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Proton-cyclotron instability induced by the thermal anisotropy of minor ions

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[1] We study ion cyclotron instabilities due to the thermal anisotropy of minor heavy ions. Very large thermal anisotropies have been observed in O^{+5} ions in coronal holes [*Cranmer*, 2001], and as is well known, the thermal anisotropy of an ion species is the free-energy source of ion cyclotron waves of the corresponding species. Nevertheless, as the heavy ion thermal anisotropy in coronal holes develops, the ions are being heated and accelerated, and therefore they acquire a drift velocity relative to the protons. Owing to the drift velocity a new instability branch develops very close to the proton gyrofrequency. In other words, heavy ion cyclotron waves can also trigger proton-cyclotron waves as a result of the drift velocity of the minor heavy ions. We propose that the proton-cyclotron waves generated by this mechanism are absorbed by the protons, and therefore this process can contribute to fast proton heating in coronal holes. *INDEX TERMS:* 7507 Solar Physics, Astrophysics, and Astronomy: Chromosphere; 7807 Space Plasma Physics: Charged particle motion and acceleration; 2164 Interplanetary Physics: Solar wind plasma; 7511 Solar Physics, Astrophysics, and Astronomy: Coronal holes; 2169 Interplanetary Physics: Sources of the solar wind; *KEYWORDS:* proton-cyclotron, ion drift, thermal anisotropy

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1. Introduction

[2] It has been generally assumed that heating and acceleration of heavy ions in the lower corona is due to resonant absorption of Alfvén waves [see, e.g., *Gomberoff et al.*, 1996; *Marsch*, 1998; *Hu and Habbal*, 1999; *Cranmer et al.*, 1999; *Isenberg et al.*, 2001]. However, low frequency Alfvén waves (0.001–0.1Hz) which dominate the power spectrum of magnetic fluctuations in the solar wind for distances larger than 0.3 AU, are not likely to heat and accelerate the heavy ions to the observed values. On the other hand, high-frequency Alfvén waves ($10-10^4$ Hz) that might be responsible for ion cyclotron heating and acceleration of these ions have not been observed yet either in the solar wind or in the corona [*Cranmer et al.*, 1999].

[3] Although high-frequency Alfvén waves have not yet been observed, there are several theoretical proposals for the generation of these waves. It has been suggested that high-frequency Alfvén waves can be generated by a turbulent cascade [*Isenberg and Hollweg*, 1983; *Tu and Marsch*, 1995]. On the other hand, it has also been suggested that high-frequency Alfvén waves can be generated by micro-flares that are then converted to ion cyclotron waves at higher coronal altitudes [*Axford and Mckenzie*, 1992, 1996].

[4] It has been recently pointed out that apart from the problem of how the high-frequency waves are generated in the solar corona, the observations on the preferential heating of O^{+5} ions [*Kohl et al.*, 1998] are not yet satisfactorily explained by the ion cyclotron resonance theory [*Tu and Marsch*, 2001]. Other approaches include fast and oblique ion cyclotron waves [*Li and Habbal*, 2001], the need to incorporate a kinetic treatment [*Isenberg et al.*, 2001; *Isenberg*, 2001], fast shock heating [*Lee and Wu*, 2000], and others. Nevertheless, there seems to be some observational evidence that ion cyclotron waves are at the origin of ion heating and acceleration [*Tu and Marsch*, 2001; *Isenberg et al.*, 2001; *Isenberg*, 2001].

[5] The motivation of this paper is the observation of the large thermal anisotropy of the O^{+5} ions in the solar corona, $T_\perp/T_\parallel \simeq 10-100$ [*Kohl et al.*, 1998]. As is well known, the thermal anisotropy of an ion species is the free-energy source for the generation of ion cyclotron waves below the corresponding ion gyrofrequency [*Gomberoff and Neira*, 1983; *Gomberoff and Vega*, 1987; *Gomberoff and Elgueta*, 1991]. Recently, the effect of O^{+5} thermal anisotropy in the generation of heavy ion cyclotron instability has been studied [*Gary et al.*, 2001; *Ofman et al.*, 2001]. One of the results of these studies is that the proton heating is very small. However, in all these studies the relative drift velocity between O^{+5} and protons was neglected. We show here that the drift velocity acquired by the heavy-ion species as a consequence of the heating process, generates proton-cyclotron waves triggered by the heavy-ion thermal anisotropy. Therefore we propose that at least partially, the drift velocity together with the heavy ion thermal anisotropy trigger the high frequency branch of the instability, which is in turn responsible for the proton heating. This effect seems

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to be most relevant for drift velocities of the order of 0.1 times the Alfvén speed, which is consistent with the observed drift velocities in this region [*Cranmer et al.*, 1999; *Tu and Marsch*, 2001]. We study this problem with a kinetic formalism within the linear semicold approximation, which seems to suffice for the purpose of this letter. Considerations beyond the linear semicold approximation, including nonlinear effects, will be considered elsewhere.

