The Role of Alpha Particles in the Emission of Plasma Waves Inside Solar Ejecta

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The enhancement of the resonant instability of right-hand polarized electromagnetic ion cyclotron waves by alpha particles for physical parameters corresponding to coronal mass ejections is studied. We focus on the effects of alpha thermal anisotropy and relative He^{++}/H^+ abundance on growth and absorption rates. The first parameter governs directly wave emission, while the second modifies also the wave speed and indirectly enhances the wave excitation.

I Introduction

Solar ejecta (also coronal mass ejections, CMEs) are a heterogeneous set of objects with the following plasma properties: (i) low proton plasma beta (see [1] and references therein), (ii) bidirectional streaming (along field lines) of suprathermal electron heat fluxes (few hundreds of eV)[2] and energetic protons ($\sim$ 1 MeV)[3], (iii) a variable n_α/n_p relative proton-to-alpha particle density which may be much higher than the average solar wind value of $\sim$ 4%[4, 5], and (iv) a thermal anisotropy ($A = T_\parallel/T_\perp - 1$) which is often negative i.e., $T_\parallel > T_\perp$, for both protons and electrons (see Richardson et al., 1997[6] and references therein). The last two properties may hold only in parts of the ejecta. Although physical parameters of CMEs evolve as they propagate away from the sun, they change little on a timescale of several hours. The excitation of right-hand polarized electromagnetic ion cyclotron waves (EICWs) depends sensitively on a number of parameters: the proton beta ($\beta_p = 8\pi n T_p/B^2$), the alpha-proton temperature ratio (T_α/T_p), the alpha-proton density ratio ($\eta_\alpha = n_\alpha/n_p$), the thermal anisotropy of each specie ($A_p = T_{\parallel,p}/T_{\perp,p} - 1$, for protons, with similar definitions for alpha particles and electrons), and the electron-proton temperature ratio (T_e/T_p).

The possibility of right-hand polarized wave activity in CMEs due to the negative proton anisotropy was studied in Farrugia et al., 1998 [7], Gratton et al., 1998 [8], Dasso et al., 1999 [9], Dasso et al., 2000 [10], and Dasso et al., 2001 [11]. Here, we focus on the influence of A_α and η_α on the growth (and absorption) rates of the waves. The former is a little known parameter not yet routinely measured in CMEs. However, on the basis of magnetic moment conservation in an expanding magnetic field, we expect that all particle species will develop a negative thermal anisotropy. Thus, it seems plausible that A_α will have the same sign of A_p, i.e., negative in most solar ejecta. The excitation of right-hand polarized EICWs is due to anomalous Cherenkov emission, and relies on a small number of ions (in the Maxwellian tail) that resonate with the wave[12]. As we shall show, there are frequency ranges where emission overcomes absorption for negative anisotropy. Thus, a negative A_α, and η_α, contribute directly to the growth rate. However, the effect of η_α is mostly indirect: adding α increases the inertia of the plasma and thereby reduces the phase velocity of the wave. Thus, more ions (protons and alphas) are brought into resonance. This leads to a considerable enhancement of EICW activity in helium-rich plasmas with respect to low η_α configurations.

II Dispersion Relation

The instability of right-hand polarized EICWs propagating parallel to the magnetic field is described by the kinetic dispersion relation (see, for example [13]),

$$k^2 c^2 = \omega^2 + \sum_s \omega_{ps}^2 \left[A + \frac{(A+1)\omega + A\Omega}{k w_\parallel} Z\left(\frac{\omega + \Omega}{k w_\parallel}\right) \right]_s , \qquad (1)$$

(summed over species indexed by s = electrons, protons, and alphas; angular frequency ω [$\omega = \omega_r + i\gamma$]; wavenumber parallel to the ambient field k; cyclotron frequency Ω; plasma Zeta function Z). In (1), all species are modelled by biMaxwellian distribution functions. Here, ω_{ps} is the plasma frequency; $w_\parallel = \sqrt{2T_\parallel/m}$, is the thermal speed (temperature in energy units and m is the mass of the particle); and c is the speed of light. Wave quantities vary as $\exp[i(kz - \omega t)]$, where the z axis is aligned with the magnetic field.

