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SOLAR PARTICLE ACCELERATION BY HIGH ENERGY DENSITY MHD TURBULENCE

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ABSTRACT

It is widely accepted that stochastic ($\omega << \Omega_{r}$) and gyroresonant ($\omega \leq \Omega_{r}$) acceleration of solar particles by magnetosonic waves is efficient only when a high energy content of such a turbulence is present. Under this condition resonant wave-particle interactions, non-resonant wave damping and non-linear interactions among these modes play the main role in determining the efficiency of particle acceleration by these waves. We analyze here the effect of the two first mentioned factors in the evolution of the turbulence spectrum and acceleration efficiency. The results allow us to determine the feasibility of particle acceleration at different levels of the flare body.

Introduction

Particle acceleration in solar flares has been studied within the frame of different mechanisms; however, observational constraints regarding time scales, amount of accelerated particles and their energy spectrum impose difficulties that avoid to have at present a general consensus about the operating acceleration mechanism (s). Among the popular mechanisms there is the so called *turbulent acceleration* where particles gain energy at the expense of damped waves. Two main approaches are distinguished in these kind of mechanisms, the so called stochastic acceleration (resonance at the armonic $s = 0$), and gyroresonant acceleration ($s \geq 1$). This kind of acceleration needs an appropiate source of waves providing a wave spectrum with high enough energy content to produce efficient acceleration in times (≤ 1 s), and so a suitable wave-particle energy exchange process for particles to draw energy from those waves producing hence their damping. There is also the need of a pre-heating mechanism to supply enough amount of particles of energy higher than the threshold injection value for efficient resonant wave-particle interactions (e.g. nonlinear Landau damping, Smith & Miller, 1995),. Several kind of turbulent waves are suceptibles of co-exist in the flare plasma, though their plausible energy source is still a controversial matter: due to mass motions, magnetic reconnection and unstabilities of macroscopic magnetized systems in flare plasma, the presence of MHD turbulence seems highly probable. MHD turbulence is characterized by three modes, the fast and slow magnetosonic modes and Alfvén waves; the slow mode can accelerate solar particlesonly at deep chromospheric levels (Gallegos and Pérez-Peraza, 1993), Alfvén waves are scarcely damped in the resonance $s = 0$, so that their contribution is rather associated to gyroresonant particle acceleration. Besides, Miller *et al (1990)* show that gyroresonant acceleration by Alfvén waves in the solar corona requires about five times the energy density required by stochastic acceleration with fast magnetosonic waves. Ignoring as usual the problem of the turbulence energy source we will limitate our discussion to stochastic acceleration by the fast MHD mode. Our goal in this paper is to determine whether or not the nonresonant damping processes and Coulomb collisions allow for efficient stochastic acceleration (Landau damping) under conditions of the flare plasma.

Basic Equations

Magnetosonic turbulence at the corona is described by a wave spectrum of the Kolmogorov type $W(k,t) = W_o(t)k^{-5/3}$ (where W_o is the energetic content of the turbulence), and its evolution is studied by a differential equation that involves several processes: nonresonat damping in the medium (viscosity, thermal conduction, Joule dissipation, etc.), turbulence injection, wave-wave interaction and cascade effects. In its simplest form, without wave-wave processes and cascade effects, it is well known that such an evolution equation becomes

$$\frac{\partial W(k,t)}{\partial t} = I(k,t) - \sum_{i=1}^{N} \gamma_i(k) W(k,t) \quad (1)$$

where I(k,t) is the turbulence source term and $\gamma_i(k)$ is the *i-th* damping rate of the *i-th* nonresonant damping process. It is usually assumed for simplicity that the turbulence energetic decay does not affect the spectral distribution. Turbulence dissipation is directly related to the efficiency with which the wave modes cede energy through their electric fields to the particles of the medium. In the case of magnetosonic waves this efficiency for resonant (Landau) damping is (Melrose, 1986; Miller, 1991)

$$\alpha_{\pm}(E, k; t) = (3\pi^2 v_{\pm}^2 / B^2 c)\langle k \rangle W_{ms}(t) \ln(v/v_{\pm}) \quad (2)$$