[6] The paper is organized as follows. In section 2 the dispersion relation for ion cyclotron waves in the presence of protons and a drifting heavy ion-species is reviewed, and the relevant properties of the system under consideration are illustrated. In section 3 the results are summarized and discussed.

2. Dispersion Relation

[7] We consider a plasma composed of electrons, a minor heavy ion component (h), and protons (p) in an external magnetic field B_0. The minor heavy ions are drifting relative to the protons along the external magnetic field, with normalized velocity $U = V_h/V_A$, where V_h is the heavy ion velocity normalized to the Alfvén velocity, $V_A = B_0/\sqrt{(4\pi n_p m_p)}$. The proton density is n_p, and m_p is the proton mass. We assume the protons to be described by a Maxwellian distribution function (we are assuming that protons have not yet acquired a thermal anisotropy or that it is still very weak in this region), and the minor heavy ions by a bi-Maxwellian distribution because of their large observed thermal anisotropy [*Gary et al.*, 2001; *Ofman et al.*, 2001]. Such bi-Maxwellian distributions have been used by the authors previously mentioned. The dispersion relation for ion cyclotron waves moving in the direction of the external magnetic field is [see, e. g., *Gomberoff*, 1992]

$$y^2 = -x + \frac{x}{y\beta_{\|p}^{1/2}} Z(\xi_p) - z_h\eta(x - yU) + \frac{z_h\eta A_h}{M_h} - \frac{z_h\eta}{M_h^2 y\beta_{\|h}^{1/2}} Z(\xi_h)(A_h(1 - M_h(x - yU)) - M_h(x - yU)), \quad (1)$$

where $x = \omega/\Omega_p$, $y = kV_A/\Omega_p$, $\eta = n_h/n_p$, $A_h = T_{\perp h}/T_{\|h} - 1$ is the heavy ion thermal anisotropy, $M_h = m_h/z_h m_p$ (with m_h the heavy ion mass,and z_h the degree of ionization of the heavy ion), Z is the plasma dispersion function [*Fried and Conte*, 1961], $\xi_p = (x - 1)/y\beta_{\|p}^{1/2}$, $\xi_h = (M_h(x - yU) - 1)/M_h y\beta_{\|h}^{1/2}$, $\beta_{\|i} = v_{\|th,i}^2/V_A^2$ where $v_{\|th,i}^2 = 2KT_{\|i}/m_i$ is the parallel thermal velocity of component i = h,p. $\Omega_i = q_i B_0/m_i c$ is the ion gyrofrequency (with q_i and m_i as the charge and mass of the ions, respectively). In this equation we have assumed a current-free system, and the reference frame has been chosen to be the proton frame [*Gomberoff*, 1992].

[8] We shall apply the results to coronal holes where $\beta_{\|i} \ll 1$. Therefore the argument of the Z-functions are much larger than 1, and we can use the semicold approximation which consists in expanding the Z-functions for large values of the arguments and keeping the lowest significant order [*Gomberoff*, 1992]. We then write $x = Re(x) + i\gamma$ and assume $\gamma \ll Re(x)$. Upon separation of real and imaginary parts, we obtain [*Gomberoff*, 1992]

$$y^2 = \frac{x^2}{1 - x} + \frac{z_h M_h \eta_h (x - yU)^2}{1 - M_h(x - yU)}, \quad (2)$$

