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SOLAR PARTICLE ACCELERATION BY SLOW MAGNETOSONIC WAVES

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ABSTRACT

Particle acceleration by slow magnetosonic waves (SMW) has been systematically disregarded. We examine the real possibility of this mode for acceleration of solar electrons on basis to a quantitative analysis. Evaluations of the times scales involved in the phenomenon allow us to determine the conditions in the solar atmosphere where resonant acceleration by the slow MHD mode may occur.

INTRODUCTION

MHD waves are very interesting for plasma heating and particle acceleration due to these waves have a compressive nature and are very sensitive to several damping processes. Such a damping is of non-resonant /1,2/, as well as of resonant nature/3-7/, and depend critically on the collisional or non-collisional behavior of the plasma. However, in spite that both modes, the fast and the slow magnetosonic waves can coexist simultaneously, only the fast mode has been studied within the frame of particle acceleration /4,8,9/ and coronal heating /10/. The slow mode (usually designed as magnetic acoustic waves /1/ because their phase velocity is close to the sound velocity v_s) has been systematically disregarded as an energization process on the basis of three main arguments /2,4/: (a) their phase velocity is lower than those of the other two modes ($\sim v_a$= Alfven speed), (b) they propagate preferentially in angles which lay very close to the magnetic field direction /4,11,12/, (c) the damping rate of the slow mode is higher than for the other two modes, so they reach only a short distance from their source.
We would like to point out that the condition for effective resonant accelerating interactions, which requires that particle velocity be larger than the wave phase velocity is less strict for the slow mode than for the other two modes, since $v_s \leq v_a$. Hence, in principle, more particles of a Maxwellian distribution are susceptibles of resonant interactions with the slow mode relative to the fast mode and Alfven waves. On this basis, objection (a) rather becomes an advantage of the slow mode. Concerning the second objection, it is well known that an important fraction of wave propagation in the sun is in the radial direction, and on the other hand the acceleration efficiency (α_-) of the slow mode takes precisely its highest values at small angles (ϕ) with respect to the magnetic field, and varies very slightly within the preferential propagation cone of 27°/13/. This can be seen from the efficiency $\alpha_\pm = (2\pi^2 V_\pm^2(\phi)/B^2 v)\int_{k_m}^{k_M} kW(k)dk$ /14,15/, where k_M and k_m define the extremes of the magnetosonic turbulence spectrum $W(k)$, B is the magnetic field strength and $V_\pm(\phi)=0.707[(v_s^2+v_a^2)\pm(v_s^4+v_a^4-2v_s^2v_a^2\cos 2\phi)^{1/2}]^{1/2}$ are the phase velocities of the fast (+) and the slow mode (-).
Related with the faster damping rate of the slow mode relative to the other modes, instead of comparing the efficiency of acceleration among the different modes, what is important is to determine whether or not the slow mode is able to accelerate particles efficiently. We examine in this work such a probability for the specific case of solar electrons, by evaluating the time scales involved in the phenomenon. So, we compare the times for wave damping with that of Resonant Acceleration, and this one with the Coulomb collisional time. For the specific task of this paper we ignore the problem of the origin of the magnetosonic waves, assuming an external source to the acceleration volume. Energy dissipation by wave-wave processes is also neglected.

WAVE DAMPING AND PARTICLE ENERGIZATION EFFICIENCY

Dissipation of the MHD turbulence appears from resonant processes (Landau damping) /2,3,14,15/ and non-resonant damping processes (mainly viscosity) /2/. Wave -particle resonance occurs when it is satisfied the relation $\omega - \nu\Omega - kv = 0$, ($\nu = 0, \pm1, \pm2...$), where ω is the wave frequency, Ω is the particle gyrofrequency, k and v are respectively the components of the wave number and particle velocity in the magnetic field direction. The nature of energy interchange in wave-particle resonance depends on the wave amplitude, the energy content of the magnetic field and the turbulence, and the energy distribution of the particles, which in turn depend on the physical conditions of the prevailing scenario. For the scenario we consider that a Kolmogorov spectrum of SMW injected into the acceleration volume coexist with the other MHD modes, and there is no wave generation therein, I(k) = 0. Resonant energization of particles (in $\nu = 0$) may be described by the diffusion coefficient D_{pk} in momentum space. For isotropic turbulence of small amplitude (with $\omega << \Omega_e$) and isotropic particle distribution with efficient angular dispersion to restatablish isotropie, D_{pk} is /14,16/