In the following, frequencies and growth rates are normalized to the proton cyclotron frequency $x = \omega/\Omega$, where $\Omega = eB_0/m_p c$ (B_0 is the background magnetic field intensity); and the normalized wavenumber $y = kv_a/\Omega$, where $v_a = B_0/\sqrt{4\pi n_p m_p}$ is the proton Alfvén velocity. For a plasma composed of protons, alphas, and electrons, Eq. (1) can be written as

$$y^2 = A_p + \frac{A_p(x+1) + x}{y\beta_{\parallel,p}^{1/2}} Z\left(\frac{x+1}{y\beta_{\parallel,p}^{1/2}}\right) + \eta_\alpha A_\alpha + \eta_\alpha \frac{A_\alpha(x+1/2) + x}{y\beta_{\parallel,\alpha}^{1/2}} Z\left(\frac{x+1/2}{y\beta_{\parallel,\alpha}^{1/2}}\right)$$

$$+ A_e \eta_e \mu^{-1} + \eta_e^{3/2} \mu^{-1/2} \frac{A_e(x - \mu^{-1}) + x}{y\beta_{\parallel,e}^{1/2}} Z\left(\frac{x - \mu^{-1}}{y\beta_{\parallel,e}^{1/2}} \eta_e^{1/2} \mu^{1/2}\right) . \qquad (2)$$

The following parameters $\beta_{\parallel,p} = 8\pi n_p T_{\parallel,p}/B_0^2$, $\beta_{\parallel,\alpha} = (8\pi n_p T_{\parallel,\alpha}/B_0^2)(m_p/m_\alpha)$, and $\beta_{\parallel,e} = 8\pi n_e T_{\parallel,e}/B_0^2$, $\mu = m_e/m_p$, and $\eta_e = n_e/n_p$ have been introduced. We solve the dispersion relation numerically using an inhouse code for the Z function. Parameters are obtained from statistical surveys[2, 6] and other case studies. From the roots of the dispersion relation, we obtain the complex dimensionless frequency $x = x_r + ig$, as a function of the wavenumber y.

III Results

The parameter n_α/n_p in CMEs is highly variable[2, 6], with n_α/n_p ranging from very small to values as high as $\sim 15 - 20\%$[5]. We consider variations of A_α around moderate A_p values, chosen here in the range $T_\parallel/T_\perp = 2 - 3$. Results of alpha particle effects on the growth and absorption rates of the EICW instability are presented in figures 1-4. Fig. 1 shows from top to bottom the absorption and emission ranges, and the phase speed, all shown as a function of η_α, which parametrizes the various curves. We show results for $\eta_\alpha = 0$, $\eta_\alpha = 0.04$, $\eta_\alpha = 0.08$, and $\eta_\alpha = 0.15$. The electrons are isotropic, $A_e = 0$. The other parameters are $A_p = A_\alpha = -0.67$, $\beta_p = 0.4$, and $T_\alpha/T_p = 4$. An in-crease in η_α increases growth rates and shifts the active range to lower frequency. When $\eta_\alpha = 0.15$, the maximum value of the growth rate is $\gamma/\Omega = 8\mathrm{x}10^{-4}$ which occurs for $\omega/\Omega = 0.56$. This corresponds to an e-folding time (τ) of 15 minutes for a 15 nT magnetic field. Since typical CMEs evolution times are many hours, this τ value is sufficiently short to allow the instability to develop.

