The Influence of Proton Thermal Properties on Electromagnetic Ion Cyclotron Wave Activity in Solar Ejecta

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Abstract. The possibility of exciting electromagnetic ion cyclotron waves in solar ejecta was proposed in earlier work (Farrugia et al., *JGR* **103**, 6543-6550 (1998)). Here we focus on the twofold aspect of the effect of the protons on this instability, specifically, the proton thermal anisotropy, $A_p=T_{\perp,p}/T_{//,p}-1$, and the non-Maxwellian tail representing bidirectionally streaming energetic protons (BPs), which are often observed in solar ejecta. Parameters expected to represent a number of solar ejecta are chosen and kept fixed. We solve the kinetic dispersion relation for a population of protons, electrons, and alpha particles. While A_p does not affect the phase speed of the waves, increasing $|A_p|$ leads to a substantial enhancement of growth rates and a widening of the unstable frequency range. Maximum growth rates increase exponentially with $|A_p|$. The BPs are modeled by a κappa distribution along the field in addition to the bi-Maxwellian describing the rest of the population. A linear relation exists between maximum growth rates and the density ratio of κappa proton to Maxwellian protons (η_κ). Saturation of the width of the unstable frequency range occurs around η_κ~10%.

INTRODUCTION

The possibility that right-handed electromagnetic ion cyclotron waves (RH-EICW) can be excited in some solar ejecta (or, coronal mass ejections, CMEs) was broached in a recent work (1). As observational basis, results from a statistical study of CMEs observed by ISEE 3 during a 13-month period when the spacecraft was near the L1 Lagrangian point, and from case studies, were taken in (1). The parameters of interest are several: proton, alpha particle, and electron thermal anisotropies ($A_p=T_{\perp,p}/T_{//,p}-1$, and similar for α's and electrons); the proton plasma beta corresponding to the group of bi-Maxwellians protons ($\beta_p = 8\pi\ n_p\ T_p\ /\ B^2$); α-to-proton relative density ($\eta_\alpha=n_\alpha/n_p$); α-to-proton temperature ratio (T_α/T_p); and electron-to-proton temperature ratio (T_e/T_p). The waves are expected to be right-handed because A_p and A_e are negative in the majority of CMEs (2). We shall assume A_α<0 also.

The large effect that α particles have on the EICW instability, in a parameter range representative of a number of solar ejecta, was shown in further work (3). It was found that while A_α influences the wave emission directly, increasing η_α increases wave growth by lowering the wave speed, thereby allowing more particles to resonate. The effect of electron thermal properties was studied in (4). The presence of electrons with A_e<0 slows down the wave speed considerably, so that more ions can be near the anomalous resonance velocity.

In this work, we concentrate on the effect of the protons. We study the effect on wave growth through (a) their thermal anisotropy, A_p; and (b) the high energy component moving along the magnetic field. With regard to (b), we note that bidirectional streaming of energetic (several keV - 1 MeV) protons have often been observed in solar ejecta (e.g., (5) and (6)). We shall find that both (a) and (b) make a significant contribution to RH-EICW emission.

EFFECT OF A_p

We study first variations of A_p. We consider a plasma composed of protons, alpha particles and electrons, each species being modeled by a Bi-Maxwellian. For this study, the choice of the other, fixed parameters are the follows: β_p=0.4, η_α=0.08, T_α/T_p=4, and A_e=0. Note that T_e/T_p is not a relevant parameter when A_e=0 (4). Certainly, not all CMEs will have these properties; they vary widely from one

CME to the other and even within the same CME. Thus η_α may vary from ~ 0 to more than 20%, and β_p may be as low as 0.01 and as high as 1 and above. Lowering η_α and/or T_α/T_p makes the effect on EICW generation less strong, and vice versa. As noted, A_e<0 favours instability, but here we take A_e=0.

