ELECTRON AND ALPHA PARTICLE INFLUENCE ON THE EXCITATION OF RIGHT HAND POLARISED ION CYCLOTRON WAVES IN SOLAR EJECTA

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Abstract

The resonant instability of right hand polarized (RHP) electromagnetic ion cyclotron waves (EICW) is studied for physical parameters of coronal mass ejections (CME), which are low proton beta, β_p, plasmas. Resonant excitation of RHP waves relies on negative ion thermal anisotropy, $A < 0$, ($A=T_\perp/T_{//}$ -1), and normally requires high β_p. We show that important enhancements of the instability are produced by two parameters, the product $|\beta_{//,e} A_e| \sim 1$ for $A_e < 0$, and high α/H^+ abundance. Although variable in the same ejecta these features are often observed in CMEs and may lead to e-folding times of a few minutes. The EICW dispersion relation is based on bi-Maxwellians for all particle species and is solved numerically. Growth and absorption rates for relevant parameter sets are presented. RHP EICW emission in $\beta_p \sim 0.1$ CMEs is found possible. This instability may help to explain the spectrum of low frequency fluctuations seen in many CMEs by WIND at 1 AU.

1. Physical effects and theory

Intense magnetic field fluctuations are being seen by WIND at 1 AU [1] at frequencies below the proton cyclotron frequency (~ 0.25 Hz in a 15 nT field). In a pilot work [2], we have examined the possibility that right hand polarized (RHP), resonant, electromagnetic ion cyclotron waves (EICW) are excited in solar ejecta with negative proton thermal anisotropy, $A_p = (T_{\perp,p}/T_{//,p})$-1. In a proton - electron plasma the instability ordinarily requires proton beta, $\beta_p \sim 0.1$ (or larger), but we found that a high α/H^+ abundance, together with $A_p = A_\alpha < 0$, lead to significant e-folding times in a number of coronal mass ejections (CME) with average β_p around 0.4. Here, however, we show that growth rate, γ, enhancements of these waves by factors of 10 to 10^3 can be produced by electron thermal properties, not included in the previous theory. Namely: (i) electron temperatures much larger than proton temperatures, $T_e >> T_p$; and (ii) negative electron thermal anisotropy, $A_e < 0$. These features are observed in many CMEs. CMEs form a heterogeneous collection of objects: individual members may have different values of, e.g., density ratio $\eta = n_\alpha / n_{H+}$, A_p, A_e, $\beta_{//,e} = (w_{//,e}/v_a)^2 (1+2\eta)(m_e/m_p)$, (parallel thermal speed $w_{//} = (2T_{//}/m)^{½}$; proton Alfven speed $v_a = B/(4\pi\, n_{H+}\, m_p)^{½}$, $\beta_{//,p} = (w_{//,p}/v_a)^2$, $\beta_{//,\alpha} = (w_{//,\alpha}/v_a)^2 (m_\alpha/m_p)$, etc.. These parameters may also vary within the same ejecta. We take sets of parameter values from statistical surveys ([3, 4]) and case studies, and solve numerically the EICW kinetic dispersion relation:

$$k^2c^2 = \omega^2 + \sum_s \omega_{ps}^2 \left[A + \frac{(A+1)\omega + A\Omega}{kw_{//}} Z_0\left(\frac{\omega+\Omega}{kw_{//}}\right) \right]_s , \qquad (1)$$

(summed over species index s = electrons, protons, and alphas; angular frequency $\omega = \omega_r + i\gamma$; wavenumber // to the ambient field k; cyclotron frequency Ω; plasma Zeta function Z_0; see [5]). In 1 each species is modeled with Bi-Maxwellian distribution functions. We focus attention on the product $|\beta_{//,e}\, A_e|$ (for $A_e < 0$), and α/H^+, whose effects on growth rates are large. Whilst A_p, A_α contribute directly to EICW growth rates, parameters $|\beta_{//,e}\, A_e|$ and α/H^+ have an indirect effect. By slowing down the wave, they bring more ions into resonance by the anomalous Doppler effect: $\omega_r - k\, v_{//} = -\,\Omega$ [6].

2. Main results on RHP wave emission - absorption

Results in figures 1-4 are in dimensionless variables: $x_r = \omega_r/\Omega_p$, $g = \gamma/\Omega_p$, $v_{//}$ is in units of v_a, and $y = k\, v_a / \Omega_p$. We first present the alpha effect alone, without electron anisotropy. Figure 1 shows the effect of increasing η in steps from 0 to 0.15, for A_e=0, giving dimensionless damping rate, $-g$, growth rate, g, and wavenumber, y, as functions of dimensionless frequency x_r, for RHP waves (with average β_p=0.4, T_α/T_p=4, $A_p = A_\alpha$=-2/3, fixed). At fixed x_r, there are small decreases of phase velocity that lead to larger g as η increases, together with shifts of the maximum growth rate to smaller frequencies. We next show the stronger effect due to electron anisotropy and temperature, with an example at smaller β_p=0.2, in Fig. 2. Here, A_e=-1/2 and T_e/T_p varies from 1 to 8, while T_α/T_p=4, $A_p = A_\alpha$=-3/4, η=0.08 are constant.