where $W_{ms}(t)$ is the turbulence instantaneous total energy content (through all the wave numbers k), $\langle k \rangle$ is a characteristic value of k in the studied range (e.g. Gallegos-Cruz & Pérez-Peraza, 1995) and $v_{\pm}$ represents the phase velocity of the fast and slow magnetosonic modes respectively. The acceleration rate of the stochastic acceleration process is defined by $dE/dt = (4/3)\, \alpha_{\pm}\, \beta E$, so that the effective acceleration time (t_{eff}) for the particle to gain energy from E_o to a given energy E is

$$t_{eff} = \int_{Eo}^{E} dE / (\tfrac{4}{3}\, \alpha_{\pm} \beta \mathcal{E}) \quad (3)$$

where β is the particle velocity in terms of the light speed c and $\mathcal{E}$ is the particle total energy. For the minimum resonant energy between the fast mode (+) and particles we consider here the injection value, E_o, as the energy corresponding to the Alfvén velocity, which in the coronal plasma is usually higher than the corresponding proton thermal energy. For calculations of the involved time scales during acceleration we have worked out three premises: *(a)* the turbulence energetic content remains constant (W_o = Cte) which means that waves are not damped in the medium, *(b)* there is only an initial turbulence injection W_o at time t = 0 which decays according to the solution of eq. (1) with I(k,t) = 0, *(c)* there is continuous injection regulated by the expression $I(k,t) = W_o(k)\, e^{-at}$, where **a** is a characteristic constant of the turbulence remaining time in the plasma. By solving eq. (1) for the three premises *(a)*, *(b)* and *(c)* it is obtained W(k,t), which integrated over all the k-space gives $W_{ms}(t)$ and introduced it in eq. (2) allows us to evaluate t_{eff}. To determine $\langle k \rangle$ it is assumed that the Kolmogorov type spectrum extends from a value k_{min} up to a value k_{max}. The corresponding minimum frequency is obtained from the assumption that resonant wave-particle interactions occur for wavelengths much larger than the gyroradius of the high energy cutoff of the proton spectrum ($\cong$ 1 GeV). Assuming that low frequency interactions take place at $\lambda \geq 10\Upsilon$ (Miller, 1991), with $\Upsilon = \beta\mathcal{E}/eB$, we obtain $\omega_{min} = 1.17 \times 10^{-7} B v_{+}$ Hz (where B is the magnetic fiel strength). The maximum frequency is taken here as the gyrofrequency of thermal protons $\Omega_P = 9.65 \times 10^3$ B Hz (Tverskoi, 1967). For the energy content we consider here values lower than the content of the average magnetic field ($W_o < B^2/8\pi$).

Wave Damping Rates. The main damping processes of magnetosonic waves in flare regions are viscosity and thermal conduction. The rates for these processes in an isotropic plasma may be derived from the expressions of Braginskii (1965) for anisotropic plasmas: we obtain in the case of viscosity of the fast mode

$$\gamma_{vis} = \eta_o \langle k \rangle^2 / (6\rho) \tag{4}$$

where ρ is the medium mass density, $\eta_o = 3.313 \times 10^{17}\ T^{5/2}/\ln\Lambda$ is the parallel viscosity coefficient (where $\ln\Lambda$ is the Coulomb logarithm). For thermal conduction we obtain

$$\gamma_{thc} = 1.208 \times 10^{18}\ \langle k \rangle^2 T^{7/2}\ /(V_A^2\, n \ln\Lambda) \tag{5}$$

where n is the medium density, V_A the hydromagnetic Alfvén velocity and T the medium temperature. For derivation of (5) we have assumed that $\Omega_e\ \tau_e >> 1$, which implies that the parallel conduction coefficient prevails in flare plasmas; Ω_e and τ_e are the gyrofrequency and collision time of electrons respectively. Therefore, particle acceleration by wave-particle processes occurs when the condition $\mathbf{t_{eff}} < \mathbf{t_{dam}}$ is fullfiled, [where the damping time t_{dam} is obtained from eq. (4) and (5)].