We solve numerically the dispersion relation of the waves for parallel propagation with respect to the ambient magnetic field, as given in (1),

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

where $y=k\ v_A/\Omega_p$, $x=\omega/\Omega_p$ (v_A: proton Alfvén velocity; Ω_p: proton cyclotron frequency; $\beta_{//,p}$, $\beta_{//,\alpha}$: parallel proton and alpha beta, respectively). Here ω and k are the (complex) frequency and (real) wavenumber of the wave, respectively; z is the plasma Zeta Function.

Figure 1 shows the result of the calculation. In the present computations, we have taken the little studied alpha particle thermal anisotropy A_α=A_p.

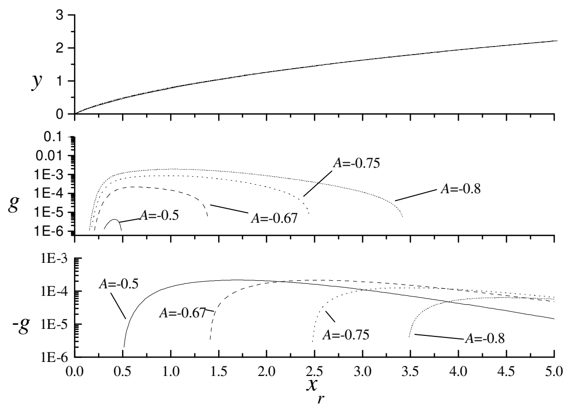

FIGURE 1. Dimensionless wavenumber y, growth rate g, and damping rate $-g$ versus dimensionless frequency x_r for right-hand polarized EICWs. Dependence on A=A_p=A_α (with β_p=0.4, T_α/T_p=4, η_α=0.08, and A_e=0 constants).

However, we quote below also results for fixed A_α=-0.67 (i.e., $T_{//,\alpha}/T_{\perp,\alpha}$=3). The panels of Fig. 1 show from top to bottom the wavenumber y (in units of Ω_p $(4\pi\ n_p\ m_p)^{1/2}/B_0$, i.e., ratio of proton cyclotron frequency to proton Alfven velocity) versus the real frequency x_r (in units of Ω_p), whose slope gives the wave speed. The last two panels show the growth rate, g, and damping rate, $-g$ (both in units of Ω_p) versus x_r. We computed for 4 values of A_p=-0.5, -0.67, -0.75, -0.8, corresponding to $T_{//,p}/T_{\perp,p}$=2,3,4,5. The first panel shows that A_p has no significant effect on the wave speed. Increasing $|A_p|$, however, has a substantial effect on the growth rate: not only is g raised by two orders of magnitude as A_p decreases from -0.5 to -0.8; the unstable frequency band increases by a factor of ~20.
Furthermore, the lower frequency cut-off shifts slowly towards lower frequencies. To give a concrete example, consider a magnetic field strength typical of CMEs (15*nT*). The maximum growth rates shown in figure 1 correspond to instability e-folding times of 46 hours, 54 minutes, 14 minutes, and 6 minutes for A_p=-0.5, -0.67, -0.75, -0.8, respectively. While CME parameters would evolve considerably during 46 hours, little change is expected for the other cases. We find further that the maximum growth rate increases exponentially with $|A_p|$ (Figure 2).

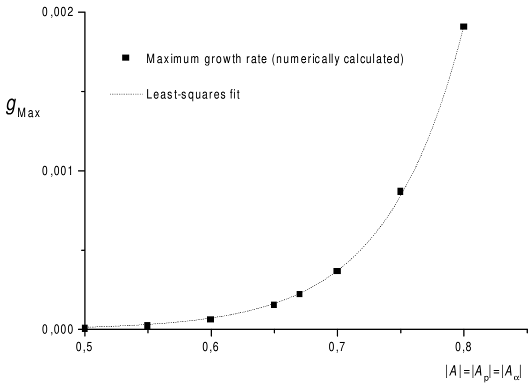

FIGURE 2. The maximum growth rate increases exponentially with $|A_p|$. g_{Max} $(|A_p|) = a \exp\{b\ |A_p|\}$. With a least-squares fit, we obtained the following values corresponding to the cases of Fig. 1: a=3.9x10^{-9} and b=16.4.

