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On the amount of thermal particles accelerated by magnetosonic turbulence in the solar corona

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Abstract

By comparing the time scales for non-resonant thermal dissipation processes of wave energy with Cherenkov particle acceleration (Landau-Damping) by the fast magnetosonic mode, within the frame of the quasi-linear approach, we determine an effective time ($t_{Eff} > 0$) for Cherenkov acceleration. Next, from the comparison of t_{Eff} with the deceleration time by Coulomb collisions (t_{coll}) we are able to estimate (1) the source physical parameters for effective acceleration within observational times, (2) the required levels of energy density of the fast mode for such acceleration of protons and electrons and (3) the amount of accelerated particles.

1. Turbulent evolution and dissipation processes.

Several studies on particle acceleration (e.g. Pérez-Peraza and Gallegos-Cruz 1994; Gallegos-Cruz and Pérez-Peraza 1995) by magnetosonic wave modes during impulsive solar flares consider the fast mode as a plausible candidate to accelerate protons in SEP events, and even (Miller 1991, 1997) for accelerate particles out of the thermal population if the initial frequency range of the turbulence shift toward the high frequency limit (i.e. $\omega \rightarrow \Omega_{e,H}$). In these studies, however, the wave dissipation processes (viscosity, thermal conduction,...) has not been considered. These dissipation processes are always present during the turbulence evolution, and they tend to inhibit the acceleration process. We attempt here to re-evaluate such plausibility including some of these effects. MHD modes are presumable produced in the solar corona by phenomena which occur routinely. Simultaneous to turbulence generation, energy is transferred from the waves to the plasma, and interchanged throughout its frequency spectrum: that occurs through a wide variety of mechanisms, such as: viscosity, thermal conduction, decay and fusion of waves, cascading effects, non-linear effects. A simplified equation describing the turbulence evolution is (e.g. Eilek 1979)

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

Where I (k, t) is the turbulence source term and $\gamma_i(k)$ is the i_{th} damping rate. In this study, two specific assumptions for I(k, t) are used: an initial injection characterized by I(k, t) = 0 in Eq. (1), and a continuos injection characterized by $I(k, t)=I_0 e^{-i\omega t}$. Here, we only present results with continuous injection, because under the initial injection no effective acceleration is reached in flare and coronal plasmas. From the work of (Braginskii 1965) on damping rates for MHD modes in a plasma with cylindrical geometry we derived the next rates for the fast mode in an isotropic plasma:

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for viscosity, we obtain

$$\gamma_{VIS}^{FAST} = \frac{k\eta_0}{2\rho}\left[\frac{1}{3}+\frac{1.5625}{(\omega_p\tau_p)^2}\right] \tag{2}$$

Where ρ is the mass density, and ω_p and τ_p are the plasma frequency and collision time for protons, respectively. For thermal conduction, we obtained

$$\gamma_{THER}^{FAST} = \frac{KTk^2\chi_{\parallel}}{\rho v_A^2 m_p n} \tag{3}$$

m_p is the proton mass, n the number density, $\chi_{\parallel}$ and $\chi_{\perp}$ the coefficients of parallel and perpendicular conduction, K is Boltzmann's constant and k the wavenumber.

2. Stochastic and effective acceleration time

The time for a particle to increase its energy from $E_0 = E_{ALF}$ up to a suprathermal energy E due to a turbulent spectrum of magnetosonic waves (e.g. Melrose 1986; Miller et al. 1991) can be determined from,

$$t_{Eff} = \int_{E_0}^{E} \{\alpha_F[E', W(t), <k>]\,\beta\}^{-1}\, dE' \tag{4}$$

where $$W(t)= \int_{k_{Min}}^{k_{Max}} \left\{ b_1 \exp[-\sum_{i=1}^{N}\gamma_i(k)t]+b_2 \exp(at)\right\} dk\,, \qquad b_1 = W_0 - b_2\,,$$

$b_2 = I_0[\gamma_i(k) - a]^{-1}$ and W_0 is the turbulence energy at t = 0. Here, $\alpha_F[E, W(t), <k>]$ is the acceleration efficiency of the fast mode. The feasibility of acceleration depends on the dissipation rates. If the characteristic dissipation time is less than the stochastic acceleration time, then there are no accelerated particles. This acceleration feasibility can also be determined if Eqs. (1) and (4) are simultaneously solved. If Eq. (4) is solved considering the dissipation processes involved in α_F then an effective acceleration time (t_{Eff}) is obtained. An analytical solution of this equation, ho ever, is not obvious. So, an iterative method must be used. A positive value of t_{Eff} implies that particles are accelerated by the magnetosonic turbulence, while if $t_{Eff} < 0$, means that waves are damped to the local plasma and not to a select number of resonant particles. Due to the broad spectra of associated photon emissions in solar particle events we assume a thick geometry in the source. To escape from the acceleration volume an accelerated particle must overcome Coulomb collisions and radiative processes. To determine this feasibility, the collision time (t_{coll}), has been calculated using the rate of loss by (Butler and Buckingham 1962). We do not consider here radiative losses. The comparison of the acceleration time with the collision time allows us to infer which particles can escape from the source.

