}$ is the density in the equatorial plane. If the total density $N = \int n_\alpha(s)(B_0/B)ds$ in a magnetic flux tube is constant, the energetic electron density measured by satellites at low altitudes can be changed considerably. If, for example, for the initial F_0, $\alpha \simeq 0.5$, $L \simeq 6$, and $h = 10^3$ km, the energetic electron density n ($h = 10^3$ km) increases by the factor 7 due to izotropization.

Now we can find the front width from (23). If $\ln(D_m/D_0) \sim 8$, the width $\Delta x \cong R_0 L \Delta\varphi_0 \sim 10^3$ km. The extent of the precipitation region depends on the free parameter ν, according to (26). The form of the precipitation pattern, which follows from the above estimations, is shown in Figure 1. The ratio $\bar{\gamma}_0/\nu$ is taken to be equal to 25, $\ln q \sim 1$, and $F_0 \propto \mu^{1/2}$.

The precipitation of protons observed simultaneously with the electron precipitation can be explained if the detached plasma region is formed as shown in Figure 1. Both sides of a detached plasma “tongue” then manifest themselves in precipitation after energetic particle injection events associated with magnetic storms.

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References

T.A. Yahnina, E.E. Titova, A.G. Yahnin, B.B. Gvozdevsky, A.A. Lyubchich, V.Y. Trakhtengerts, A.G. Demekhov, J.L. Horwitz, J. Manninen and T. Turunen. Some features in the energetic electron precipitation pattern near the plasmapause in the evening sector, In the Proceedings of XIX Annual Apatity Seminar of “Physics of Auroral Phenomena”, Apatity, 1996, p. 70-72.

P.A. Bespalov and V.Yu. Traktengerts. The cyclotron instability in the Earth radiation belts. In M.A. Leontovich, editor, *Reviews of Plasma Physics*, volume 10, pages 155-192. Plenum, New York, 1986.

V.Yu. Trakhtengerts. Magnetosphere cyclotron maser: Backward wave oscillator generation regime. *J. Geophys. Res.*, 100, 17,205-17,210, 1995.