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Acceleration of Solar Particles by Short Wavelenght Turbulence

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Abstract

We analyze the efficiency of acceleration of solar particles by Electrostatic Cyclotron Wave Modes, ECWM, (Bernstein modes) in solar flare plasmas. On basis to the Diffusion Coefficient of particles interacting with a spectrum of ECWM, we show in this preliminar work that particle acceleration efficiency by this kind of turbulence is higher than with other longitudinal waves (Langmuir turbulence), with the advantage that it may be easy to identify potential sources of ECWM through current-driven instabilities confined to narrow filments in the solar atmosphere.

1 Introduction

Particle acceleration by wave-particle scattering is the most well known acceleration process in plasma astrophysics. Depending on the harmonic number s involved in the resonance the acceleration process has been often distinguished with the terms of stochastic, Fermi-type and resonant scattering. Though the way that particle parallell and transversal momentums are affected depend on the resonant interaction at a given s, here we will keep only the term of stochastic acceleration whathever the sth harmonic involved. In general, this kind of processes tend to be more effective the smaller the turbulence scale is, so that high-frequency (HF) turbulence is expected to be more efficiente for accelerating particles. However, HF waves are almost not in resonance with thermal particles, in such a way that their effectivness is rather important for accelerating fast particles. On the other hand, low-frecuency (LF) oscillations resonate with the thermal particles and are therfore strongly damped, contributing rather to the turbulent heating of plasma prticles. This sitution has lead to the reserch of specific wave modes (mainly MHD turbulence) that allows for effective acceleration of solar particles of any energy (for instance [1-3]). In particular the case $\lambda \gg r_g$ (wavelength much higher than the particle gyroradius) has been widely study wthin the frame of the cold plasma approximation. To avoid a strong damping of such modes, the extreme case $\lambda \leq r_g$ could be evocated, however, this leads to aberrantly high injection energies for acceleration, since in fact the situation $\omega \geq \Omega$ (ω = wave frequency, Ω = particle cyclotron frecuency) cannot be adequately studied by the cold plasma model, but must be done within the frame of the warm plasma model [4]. In this schema, the case $\lambda \leq r_g$ leads to the appearance of resonant waves which extreme frequencies correspond to hybrid modes that mix in a continum and to modes which frequencies are close to the particle cyclotron frequencies in the plasma ($\omega \approx s\Omega \gg \mid k_{\parallel} v_{\parallel} \mid$), that propagate either parallely or nearly perpendicularly to the field lines. The later are known as Bernstein modes, [5], and are longitudinally polarized over most of the range of interest, so that they behave as electrostatic waves since $\vec{E} = \vec{\nabla}\Phi$. This mode, herafter designated as ECWM, is mostly generated by instabilities derived from anysotropies in particle distributions, as for instance beams of suprathermal electrons, or whenever a narrowly confined current density exceedes a given threshold to trigger an unstable situation that drives the turbulence. Assuming, that ECWM resonate with plasma particles, at least in some definite velocity-space bands [6], we examinate here the acceleration efficiency of these waves in solar flare plasma.

2 Particle Diffusion by ECWM

Diffusion of particles by isotropic longitudinal turbulence when there is efficient angular dispersion ($v_\perp \gg v_\parallel$) is evaluated through the momentum diffusion coefficient [7,8]

$$D_{pk} = \sum_{s=-\infty}^{\infty} \int \frac{d^3\vec{k}}{(2\pi)^3} W(\vec{k},\vec{p},s) N(\vec{k}) (\Delta p)^2 \tag{1}$$

where $N(\vec{k})$ is the wave occupation number and $W(\vec{k},\vec{p},s)$ is the probability for gyromagnetic emission, [7], that for induced processes may be expressed as

$$W(\vec{k},\vec{p},s) = \frac{2\pi q^2 R(\vec{k})}{\mathcal{E}_o \hbar \mid \omega(\vec{k}) \mid} \left| e^*(\vec{k}) V(\vec{k},\vec{p},s) \right|^2 \delta\left[\omega(\vec{k}) - s\Omega\gamma^{-1} - k_\parallel v_\parallel\right] \tag{2}$$

where $R(\vec{k})$ is the ratio of the energy content in the longitudinal component of the electric field to the total energy wave, and that we approximate here as $R(\vec{k}) \approx V_A^2/2c^2$, ($V_A$ and c are the Alfven and light velocities respectively); $V(\vec{k},\vec{p},s)$ quantifies the effect of consider a finite Larmor radius in the plasma dielectric tensor [4], and in the small gyroradius limit $V(\vec{k},\vec{p},s) \approx \frac{1}{2}v_\perp(1,-is,0)$ with $s = \pm 1$, $\omega(\vec{k})$ is the wave dispersion relation, e^* is the conjugate complex of the wave polarization vector, which in this case may be approximated as $e^* \simeq (\omega \Omega_p^{-1}, -i, 0)$, Ω_p is the proton gyrofrenquency and $\Delta p = \hbar\omega(\vec{k})/v$ in a polar spheric geometry. Setting $s = 1$ (since $s = -1$ does not contribute), $\omega \approx s\Omega \gg \mid k_\parallel v_\parallel \mid$ and $\sin\alpha = v_\perp/v$. Hence eq. (1) for the case of diffusion of electrons by the Bernstein mode becomes