3. Results and discussion.

To obtain the effective acceleration time, the specific forms of γ_{VIS}^{FAST}, γ_{THER}^{FAST} and the characteristic wavenumber $<k> = \int_{kmin}^{kmax} kW(k)W_0^{-1}dk$ (Atcherberg 1981) must be used, and to calculate <k> the most common limits for the turbulence (Miller 1991, Gallegos-Cruz and Pérez-Peraza 1995) were used. To determine the instantaneous energy of the turbulence W(t), values of W_0 in the interval $10^{-3} \le W_0/W_B \le 1$ (where W_B is the magnetic field energy) were used, those values lie between the most used in the literature. In some cases, however, in order to obtain more evident results $W_0 \approx W_B$ was also used. Figure 1 shows curves for effective acceleration times (t_{Eff}), and curves for loss collision times (t_{coll}) for accelerated protons under the physical conditions of a solar flare, $T = 10^7$ K, $n = 5x10^9 cm^{-3}$, B = 100 G (Miller 1991), and $E_0 = 49.6$ KeV. It is important to observe that $E_0 >> E_{Ther} = 1.5$ KT. As it is shown, when $W_0 = 40$ erg cm^{-3} (dashed line) protons are accelerated from E_{Alf} up to energy $E \approx 20$MeV (in this energy range $t_{Eff} < t_{coll}$) before they are returned to the thermal background by Coulomb collisions. In contrast, for $W_0 = 50$ erg/cm^3 (dotted line) $t_{Eff} < t_{coll}$ always, so accelerated protons overcome the Coulomb collision barrier, and they never return to the thermal background. In these two cases, however, the effective acceleration times are always greater than 1s. The curve with $W_0 = 280$ erg cm^{-3} (dash and doted line) shows protons that were accelerated up to energies E > 1GV in times less than 1s. To estimate the number of thermal particles (protons or electrons) susceptible to be accelerated, the distribution function of thermal particles from $E_0 = E_{Alf}$ was used: for this case we obtained $N = 6.8 \times 10^{23}$ protons. Figure 2 to 4 are similar to the previous one, for other physical conditions (out of the flare). Figure 4 corresponds to electrons. The overall analysis of these results for acceleration of thermal protons indicates that in solar flare conditions (Figure 1), turbulence levels $W_0 > 280$ erg cm^{-3} are required to accelerate protons, whereas in surrounding regions to the flare plasma (Figure 2 - 4) the efficiency of the acceleration process is improved to reasonable turbulence levels ($W_0 \approx$ 3.5 erg cm^{-3}). The fundamental problem to accelerate protons by fast magnetosonic turbulence in the flare region, or in its surroundings, concerns the threshold energy, which is $E_{Alf} >> E_{Ther}$, and therefore the number of protons susceptible to be accelerated is very small compared to the number deduced from observational records. In all the cases analyzed it was found that this number is between 8×10^{22} and 4.5×10^{24} protons, whereas the observational records indicate numbers $\le 10^{36}$ for protons and up to 10^{41} electrons (Chupp 1996). The behavior of acceleration of electrons is globally similar to proton acceleration, though the required energy levels are much higher than those expected in the solar corona.

4. Conclusions

- There are physical conditions within the solar corona, where the fast magnetosonic turbulence (in the frequency range $\omega << \Omega_H$) can accelerate protons from a thermal distribution up to energies E > 1GV in times t < 1s. The number of accelerated protons by this process, however, is many orders of magnitude smaller than the number calculated from observational records..
- Accelerating conditions of electrons by fast MHD waves (in the range $\omega << \Omega_H$) from thermal to suprathermal energies can hardly exist in the solar corona, although may be toward the chromosphere. All energized electrons lose their energy through Coulomb collisions near to the mean thermal energy, and the energy obtained from the turbulence goes to plasma heating. This fact is in agreement with previous inferences made by others authors (Miller 1997).

