ENERGETIC PARTICLES IN A FLARE LOOP : SPECTRA AND RADIATION SIGNATURES

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ABSTRACT. It has been shown that high energy particle spectra, particle dynamics, and radiation in a flare loop are determined by wave-particle interactions. The electron-whistler interaction occurs under conditions of strong pitch angle diffusion that makes the particle distribution function isotropic. The flare loop electrons retain information about the particle source spectrum. The interaction of energetic ions with Alfven waves is characterized by strong, moderate, and weak diffusion. The time delays in hard X-ray and gamma-ray emission during one-step acceleration processes might be understood in terms of a trap-plus-turbulent propagation model. The density of precipitating particles is less than or equal to the trapping one. Radiation signatures of flare loop electrons are discussed.

1. INTRODUCTION

Pitch angle diffusion plays a very important role in the dynamics and radiation of the energetic particles in a solar flare loop. The accelerated particles diffuse into a loss-cone due to pitch angle scattering and precipitate toward the loop footpoints. The interaction of electrons with E > 10 keV with chromospheric plasma near the loop footpoints leads to hard X-ray emission. Gamma-ray line emission is produced by precipitation of ions with E > 10 MeV. According to Bespalov and Trakhtengertz (1986) the three modes of pitch angle diffusion are possible :

(i) Weak diffusion is realized when $\sigma T_o < T_d$, where T_d is the diffusion time, σ is the mirror ratio, $T_o = L / 2v$ is the depletion time of the loss cone, L is the loop length, and v is the energetic particle velocity. The loss cone is always empty.

(ii) Moderate diffusion corresponds to the inequality $T_o < T_d < \sigma T_o$. Filling of the loss cone is essential and the particle distribution function is close to an isotropic one. These diffusion modes were defined by Kennel and Petschek (1966). Bespalov and Trakhtengertz (1986) have shown that there exists a still more efficient scattering process:

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(iii) Strong diffusion, $T_d < T_o$, occurs when the particle source is powerful enough. The particle changes direction several times during one transit time of the loop due to effective scattering on the waves and the particle propagation velocity may be much lower as compared with cases (i) and (ii). The pitch angle scattering may be due either to Coulomb collisions or to wave-particle interactions. In the trap-plus-precipitation model by Melrose and Brown (1976) collisions lead to weak pitch angle diffusion. In spite of wave-particle interaction in a flare loop only weak diffusion was considered in many papers (Aschwander et al., 1989; Hulot et al., 1989). Moderate diffusion in a flare loop due to Alfven wave-ion interaction was investigated by Zweibel and Haber (1983) and Bespalov and Zaitsev (1986). Bespalov et al. (1987) drew attention to the possibility of strong pitch angle scattering in a flare and suggested a trap-plus-turbulent propagation model.

In the present report we will show that the dynamics of the flare accelerated particles are determined mainly by wave-particle interactions. Moreover, for high energy electrons wave-particle interactions occur in the strong diffusion regime only. Particle diffusion on waves is responsible for particle spectra formation and affects flare radiation signatures.

2. CYCLOTRON INSTABILITY IN A FLARE LOOP

Energetic particles with a loss cone anisotropy may be unstable against small-scale electromagnetic wave excitation. In the context of pitch angle diffusion cyclotron resonant interaction with whistlers $\omega = \omega_e(kc/\omega_p)^2$ is the most important for the electrons. The waves grow at a rate (Kennel and Petschek, 1966)

$$\gamma \approx \frac{n_1}{n_0}\,\frac{\omega_e}{\sigma} \qquad (1)$$

where n_1, n_0 refer to the densities of the energetic particles and the background plasma, and $\omega_e = eB/mc$. From the cyclotron resonance condition $\omega - k_\parallel v_\parallel = \omega_e$ and the anisotropy threshold $\omega < 3\,\omega_e/(2\sigma+1)$ we find that the energy of the electrons interacting with whistlers must exceed the value

$$E_{min} \approx 14\,\frac{(\sigma-1)^3}{(2\sigma+1)^2}\left(\frac{v_A\ \mathrm{cm\ s^{-1}}}{10^8}\right)^2 \mathrm{keV}\ , \qquad (2)$$

where v_A is the Alfven velocity. For $v_A \approx (1-3)\,10^8$ cm s^{-1} and $\sigma \approx 10$, for example, from Eq.(2) we obtain $E_{min} \approx 20 - 200$ keV. The energetic particle density instability threshold under flare loop conditions is about $n_1/n_0 \approx 10^{-9} - 10^{-8}$ and determined by Joule dissipation or by

Landau damping.