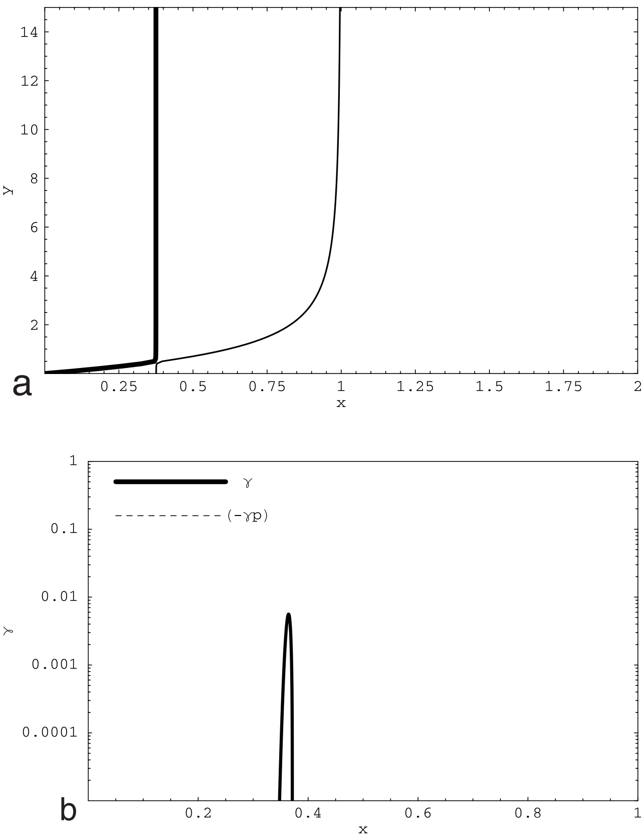

Figure 1. (a) Dispersion relation given by equation (2), x versus y, for $\eta = 0.0002$, $\beta_{\|O^{+6}} = 0.0004$, $A = 100$, $U = 0$. (b) Corresponding ion cyclotron growth rate.

and

$$\gamma = \frac{\sqrt{\pi} z_h \eta}{M_h^2 y \beta_{\|h}^{1/2}} \frac{G(x,y)}{F(x,y)} exp\left[-\left(\frac{1 - M_h(x - yU)}{M_h y \beta_{\|h}^{1/2}}\right)^2\right] - \frac{\sqrt{\pi} x}{y\beta_{\|p}^{1/2} F(x,y)} exp\left[-\left(\frac{1 - x}{y\beta_{\|p}^{1/2}}\right)^2\right]. \quad (3)$$

[9] In the last expression

$$G(x,y) = A_h(1 - M_h(x - yU)) - M_h(x - yU)$$

$$F(x,y) = \frac{(2 - x)x}{(1 - x)^2} + \frac{z_h M_h \eta (x - yU)(2 - M_h(x - yU))}{(1 - M_h(x - yU))^2}.$$

[10] Equation (2) is the cold plasma dispersion relation for ion cyclotron waves in the presence of two ion components. On the other hand the growth/absorption rate is given by equation (3). The first term in equation (3) corresponds to heavy ion cyclotron growth and damping rates, while the second term corresponds to proton absorption rate (for zero proton thermal anisotropy). In the following we will evaluate each term separately. Although this is not the standard procedure, it will prove useful. In equations (2) and (3), x is now purely real, $x = Re(x)$.

[11] In the following we shall study the effect of varying the minor heavy ion drift velocity.