The third panel shows that beyond the upper cutoff of the unstable frequency band, wave damping occurs which reaches a shallow maximum before decreasing. Results for A_α=-0.67 (all other parameters being kept the same) [not shown] indicate basically similar behaviour except for the growth rate curve for the lowest $|A_p|$, where g now reaches a maximum value of >10^{-4} and the unstable range extends from 0.2 to 1. Furthermore, the lower frequency cut-offs for different A_p now practically coincide.

EFFECT OF KAPPA PROTONS

To study the effects of bidirectional streaming of energetic protons (BPs) on the waves, we consider an additional component of non-Maxwellian protons. For the distribution function of the BPs we take a product of a Maxwellian in the direction perpendicular to magnetic field, and a κ-function in the parallel direction. The κ-distribution function has a similar shape to the Maxwellian for energies below the thermal energy, but it is not so for high energies, where it has a power law decay with velocity (7), $f_\kappa \sim v^{-2\kappa}$. The relative abundance of this additional group of protons, $\eta_\kappa=n_\kappa/n_p$ (note that n_p is not the total proton density), the thermal anisotropy of κ-protons (A_κ), and the relative temperature (T_κ/T_p) are added to the previous list of relevant parameters. The dispersion relation we now solve is eq. 1 to which is added a term corresponding to the BPs. We take κ=3 acording to observations in (5). This new term is

$$\eta_\kappa[\tfrac{2}{3}+A_\kappa\tfrac{5}{3}-\frac{8}{y\beta_{//,\kappa}^{1/2}\sqrt{27}}Z_2(\sqrt{\tfrac{2}{3}}\frac{x+1}{y\beta_{//,\kappa}^{1/2}})+ (A_\kappa+1)\sqrt{8}\frac{x+1}{y\beta_{//,\kappa}^{1/2}}Z_3(\sqrt{2}\frac{x+1}{y\beta_{//,\kappa}^{1/2}})] , \quad (2)$$

where,

$$Z_2(\xi)=\frac{3\xi^2/4+9\mathrm{i}\xi\sqrt{2}/4-4}{(\xi+\mathrm{i}\sqrt{2})^3}, \quad (3)$$

and

$$Z_3(\xi)=-\frac{5\xi^3/6+10\mathrm{i}\xi^2\sqrt{3}/3-29\xi/2-8\mathrm{i}\sqrt{3}}{(\xi+\mathrm{i}\sqrt{3})^4} \quad (4)$$

Note that $\beta_{//,\kappa}=8\pi\ n_p\ T_{//,\kappa}/B^2$, where n_p is the bi-Maxwellian proton density. Z_κ is the modified plasma dispersion function (7).

Figure 3 shows the results in the same format as Fig. 1., with β_p=0.4, $A_\alpha=A_p=A_\kappa$=-0.67, T_α/T_p=4, η_α=0.08, and A_e=0. We assume $T_\kappa=2T_p$ so that the parallel thermal velocities of the bi-Maxwellian and κappa distribution functions, respectively, coincide. We calculate for 5 values of η_κ=0, 0.01, 0.05, 0.10, 0.15. As for the case of A_p, the wave speed is almost unaffected by η_κ. The growth rates and the widths of the unstable frequency bands increase as η_κ increases. Thus, e.g., maximum g for η_κ=5% is ~3 times that for η_κ=1%, and the unstable frequency range, x_r, is about twice as wide. Note that when η_κ goes from 0 to 15%, maximum g goes from ~2x10^{-4} to ~5x10^{-3}, a 25-fold increase, a large effect. Comparing Figures 1 and 3, we see that the effect of η_κ and A_p on the EICW instability are qualitatively similar.