$$D_{pk} = \frac{\pi}{8}\, p^2 \langle k\rangle \frac{V_\pm^2(\phi)}{v} \frac{W_{ms}}{W_B} \ln(v/V_\pm(\phi)) \qquad (\text{momentum}^2/\text{s}) \qquad (1)$$

where W and $W = B^2/8\pi$ represent the energy contents in the turbulence and in the average magnetic field respectively and $\langle k\rangle$ a the characteristic wavelength in the wave spectrum $W(k,t) = W(t)k^{-5/3}$ (energy density per wave number k) which value is obtained from/18/: $\langle k\rangle = \int_{k_m}^{k_M} [1/W(t)]k'W(k',t)dk' =$

$2(k_1^2 k)^{1/3}[1 - (k_1/k_2)^{1/3}][1 - (k_1/k_2)^{2/3}]^{-1}(\text{cm}^{-1})$ where $k_1 = k_{min}$ and $k_2 = k_{max}$.

Considering that acceleration is due to scattering and the accelerating scatterers are hard spheres with masses much larger than those of particles, the diffusion coefficient which appears from the Boltzman equation /17/ is $D_{PK} = \alpha p^2/3\beta$. Equating this expression with equation (1) the acceleration efficiency for slow magnetosonic waves is

$$\alpha_- = (3\pi^2/B^2)[V_-^2(\phi)/c]\langle k\rangle W_{ms} \ln[v/V_-(\phi)] \qquad (2)$$

for evaluation of k_{max} we consider the upper cutoff in the wave frecuency spectrum at the gyrofrecuency of protons $\omega_{max} \cong \Omega_H = 9.65 \times 10^3 B$ Hz /18,19/. Since $V(\phi) \le v_s$, hence $k_{max} \cong \omega_{max}/v_s \cong B/T^{1/2}$. For the determination of the cutoff at low frecuencies, a simple assumption is made /20/: since resonance occurrs for $\lambda >> r_e$ (r_e= electronic gyroradius) we assume $\lambda_{min} = 10 r_e$, so that $k_{min} = 2\pi/\lambda_{min} = 2.6 \times 10^{-4} B$. With these extreme values of the wave spectrum we obtain the value of $\langle k\rangle$, in such a way that we have the elements to evaluate equation (2) with the exception of $W_O = W_{ms}|_{t=0}^{\langle k\rangle}$ which may be considered as the free parameter of the model. It is worth to say that because the upper cutoff frequency at k_2 occurs when $\Omega_H << \Omega_e$, the condition to derive D_{pk} for $\nu = 0$ is fullfilled.

TIME SCALE FOR ACCELERATION

Assuming that the energy diffusion rate is negligible relative to the systematic rate (which is not always true /21/), then the acceleration rate may be written as $(dE/dt) = \alpha_R \beta \varepsilon$, where ε = total energy and $\alpha_R = \alpha_-$, so that t_R is the time for particles of initial energy E_i to be accelerated up to an energy E by resonant interactions with SMW which, transmit their energy to particles at a rate /3,22/

$$\gamma^R = \left[(\pi/8)(m_e/m_H) \left[\frac{V_-^4(\phi) + 2\cos^2(\phi) v_s [\cos^2\phi\, v_s - V_-^2(\phi)]}{V_-^2(\phi) - \cos^2\phi\, v_s^2)(2V_-^2(\phi) - v_a^2 - v_s^2)} \right] \right]^{1/2} \langle k\rangle V_-(\phi) \quad (s^{-1}) \qquad (3)$$

The non-resonant damping rates for viscosity and thermal conductivity in an isotropic plasma ($k_\perp \cong k_\parallel$) are /1/

$$\gamma^{vis} = (7\langle k\rangle^2/6\rho)\mu = (7k\rangle^2/6\rho)(0.4 m_H^{1/2}(K_B T)^{5/2}/e^4 \ln\Lambda) = 1.59\times10^9 \langle k\rangle^2 (T^{5/2}/n\ln\Lambda) \quad (s^{-1}) \qquad (4)$$

$$\gamma^{th} = (4K_B T/9\rho V_-^2(\phi))\langle k\rangle\, \kappa = (4K_B T/9\rho V^2(\phi))\langle k\rangle^2 (10.2 (K_B T)^{5/2}\, m_e^{1/2} e^4 \ln\Lambda) =$$