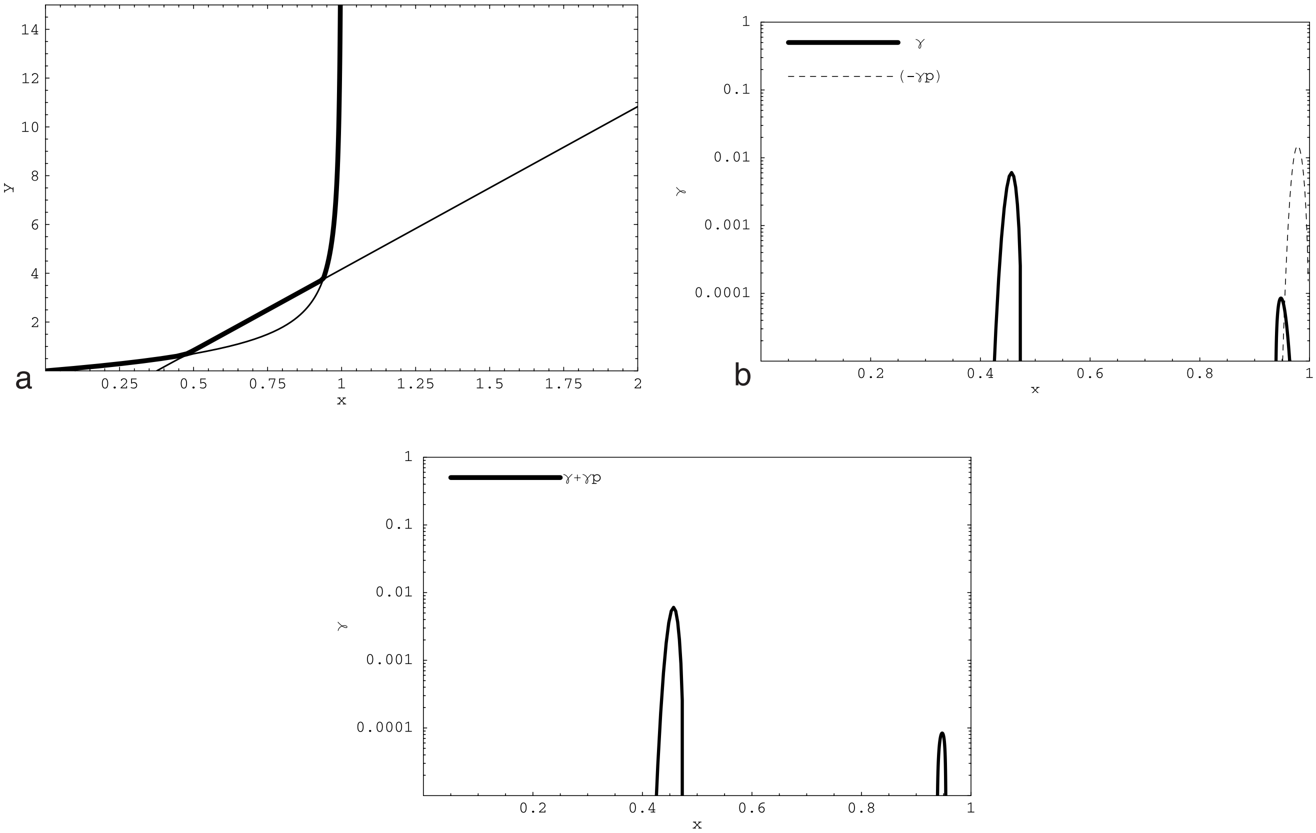

Figure 2. (a) Same as Figure 1a but for $U = 0.15$. (b) Same as Figure 1b but for $U = 0.15$. Full lines are for the growth rates of the O^{+6} ion cyclotron waves, given by the first term in equation (3). Dashed line is due to the proton absorption given by the last term in equation (3) with $\beta_{\|p} = 1.28 \times 10^{-5}$. (c) The combined growth rate given by the full equation (3), suggesting that some of the waves are able to propagate, while others are absorbed by the protons.

[12] In Figure 1a we show the dispersion relation for ion cyclotron waves, equation (2), for O^{+6} ions and protons. We use O^{+6} ions instead of O^{+5} ions because they are much more abundant, and the effect we want to illustrate depends on the heavy ion concentration (being larger for larger branching ratios). Therefore in order to illustrate more clearly the effect, we are assuming that the O^{+6} ions also have a large thermal anisotropy which, to the best of our knowledge, has not yet been measured. Thus for the O^{+6} we have taken $\eta = 0.0002$, $A = 100$, $\beta_{\|O^{+6}} = 0.0004$, and $U = 0$. In Figure 1b we show the growth rate versus x. One can see that the growth rate occurs below the O^{+6} gyrofrequency as expected. From equation (3) it follows that for $U = 0$ there is a marginal mode given by $x_m = A_h/M_h(A_h + 1)$ so that the instability is always to the left of the species gyrofrequency [see, e. g., *Gomberoff and Neira*, 1983]. However, we shall show that as the drift velocity increases, there is a new instability region very close to the proton gyrofrequency.

[13] In Figure 2 we have considered the same model of Figure 1, but we have raised $U = 0.15$. Figure 2a shows the dispersion relation. The continuous line of Figure 2b represents the ion cyclotron growth rate, by considering only the first term in the right hand side of equation (3). There is now a new instability region close to the proton gyrofrequency. Let's assume an initial situation in which the protons are very cold, namely $\beta_{\|P} = 1.28 \times 10^{-5}$, and that the ion cyclotron waves are generated by the heavy ion thermal anisotropy and relative ion drift. The proton absorption, given by the last term of equation (3), is shown as the dashed curve in Figure 2b, while Figure 2c shows the combined growth rate given by the full equation (3). Some of the waves close to the proton gyrofrequency are able to propagate, but others are absorbed by the protons.