♦ Our quasi-linear analysis, including a threshold injection energy for resonant wave-particle interaction indicates that the number of accelerated particles is much low than the obsevational one. In fact, in a region of volume 10^{27} cm^3 and density 10^{10} cm^{-3} roughly only 1-proton in 10^{14} and 1-electron in 10^{17} could be accelerated. Recent works (Lenter & Miller 1998 and references therein) show that a no-linear analysis including cascade effects ($\omega \rightarrow \Omega_H, \Omega_e$) may explain observations: the injection energy can be negligible and the acceleration efficiency increases: if E_0 can be reduced to values ≤ 1.5 KT, then about half of the 10^{37} local particles would be susceptible of accelerating resonance, in agreement with observations. Also, acceleration efficiencies would be much higher than the values found in this work; $\alpha_F \sim 10^{-7} - 10^{-4}$ s at E_0 evolving to $10^{-2} - 10^{-1}$ s at 1 GeV. We will perform quantitative calulations at this regard and will report elsewhere.

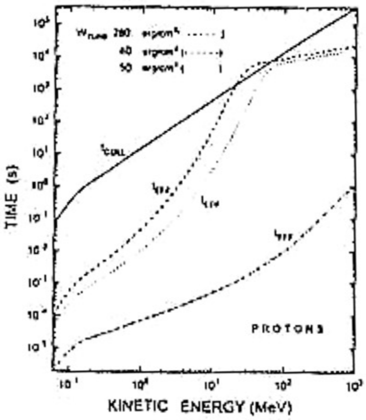

Fig. 1 Time scales for proton acceleration by fast magnetosonic wave mode T=10^7K, n=5×10^9cm^{-3} B=100G, E_0=4.05x10^{-3}MeV, N_0=[illegible] protons

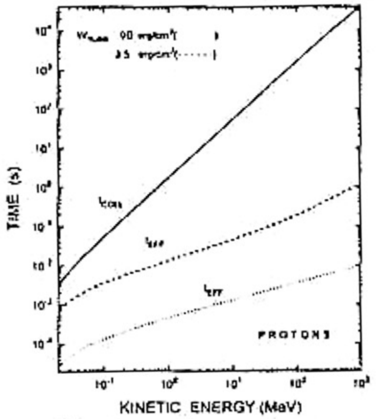

Fig. 3 Time scales for proton acceleration by fast magnetosonic wave mode T=10^6K, n=5×10^{10}cm^{-3}, B=150G, E_0=1.148x10^{-3}MeV, N_0=4.5x[illegible] protons

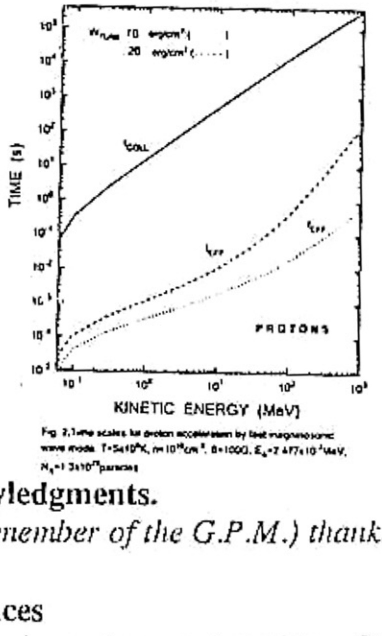

Fig. 2 Time scales for proton acceleration by fast magnetosonic wave mode T=5×10^6K, n=10^{10}cm^{-3}, B=100G, E_0=[illegible]MeV, N_0=[illegible] protons

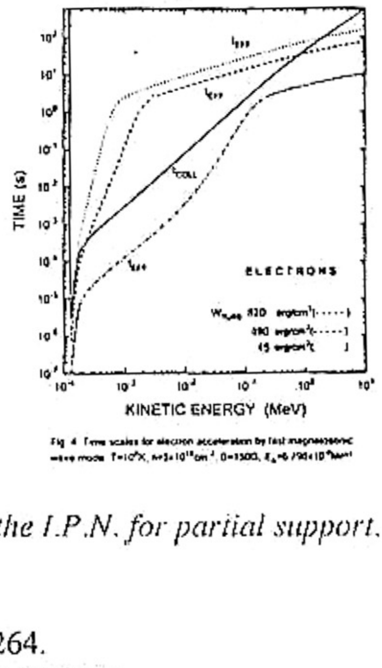

Fig. 4 Time scales for electron acceleration by fast magnetosonic wave mode T=10^6K, n=5×10^{10}cm^{-3}, B=150G, E_0=[illegible]

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