We note a considerable slowing down of the wave speed and a correspondingly large increment in g (up to 0.015). When compared with Fig. 1, substantial growth rates extend over a wide frequency range, and reach down to lower frequencies. The origin of this effect is illustrated in Fig. 3, where the change of the resonant velocity of the αs, v_{res}, is shown vs x_r, for the same parameter set of Fig. 2, as T_e/T_p varies. When T_e/T_p increases from 1 to 8, the minimum of v_{res} is lowered by a factor ~ 2, which implies a ~ 50-fold increase in the bi-Maxwellian for $v_{//,\alpha} = v_{res}$, so that many more ions can resonate. Protons undergo a similar effect. A calculation with β_p=0.1, T_e/T_p=10, A_e=-2/3, T_α/T_p=4, A_p=A_α=-9/10, and η=0.08 gives maximum $g \sim 3 \times 10^{-3}$, i.e., still a significant growth rate for CME conditions. Thus, EICW excitation may be found also for low β_p ~ 0.1, thus encompassing more CMEs. Finally, we present the electron thermal anisotropy effect in Fig. 4, where A_e changes from 0 to -0.86. Here β_p=0.08, β_e=0.8 (i.e., T_e/T_p=7.7), T_α/T_p=4, A_p=A_α=-0.86, and η=0.15 are fixed. For A_e=-0.86, g reaches the 0.01 range, although β_p is as low as 0.08. The absorption is shifted to very high frequencies, x_r>5. The growth rate is a strongly nonlinear function of A_e. As A_e changes from 0.67 to 0.86, g increases by about three orders of magnitude and the instability range is more than doubled. In summary, these effects may help explain the spectrum of low frequency fluctuations seen in many CMEs by WIND at 1 AU.

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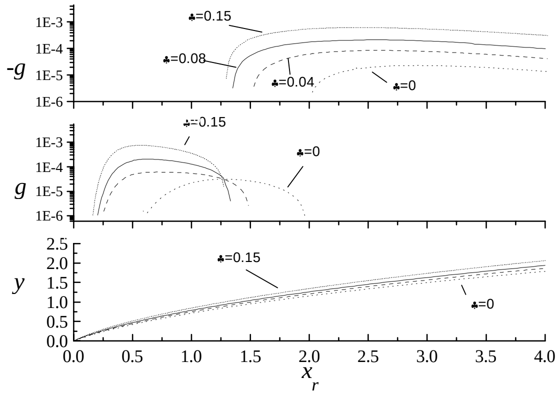

Fig. 1. Dimensionless damping rate -g, growth rate g and wavenumber y vs dimensionless frequency x_r for RHP waves. Dependence on alpha particle properties: variations of η (with A_p=A_α=-2/3, β_p=0.4, T_α/T_p=4 constants).

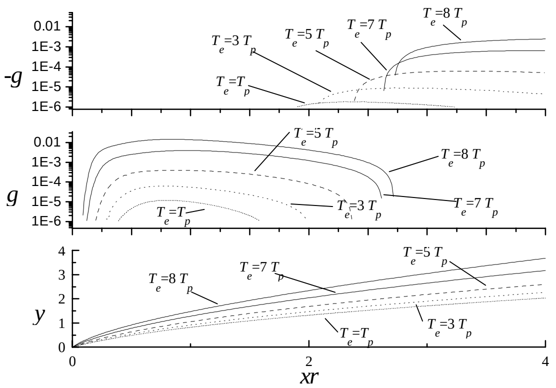

Fig. 2. Similar to Fig. 1 but showing dependence on T_e/T_p: variations of T_e (with A_p=A_α=-3/4, A_e=-1/2, β_p=0.2, T_α/T_p=4, η=0.15 constants).

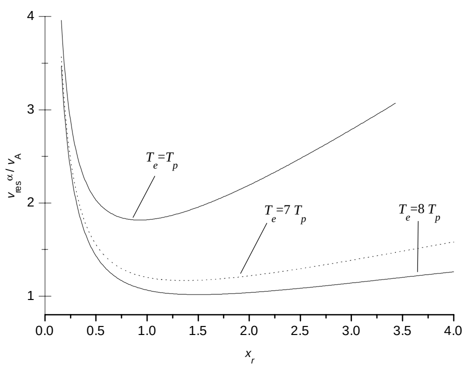

Fig. 3. v_{res}/v_a as a function of x_r. Dependence of v_{res} on T_e/T_p. Same constant parameter set as in Fig. 2.

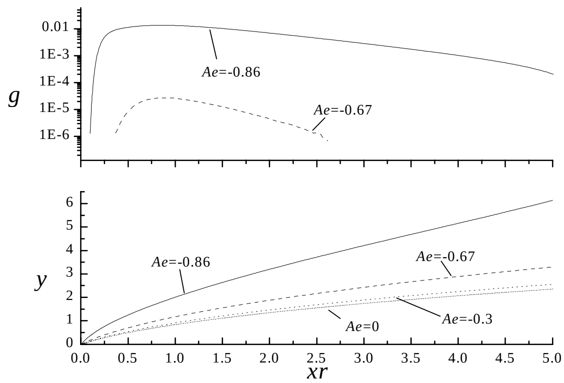

Fig. 4. Similar to Fig. 1 but showing electron thermal anisotropy effect (with A_p=A_α=-0.86, β_p=0.08, β_e=0.8, T_α/T_p=4, η=0.15 constants).