[14] Figure 3 shows the equivalent to Figure 2a but for $\beta_{\|p} = 0.0064$. The proton absorption term, given by the last

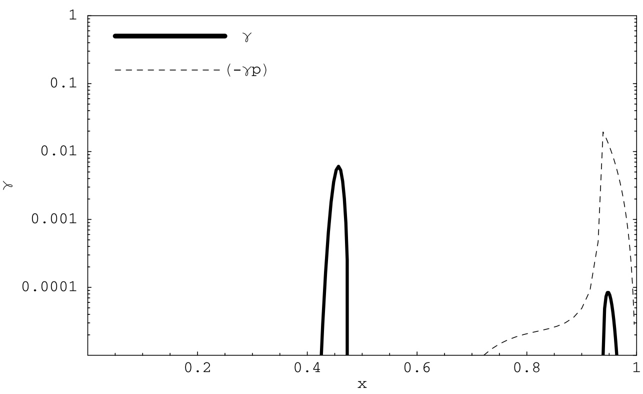

Figure 3. Same as Figure 2b but for $\beta_{\|p} = 0.0064$. The proton absorption completely washes out the high-frequency ion cyclotron waves.

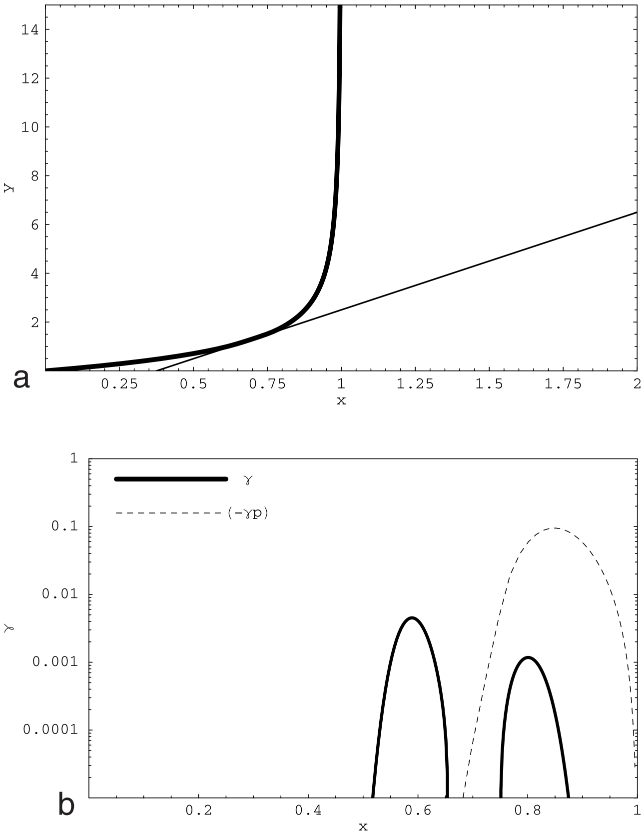

Figure 4. (a) Same as Figure 2a but for U = 0.25. (b) Same as Figure 3 but for U = 0.25.

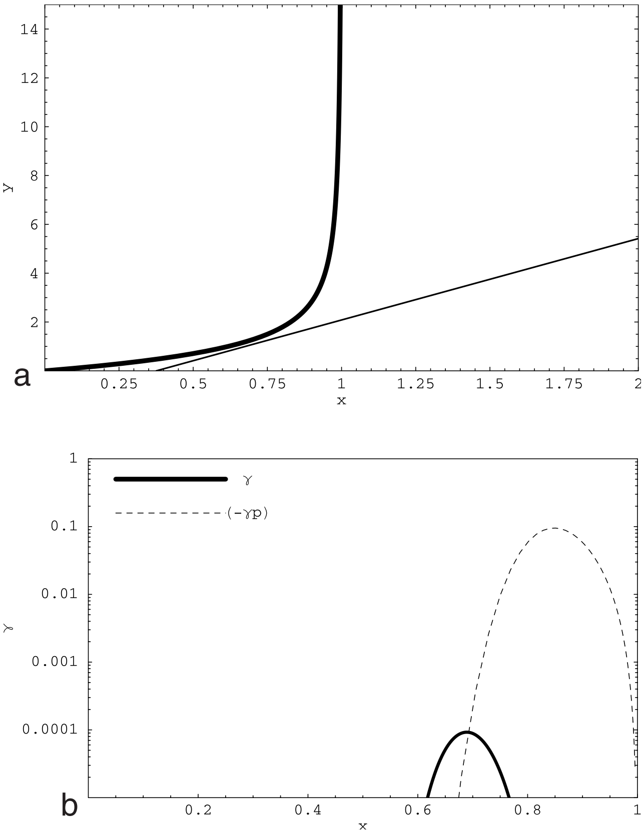

Figure 6. Same as Figure 4 but for U = 0.30.