Energization and Collisional Losses of Particles. Though particle energization may occurs under the previously mentioned condition between acceleration and damping times, that does not assure that particles escape from the thermal distribution to produce an acceleration energy spectrum. They also need to overpass the barrier of energy losses , which in the case of ions in flare regions the most relevants are collisional Coulomb losses. So, an additional condition must be fullfiled: $\mathbf{t_{eff}} < \mathbf{t_{coll}}$; $\mathbf{t_{coll}}$ is the time taken for a particle of energy E to cede its energy excees over thermal energy ($\Delta E = E - (3/2)KT$) to the medium. A practical expression of Coulomb losses $(-dE/dt)_{loss}$ in finite-temperature plasmas is that given by Butler and Buckingham (1962), which analytical integration is quite complex, however for our goal, the so called rational numerical approximations (Abramowitz & Stegun, 1965) give a quasi-exact description.

Results

Our analysis was done for typical plasma parameters from the low to the high coronal flare body ($10^9 \leq n \leq 10^{11}$ cm^{-3}; $10^5 < T < 10^7$ **K**; $B \leq 50$ Gauss). Under these physical conditions the results obtained within the frame of premises (*a*) and (*b*) indicate that there is no effective stochastic acceleration of thermal particles with initial velocity V_A, so, hereafter we will center on the results obtained within the frame of premise *(c)* that we are graphically shown on the next figures. Fig. 1 illustrates the comparison of the non resonant and resonant rates at five different locations in the flare plasma which corresponding parameters are tabulated in Table 1. It can be appreciated that effective wave-particle energy transfer is obtained under conditions of point 5, where even the thermal conduction is lower than Landau damping. Fig. 2 shows that under conditions of that location (point 5), thermal protons of energy $E_o \equiv E_{alfven} = 6$ KeV may reach energies $\cong 1$ GeV in times of $\cong 1$ *s*; since in that energy interval, $t_{eff} < t_{coll}$, the accelerated protons never turn back to the thermal background they form thus an acceleration spectrum of energetic protons.

Conclusions

A preliminar approch (ignoring nonlinear and cascade effects) of the real possibilities of stochastic acceleration in solar flare plasmas leads to conclude that under conditions of continuous injection of fast magnetosonic turbulence, with a mean life time of about 1 *s*, protons and electrons may be accelerated according to observational energies and time scales values in the bottom part of the coronal flare body and the top of the chromospheric flare. However, since the injection (Alfvén) energy is higher than the mean thermal particle energy the requirement of a particle pre-heating step cannot be avoided if one needs to reproduce the observational amount of accelerated particles

Table 1. Physical Parameters of Solar Flare Coronal Plasmas.

POINT	DENSITY (cm^{-3})	TEMPERATURE (K)	MAGNETIC FIELD (Gauss)
1	6×10^9	7.5×10^6	50
2	7×10^9	5×10^6	50
3	8×10^9	3×10^6	50
4	1×10^{10}	1×10^6	50
5	1×10^{10}	3×10^5	50

Figure 1.

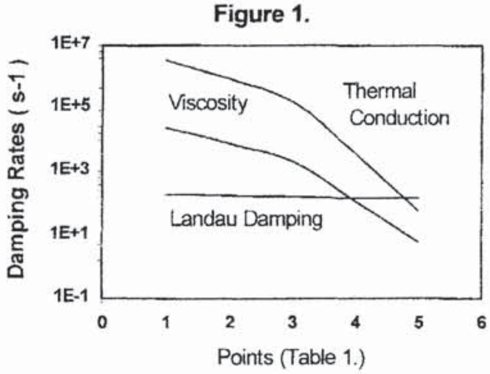
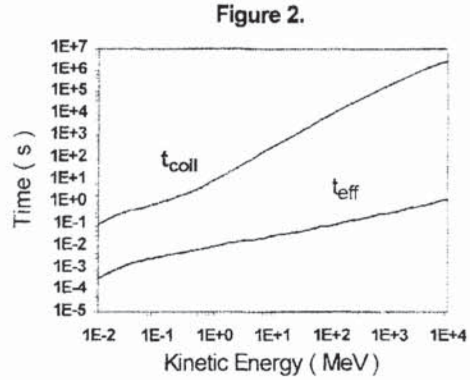


Figure 2.



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