Anisotropic ions generate Alfven waves $\omega = k_{\parallel} v_A \approx \omega_i v_A / v$ with a growth rate of the order of (Kennel and Petschek, 1966)

$$\gamma \approx \frac{n_1}{n_0} \frac{\omega_i^2}{\omega\sigma} , \qquad \omega_i = \frac{eB}{Mc} \tag{3}$$

The instability threshold $n_1/n_0 \approx 10^{-8}$ is determined either by ion viscosity or by Landau damping. By assuming that in the magnetic loop with a volume 10^{26} cm^3 the number of accelerated particles is about $10^{30} - 10^{32}$ for a typical value of $n_0 \approx 10^{11} - 10^{12}$ cm^{-3}, we obtain $n_1/n_0 \approx 10^{-8} - 10^{-6}$. Thus, there is no problem to excite the whistlers and Alfven waves by high energy particles in a flare loop.

3. WAVE PARTICLE INTERACTION

Wave particle interaction is described by quasi-linear equations for the distribution function of the energetic particles f and for the spectral density of the wave energy W_k:

$$\begin{aligned} \frac{df}{dt} &= \frac{\partial}{\partial v_i} D_{ij} \frac{\partial f}{\partial v_j} + j \\ \frac{dW_k}{dt} &= (\gamma - \nu)\, W_k \end{aligned} \tag{4}$$

where D_{ij} is the diffusion coefficient, j is the particle source, and ν is the damping rate. The condition $T_d < T_o$ is a necessary, but not sufficient condition for strong diffusion. The full criterion has been found by Bespalov and Trakhtengertz (1986) on the basis of Eqs. (4). In the strong diffusion limit the integral particle source power

$$I = \iint \frac{B_{max}}{B}\, j\, d^3v dz$$

exceeds the critical value

$$I_* \approx \frac{cB\sigma}{4\pi eL} \tag{5}$$

It should be noted that I_* does not depend on the particle species. Setting $L \approx 10^9$ cm, $B \approx 10^3$ G, $\sigma \approx 10$,into Eq. (5), we obtain $I_* \approx 5\ 10^{13}$ $cm^{-2}s^{-1}$. In the steady-state case the particle flux towards the loop footpoints is equal to the integral source power 2S = I. It follows from hard X-ray data that the typical value of electron flux is of the order of $S_e \approx 10^{15} - 10^{17}$ $cm^{-2}s^{-1}$ $\gg S_*$. The ion fluxes producing gamma-ray line emission are usualy two or three orders of magnitude less. This implies that for flare loop electrons the strong diffusion limit is formed easily and the electron distribution function is isotropic. For energetic ions strong, moderate, and weak diffusion limits are possible.

Under strong diffusion conditions instead of free particle propagation along the loop axis, turbulent propagation occurs with the wave group velocity, which is the whistler group velocity for electrons and Alfven velocity for ions. The particle turbulent propagation time from the top of the loop to the footpoint for electrons and ions can be written in the following form (Bespalov et al., 1987)

$$t^{e}_{turb} \approx \frac{m}{M}\,\frac{v}{v_A}\,\frac{\sigma L}{2v_A}\,, \qquad t^{i}_{turb} \approx \frac{\sigma L}{2v_A} \qquad (6)$$

From Eqs. (5) and (6) we can estimate the critical density of energetic electrons n_* in the strong diffusion limit. Keeping in mind that $S_* \approx n_* v_{turb} \approx 2.5\ 10^{13}$ cm^{-2}s^{-1}, we find $n_* \approx 6\ 10^{3}$cm^{-3}. Hence, the value of n_* is very close to the whistler cyclotron instability threshold $n_1 \approx 10^3 - 10^4$ cm^{-3}. This estimate indicates a very important point : under flare loop condition the whistler-electron interaction is realized in the form of strong diffusion.

The event of 4 August 1972 is a good example of strong diffusion. The hard X-ray time delay was smoothly increasing with the increase of photon energy up to 5 s until a photon energy of 150 keV where it increases suddenly to 15 s (Bai and Ramaty, 1979). This jump may be caused by the transition from collisional diffusion to strong difusion of electrons on whistlers when the electron energy exceeds the threshold value (2). As follows from Eqs. (6) the ion-to-electron turbulent propagation time ratio is $t^{i}_{turb}/t^{e}_{turb} \approx 10$.