$$D_{B,e} = \frac{\omega_p^2 V_a^2 p + \sin^2\alpha}{8\mathcal{E}_o c^2 v} \int \frac{d^3\vec{k}}{(2\pi)^3} \mathcal{W}(\vec{k}) \left(1 + \frac{\Omega_e}{\gamma\Omega_p}\right)^2 \tag{3}$$

$$= \left[\frac{\omega_p^2 V_A^2 (M/m)^2}{96\pi^3 \mathcal{E}_o c^3 n} \int k^2 \mathcal{W}(\vec{k}) d\vec{k}\right] \left(1-\beta^2\right) p/\beta = \mathcal{D}\left(1-\beta^2\right) p/\beta \tag{4}$$

where $\mathcal{W}(\vec{k})$ is the frequency spectrum of the turbulence which appears from the occupation number, M and m are the proton and electron mass respectively, n is the electron plasma density, ω_p is the plasma frequency, Ω_e is the electron gyrofrequency and $\mathcal{E}_o = 1$ is the permitivity. The equivalent expression for protons may be obtained from [4] as

$$D_{B,p} = \left[\frac{\omega_p^2 V_A^2}{96\pi^3 c^3 n} \int k^2 \mathcal{W}(\vec{k}) d\vec{k}\right] \frac{p}{\beta\left[1 + (1-\beta^2)^{-1/2}\right]^2} = \mathcal{D} \cdot \frac{p}{\beta\left[1 + (1-\beta^2)^{-1/2}\right]^2} \tag{5}$$

Now, in order to compare the diffusion efficiency of ECWM with other longitudinal turbulence, let us consider Langmuir waves, which diffusion coefficient according to [7,8] is

$$D_L = \left(2\pi^2 e^2 \omega_p^2 / c^3 \mathcal{K}_L^3 \beta^3\right) W_L \tag{6}$$

where W_L is the energy density of the Langmuir turbulence, $\vec{\mathcal{K}}_L$ is the characteristic wave vector for this turbulence and e is the electron charge. Bringing about the ratio of the Langmuir diffusion coefficient to the Bernstein (ECWM) diffusion coefficients we obtain for electrons,

$$R_1 = \frac{D_L}{D_{B,e}} = \frac{192\pi^5 e^2 (M/m)^2 n}{V_A^2 \mathcal{K}_B^2 \mathcal{K}_L^3} \cdot \frac{W_L}{W_B} \cdot \left[\beta^2 \left(1-\beta^2\right) p\right]^{-1} \tag{7}$$

where $W_B = \int \mathcal{W}(\vec{k}) d^3\vec{k}$ is the energy density of the ECWM. Similarly for protons we obtain

$$R_2 = \frac{D_L}{D_{B,p}} = \frac{192\pi^5 e^2 n}{V_A^2 \mathcal{K}_B^2 \mathcal{K}_L^3} \cdot \frac{W_L}{W_B} \cdot \left[1 + \left(1-\beta^2\right)^{-1/2}\right] \left(\beta^2 p\right)^{-1} \tag{8}$$

For evaluation of the characteristic vectors $\vec{\mathcal{K}}_B$ and $\vec{\mathcal{K}}_L$ we assume that the wavelength $\lambda_B \approx r_g$, so that $\mathcal{K}_B = 2\pi/\lambda_B = 2\pi e B/E$ (E is the total energy of particles); hence, for thermal electrons ($\beta_T = 5.64 \times 10^{-2}$), $\mathcal{K}_B \approx 0.1\ cm^{-1}$ and for $E \approx 11\ MeV$ ($\beta = 0.999$), $\mathcal{K}_B \approx 5 \times 10^{-2}\ cm^{-1}$, so that we can consider a mean value $\overline{\mathcal{K}_B} \approx 7.5 \times 10^{-2}\ cm^{-1}$. For Langmuir waves the range goes from $\mathcal{K}_L \sim 1/\lambda_d$ up to $\mathcal{K}_L \ll \lambda_d$, so that $\overline{\mathcal{K}_L} \approx 0.1\ cm^{-1}$. Under the assumption that $W_L \simeq W_B$ we obtain

$$R_1 = 3.95 \times 10^{-23} \left[\beta^2 \left(1-\beta^2\right) p\right]^{-1} \tag{9}$$