$$= (1.45\times10^{11}/V^2(\phi)\langle k\rangle^2 (T^{7/2}/n\ln\Lambda) \qquad (s^{-1}) \qquad (5)$$

where e = electronic carge, K_B= Boltzman Constant, $\ln\Lambda$ = Coulomb Logarithm and m_H and m_e are the proton and electron mass respectively, ρ = mass density and $n(cm^{-3})$ = density. It must be noted the correct value $K_B^{5/2}$ /1/ instead of the mistake introduced very often in the literature as $K_B^{7/2}$, so that $\gamma^{th} \cong K_B^{7/2}$ instead of $\gamma^{th} \cong K_B^{9/2}$. Since $V\_(\phi) \cong v_s \cong 10^4\ T^{1/2}$, equation (5) may be rewritten as $\gamma^{th} = 1.45 \times 10^3 \langle k \rangle^2 (T^{5/2}/n\ln\Lambda)$ (s^{-1}), so that $\gamma^{vis}/\gamma^{th} \cong 10^6$, i.e. thermal conductivity is negligible relative to viscosity. Therefore, hereafter we will consider $\gamma_{NR} \cong \gamma^{vis}$, and as far as $\gamma_{NR} > \gamma_R$ no efficient acceleration may occur. Since we are ignoring dissipation by wave-wave processes, the criterion to be fulfilled for particle acceleration is $t_R < t_{NR}$. In the absence of any wave generation process the energy content of waves dissipes according the law

$$\frac{\partial W_{ms}}{\partial t} = - \gamma_d W_{ms} \qquad (6)$$

hence $t_d = - \ln(W_{min}/W_o)/\gamma_d$ is the time for waves of initial energy density W_o to dissipate its energy to a value $W_{min} \sim K_B T$ below of which energization of the medium by non-resonant processes (t_{NR}) or acceleration of particles by the resonant process (t_R) is not efficient any more. The acceleration time when $t_R < t_{NR}$ may be evaluated as follows: from equation (6) $W_{ms}(t) = W_o e^{-\gamma_d t}$ where $W_{ms}(t) = \int_{k_{min}}^{k_{max}} W_{ms}(k,t)dk$; if there is free acceleration, without energy dis-dissipation, $\gamma_d = 0$, equation (2) becomes $\alpha_R = 3\pi^2 (V\_^2(\phi)/c)(W_o/B^2)\langle k \rangle \ln(v/V\_(\phi))$; on the other hand, from the acceleration rate and equation (2) we can rewrite $\alpha\_ = \alpha_R e^{-\gamma_d t}$, so that $dE = \alpha\_\beta\varepsilon dt = \alpha_R e^{-\gamma_{NR} t} \beta\varepsilon dt$, where the information about resonant acceleration by resonant damping is in α_R, and the information about wave dissipation to the plasma is in γ_{NR}, therefore, $\int_{E_i}^{E} dE'/\alpha_R \beta\varepsilon = \int_0^t e^{-\gamma_{NR} t} dt$ so that the net acceleration time with both resonant and non-resonant processes is $t_{acc} = (1 - \gamma_{NR} t_R)/\gamma_{NR}$, where $t_R = \int_{E_i}^{E} dE'/\alpha_R \beta\varepsilon$; hence, in order that t_{acc} be a real number $1 - \gamma_{NR} t_R \geq 0$ that is, the acceleration is only possible when $\gamma_{NR} t_R \leq 1$, and there is an upper cutoff in the acceleration spectrum when $\gamma_{NR} t_R = 1$.