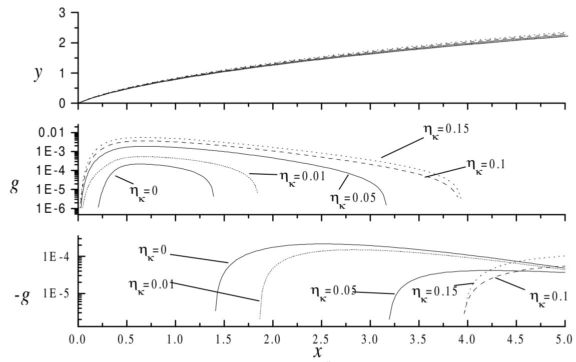

FIGURE 3. Same as Figure 1, but showing on η_κ (with β_p=0.4, $A_p=A_\alpha=A_\kappa$=-0.67, T_α/T_p=4, η_α=0.08, T_κ/T_p=2, and A_e=0 constants).

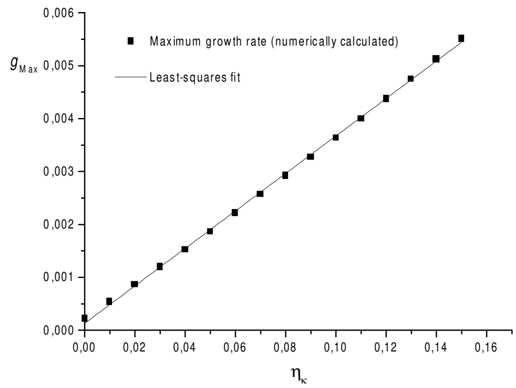

FIGURE 4. The maximum growth rate depends linearly on η_κ. $g_{\mathrm{Max}}(\eta_\kappa)=a_1\ \eta_\kappa+b_1$. With a least-squares fit, we obtained the following values corresponding to the cases of Figure 3: a_1=0.0354 and b_1=0.0001.

Further analysis (Figure 4) shows that g_{Max} increases linearly with η_κ as $g_{Max}=a_1\ \eta_\kappa+b_1$, where, for the chosen parameters a_l=3.5x10^{-2} and b_l=1.3x10^{-4}. Figure 5 shows the extent, Δx_r, of the unstable frequency band as a function of η_κ. The relation shown by the continuous line is represented by a-b exp{-c η_κ^d}, where a=4.01, b=2.76, c=45.40, and d=1.22 for the set of parameters chosen. The width of the unstable frequency range saturates near η_κ=10%.

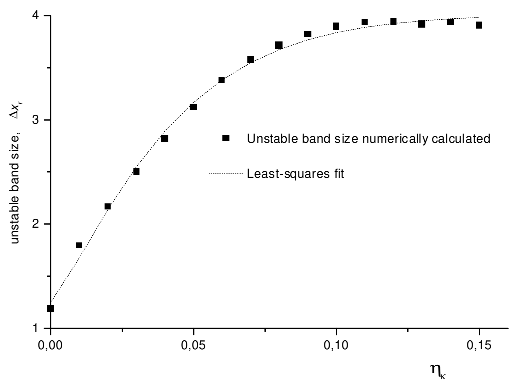

FIGURE 5. The unstable band size (Δx_r) increases with η_κ as Δx_r= a - b exp{c η_κ^d}. With a least squares fit, we obtained the following values corresponding to the cases of Figure 3: a=4.01, b=2.76, c=45.40, and d=1.22.

CONCLUSIONS

This study has highlighted two proton parameters on the excitation of EICWs in solar ejecta: the thermal anisotropy, A_p, and the relative density of energetic protons streaming along the field. Together with bidirectional streaming of suprathermal electrons (2), these latter are often observed in solar ejecta (5, 6), and they can make a significant contribution to EICW excitation even in as low a concentration as 1%. The effects of A_p can also be substantial.

We do not expect EICWs to be excited in all ejecta since other parameters, kept fixed here, may vary over a wide range. However, based on statistical studies and more recent work (e.g., (8)), we believe that some ejecta will sustain electromagnetic ion cyclotron waves. This, in turn, might be important to help understand the unusually high levels of magnetic field fluctuations observed in the last 4 years by Wind (e.g., (9)).

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