When the absolute value of the alpha particle thermal anisotropy is increased with respect to the case $A_\alpha = A_p$, an enhacement of growth rates and a broadening of the emission range ensues. In fact, an increment of the parallel temperature of the alpha particles, keeping the average temperature ($T_\alpha/T_p = 4$) constant, increases $\beta_{\parallel,\alpha}$, which in turn augments the instability. This effect can be observed in the Fig. 2, where we vary A_α ($= -0.5, -0.58, -0.67, -0.75$) while keeping other parameters fixed at $A_p = -0.67$, $\beta_p = 0.4$, $T_\alpha/T_p = 4$, $\eta_\alpha = 0.15$. Again $A_e = 0$. For $A_\alpha = -0.75$, the maximum growth rate is $g = 2\mathrm{x}10^{-3}$, and the unstable x_r interval extends from ~ 0.2 to ~ 1.8. Conversely, when A_α/A_p is smaller than 1, the active range is reduced and the low-frequency cut-off of the absorption is shifted to lower frequencies. For example, when A_α/A_p decreases by $\sim 14\%$, from $A_\alpha/A_p = 1$ to $A_\alpha/A_p = 0.86$, the beginning of the absorption range is

shifted to $x_r \sim 0.9$. At $x_r = 1$, we find instability with a growth rate $g = 3.5 \times 10^{-4}$ when $A_\alpha = A_p = -0.67$. When $A_\alpha = -0.58$, at the same frequency we find absorption instead, with damping rate $-g = 5 \times 10^{-5}$.
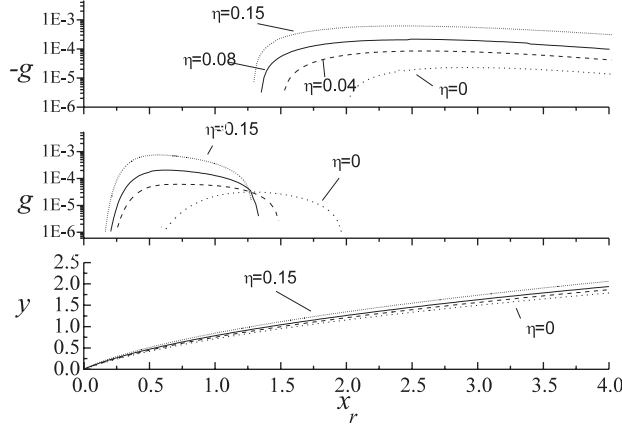

Figure 1. Dimensionless damping rate $-g$, growth rate g and wavenumber y versus dimensionless frequency x_r for right-hand polarized EICWs. Dependence on η_α (with $A_p = A_\alpha = -0.67$, $\beta_p = 0.4$, $T_\alpha/T_p = 4$, and $A_e = 0$ constants).
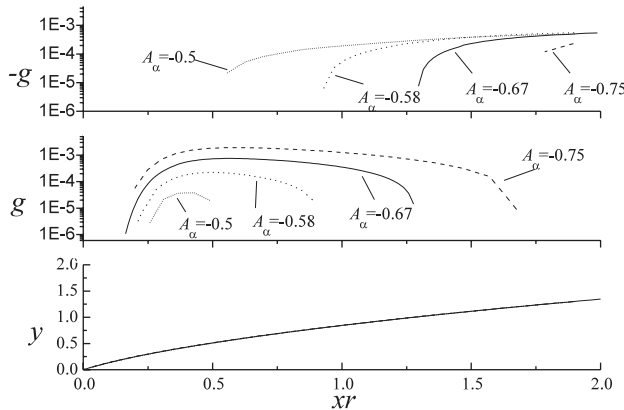

Figure 2. Same as Fig. 1 but showing on A_α (with $A_p = -0.67$, $\beta_p = 0.4$, $T_\alpha/T_p = 4$, $\eta_\alpha = 0.15$, $T_e = T_p$, and $A_e = 0$ constants).