Therefore, as both electrons and ions are accelerated simultaneously, the bulk of the ions will reach the footpoints several seconds or tens of seconds later than the electrons. As a result, gamma-ray line emission peaks will be delayed with respect to corresponding peaks of hard X-ray emission (Bespalov et al., 1987). This supports the idea that the electrons and ions are accelerated in a flare simultaneously (Chupp, 1983).

4. PARTICLE SPECTRA

The energetic particle spectra in a flare loop contain very important information on the flare acceleration process. Thus, the question arises : what is the difference between the spectra of particles interacting with waves and the particle source spectrum ? Bespalov and Zaitsev (1986) have shown that the spectra of proton fluxes for weak and moderate diffusion do not depend on the source spectrum but are determined by the index p in the wave damping rate $\nu = \nu_0(k/k_0)^{2p}$ only:

$$\begin{aligned} &S_i \sim E^{-p+1/2}, \text{ weak diffusion} \\ &S_i \sim E^{-p-3/4}, \text{ moderate diffusion}\,, \end{aligned} \qquad (7)$$

where p = 1 for ion viscosity damping and for Landau damping. In the strong diffusion limit the situation is different. The particle distribution function retains information on the source spectrum (Bespalov et al., 1990) :

$$f(E) \approx t_{turb} j(E) \sim \begin{cases} j(E) & \text{for ions} \\ E^{1/2} j(E) & \text{for electrons} \end{cases} \qquad (8)$$

5. RELATION BETWEEN HARD X-RAY AND MCW RADIATION ELECTRONS

There exists a well known discrepancy between the number of electrons inferred from the hard X-ray emission N_X and the gyrosynchrotron radio emission $N_R \approx (10^{-3} - 10^{-5}) N_X$. This implies that the number of trapped electrons producing mcw radiation is much less than the number of precipitating ones. However, such a situation is impossible in a flare loop. Indeed, we have shown that for electrons with $E > E_{min}$ the typical pitch angle diffusion mode is strong diffusion which makes the electron distribution function isotropic. For an isotropic distribution the particle density is constant along the magnetic loop, i.e. $N_R \gtrsim N_X$. In case of weak or moderate diffusion $N_R >> N_X$. In order to resolve this discrepancy there exists only one way out : low emissivity of gyrosynchrotron emission due to a moderate value of B < 300 G (Gary, 1985).On the other hand Kai (1982) assumed that the electrons generating mcw emission have an anti-loss-cone distribution function. Such a distribution function cannot be formed in a flare loop because of strong diffusion.

6. CONCLUSIONS

We are apt to conclude this report by summarizing the results as follows:

1. The energetic particle spectra, particle dynamics and radiation in a flare loop are determined mainly by wave-particle interaction. 2. The strong pitch angle diffusion threshold implies that the flux of precipitating particles must be more than $10^{13} - 10^{14}$ $cm^{-2}s^{-1}$ which is easily realized in a flare loop. The most probable diffusion mode for high energy electrons interacting with whistlers is strong diffusion. For energetic ions the strong, moderate, and weak diffusion on Alfven waves are possible.

3. Under strong diffusion energetic particles retain information on the particle source spectra.

4. Time delays in hard X-ray and gamma-ray emission can be explained in the framework of a one-step acceleration process due to turbulent propagation of particles under strong diffusion conditions.

5. The density of precipitating particles in a flare loop is less than or equal to the density of trapped ones. The discrepancy between mcw and hard X-ray radiating electrons can be resolved by low emissivity of gyrosynchrotron emission.

It should be noted also that the mcw radiating electrons in a flare loop are almost isotropic due to strong diffusion. Nevertheless, isotropic electrons with a gap may be responsible for electron cyclotron maser emission (Blanken and Kuckes, 1969).

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DISCUSSION

SMITH: If one tries to accelerate the protons by resonant Alfvén waves in the 7 June 1980 flare, one finds that the protons propagate in strong diffusion. However, this bottles up the protons so effectively that you cannot explain the rapid time-scales in this flare.

STEPANOV: If the Alfvén waves are generated not by energetic ions but by an ambient source the situation will be different. In order to determine the diffusion regime we need the level of Alfvén waves instead of the particle source power.

SIVARAM: (i) What are the energies of the gamma-ray lines and what are they caused by?
(ii) What is the energy of the hard X-rays? What is the time delay?

STEPANOV: (i) The energy of the solar gamma-ray line emission is 0.2-6.4 MeV. This emission is caused by interaction of > 10 MeV ions with photospheric plasma.
(ii) The energy of hard X-ray emission is 10-500 keV. The time delay is several seconds typically.