RESULTS AND DISCUSSION

To determine the physical conditions (scenarios) where slow magnetosonic waves may accelerate thermal particles up to energies beyond the collisional barrier, we have considered several sets of values of T, n, B, according to different depths of the quiet and active solar atmosphere. Our results indicate that the conditions under which such an acceleration process is most likely to occur are in regions of $T \leq 10^4$K, $n \geq 2 \times 10^{12} cm^{-3}$, $B \leq 200$ gauss, that is near the base of chromospheric flares, or the deep quiet chromosphere. The initial wave energy content W_o has been chosen according to typical values of magnetosonic turbulence in the solar atmosphere /20/. For the set of parameters employed, it can be appreciated that $t_R < t_{NR}$, and that an increase in the wave propagation angle from $\phi = 5^\circ$ to $\phi = 10^\circ$ implies a slight decrease in time acceleration, whereas an increase of the wave energy density from 1 erg/cm^3 to 5 erg/cm^3, keeping the same propagation angle, leads to a drastic decrease in the acceleration time. It can also be seen that an increase in the propagation angle ϕ does not affect sensitively the acceleration time. Therefore, the crucial parameter defining the acceleration is just our free parameter W_o, indicating that the feasibility of acceleration of solar electrons is higher at lower depths in the atmosphere, where the collisional barrier for thermal particles becomes an important inhibiting factor. It can also be seen in the Figures that Coulomb losses only inhibits acceleration at $E_c \leq 1$ KeV, so that rather electrons of the high Maxwellian tails with $v \geq V\_(\phi)$ are susceptible of acceleration. From this preliminary work it can be concluded that acceleration of thermal particles by may be an interesting alternative for the impulsive phase of solar flares, in regions of extension $\le 10^2$ wavelengths /22/. According to the conventional models discussed in$_3$/23/, the source of hard x-rays, EUV and optical radiation is at $n \ge 10^{12}\,cm^{-3}$, when particles are injected from the corona. So, two alternatives should be quantitatively analyzed: SMW acceleration region is in the chromospheric base of flares, and particles escaping the energy loss barriers climb up to the corona, or, particles accelerated in a preliminary stage in the corona, and injected downwards undergo a second acceleration step at the level of the chromosperic roots of the flare, where the impulsive radiation is produced during acceleration. For efficient acceleration with SMW at high levels in the corona, where collisional losses become unrelevant, three main conditions are re quired: (i) a wider wave frequency spectrum than the one considered here and $a\omega_{min}$ determined on basis to a more precise criterion than our assumption ($\lambda \sim 10\rho_e$), (ii) the consideration of a turbulence generating source giving an ef ficient wave grow rate, (iii) an initial suprathermal distribution of the electrons from a preliminary acceleration step.

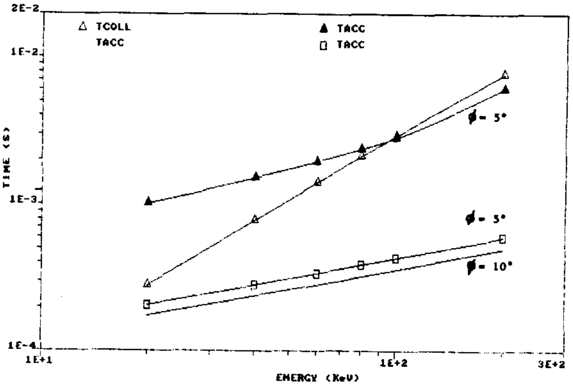

Fig. 1. Acceleration time scales: T=7x10[illegible]K, n=5×10^{13}cm[illegible], B=150 Gauss
. W_o=5 erg/cm[illegible], t_R= 1.94x10[illegible]s, t_{NR}= 7.25x10[illegible]s, E_{max}= 4.95 MeV
□ W_o=5 erg/cm[illegible], t_R= 2.56×10^{-4}s, t_{NR}= 7.25x10[illegible]s. E_{max}= 249 KeV
▲ W_o=1 erg/cm[illegible], t_R= 2.42×10^{-4}s, t_{NR}= 6.82x10[illegible]s, E_{max}= 247 KeV

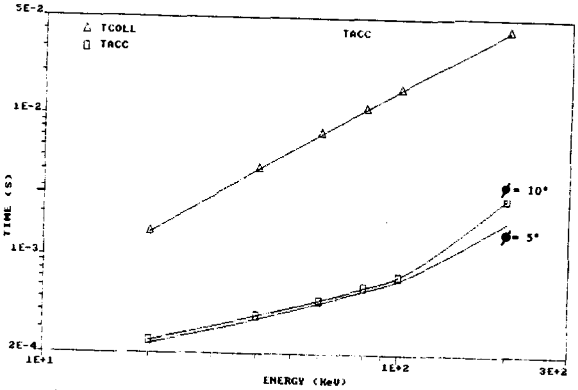

Fig. 2. Acceleration time scales : $T=10^4$K, $n=9.5\times10^{12}cm^{-3}$, B=100 Gauss
. W_o= 5 erg/cm[illegible], t_R= 4.22×10^{-4}s, t_{NR}= 1.57×10^{-2}s. E_{max}= 219 Kev
□ W_o= 5 erg/cm[illegible], t_R= 2.61×10^{-3}s, t_{NR}= 1.57×10^{-2}s, E_{max}= 204 Kev

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