We include the contribution of anisotropic electrons in figures 3 and 4. Fig. 3 shows a case in which the instability is eliminated (and we obtain absorption instead) when A_α goes from $A_\alpha = -0.5 (= A_p)$ to $A_\alpha = -0.4$ keeping $A_p = -0.5$, $\beta_p = 0.4$, $T_\alpha/T_p = 4$, $\eta_\alpha = 0.08$, $T_e = T_p$, and $A_e = -0.5$ constant.
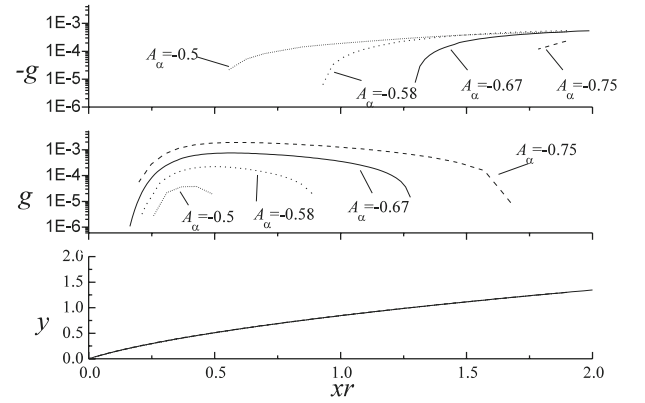

Figure 3. Same as Figure 2, with $A_p = -0.5$, $\beta_p = 0.4$, $T_\alpha/T_p = 4$, $\eta_\alpha = 0.08$, $T_e = T_p$, $A_e = A_p$ constants.

Somewhat larger absolute values of anisotropies are considered in Fig. 4. Here, we choose $A_\alpha = -0.4, -0.5, -0.67, -0.75$, for a configuration with $A_p = -0.67$, $\beta_p = 0.4$, $T_\alpha/T_p = 4$, $\eta_\alpha = 0.08$, $T_e = T_p$, and $A_e = -0.67$. A gap in the unstable range (second panel) is formed when $A_\alpha = -0.4$. In this gap an absorption band appears.
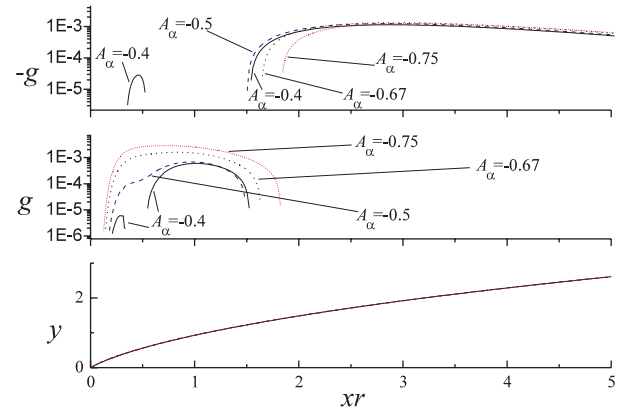

Figure 4. Same as Figure 2, with $A_p = -0.67$, $\beta_p = 0.4$, $T_\alpha/T_p = 4$, $\eta_\alpha = 0.08$, $T_e = T_p$, $A_e = A_p$ constants.

IV Conclusions

Summarizing, we examined the effect of variations in thermal anisotropy and abundance of alpha particles on the growth and absorption rates of EICWs in parameter regimes typical of many CMEs. Increasing n_α/n_p and/or the alpha-to-proton anisotropy ratio produce enhancements of growth and absorption rates. An increment of n_α/n_p also shifts the active range to lower frequencies. When the ratio of alpha-to-proton thermal anisotropy increases, an absorption band may appear between two unstable ranges. To advance studies like the one reported here, it would be desirable to measure the alpha particle thermal anisotropy routinely in CMEs, since as we have shown the right-hand polarized EICW instability is very sensitive to this parameter.

The alpha abundance also influences the growth rate by its effect on the phase velocity of the waves. These properties may help to explain the spectrum of low frequency fluctuations seen in many CMEs by WIND at 1 AU [14].

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