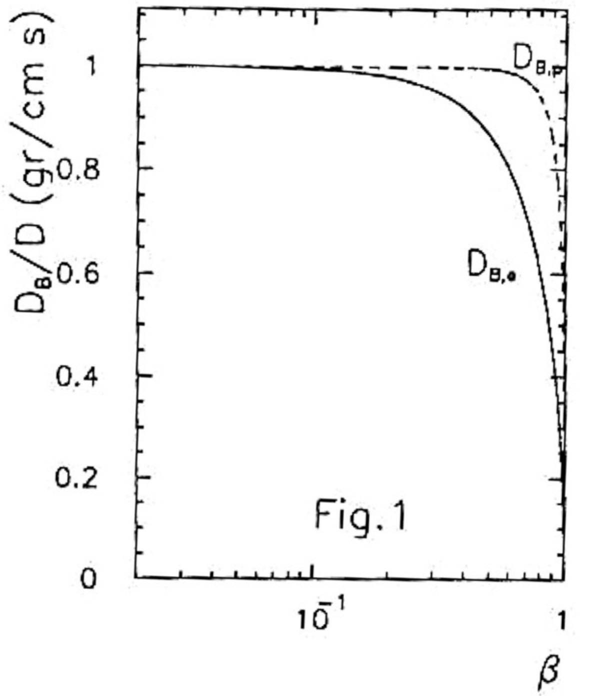
For protons the range of energy considered is from thermal energy up to 1 GeV, $\overline{\mathcal{K}_B} \approx 2 \times 10^{-4}\ cm^{-1}$, so that following the same procedure we obtain

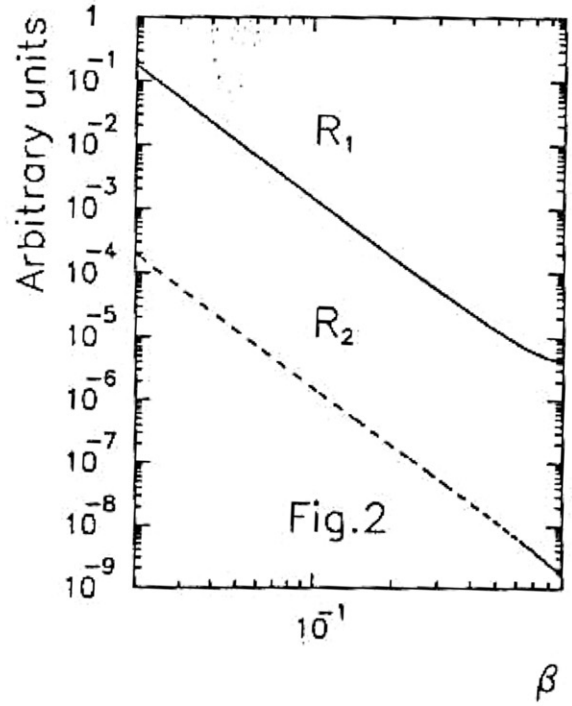
$$R_2 = 1.33 \times 10^{-16} \left[1 + \left(1-\beta^2\right)^{-1/2}\right] \left(\beta^2 p\right)^{-1} \tag{10}$$

3 Results and Conclusions

On figs.1 & 2 we plotted the ECWM diffusion coefficients and the ratio of the diffusion coefficient of Langmuir to ECWM turbulence versus particle velocity respectively, for both electrons and protons under typical solar flare plasma conditions: $n = 5 \times 10^9\ cm^{-3}$, $B = 100\ G$ and $T = 10^7\ K$. From these plots it can be seen that whenever $W_B \approx W_L$ it is obtained $D_B \gg D_L$ in most of the energy range of solar particles, except at ultrarelativistic energies ($\beta \approx 1$), because there is an inversion in R_1 when $\left[\beta^2 \left(1-\beta^2\right) p\right]^{-1}$ reaches its maximum. Since the acceleration efficiency of stochastic acceleration processes depends directly on the Diffusion Coefficient (which contains the dynamics of the particle-wave interaction) it can be infered that turbulence of the kind of ECWM may become highly efficient for acceleration of solar flare particles, mainly in the low energy domain, provided that such a turbulence resonates with solar flare particles. **A deep study must be done to prove that such a resonance is established under flare plasma conditions.**

Figure 1: *Eqs.(4) and (5) normalized to unity showing that acceleration efficiency is higher at low energies, braking down at high energies.*
Figure 2: *Eqs.(9) and (10) showing that acceleration efficiency with ECWM is much higher than with Langmuir waves (this predominance increases with particle energy).*





In view of these preliminar results, and on basis of the results reported in [6] indicating that ion Bernstein waves absorb in a preferntial form some pre-selected resonant ion species, we conclude that ECWM offer promising perspectives for the study of both, electron and ion acceleration from low energies, in a selective manner and with a relatively high efficiency.

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