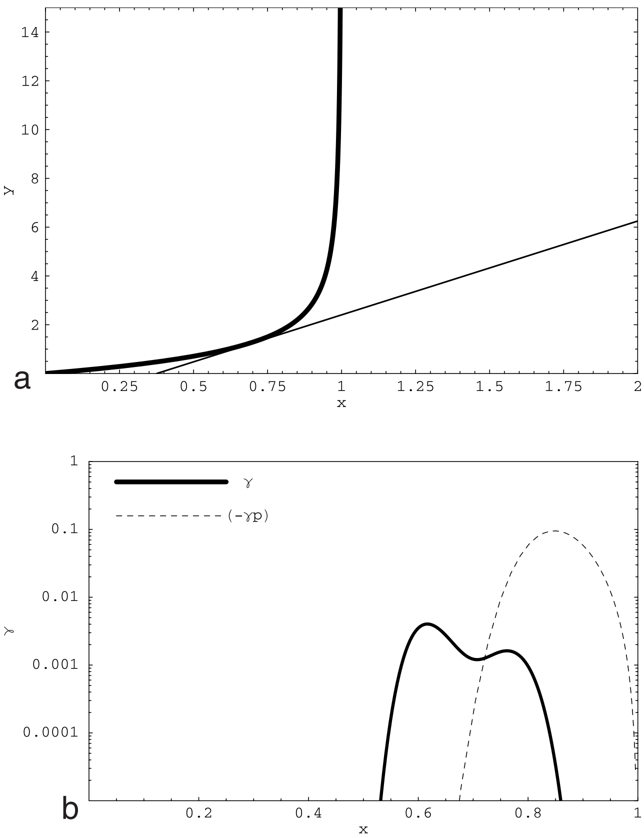

Figure 5. Same as Figure 4 but for U = 0.26.

term in equation (3), washes out completely the high frequency branch of the growth rate. On the basis of energy conservation we believe that even under these conditions, the energy content of the growth rate should be absorbed by the protons, leading, thereby, to proton heating. This heating should be effective until the O^{+6} thermal anisotropy has been dissipated.

[15] In Figure 4 we have increased the drift velocity further to U = 0.25, using again $\beta_{\parallel p}$ = 0.0064. Figure 4a shows the dispersion relation, and Figure 4b shows the instability spectrum. The two instability branches have moved toward each other. The maximum growth rate of the high-frequency instability has increased while the other one has decreased. Here again, when the proton absorption effects are considered, the high-frequency branch of the instability is again stabilized by the proton absorption corresponding to the dashed line.

[16] For larger drift velocities the two instability branches merge into just one instability branch. This is illustrated in Figure 5b for U = 0.26. Figure 5a shows the corresponding dispersion relation. The instability also becomes narrower and the maximum growth rate decreases very fast with increasing drift velocity. In Figure 6 these effects are illustrated for U = 0.3. The maximum growth rate has decreased by over one order of magnitude relative to the case of Figure 5.

[17] In Figures 1–6 we can see that the ion cyclotron growth rate depends strongly on the drift velocity of the ions. This can be seen more clearly in Figure 7, where we have plotted the maximum growth rate of the high-fre-

quency branch as a function of U, for the same parameters as before, with $\beta_{||O^{+6}} = 0.0004$. There seems to be an optimal drift velocity for the parameters considered.

3. Discussion

[18] We have considered a plasma with two ion components. We have assumed a positive thermal anisotropy for the heavy ion component. It is well known that if the ion components are at rest relative to each other, the system is unstable to ion cyclotron waves in a region below the heavy ion gyrofrequency [see, e. g., *Gomberoff*, 1992]. As pointed out in section 1, the thermal heavy ion anisotropy leads to a very weak proton heating [*Gary et al.*, 2001]. In the absence of oxygen-proton drift velocity, this result could have been anticipated, because all the energy content in the oxygen thermal anisotropy goes into ion cyclotron waves below the oxygen gyrofrequency. As mentioned before, for zero drift velocity the marginal mode for the O^{+6} lies below the corresponding gyrofrequency, far from the proton gyrofrequency. We have shown that as soon as the heavy ions acquire a drift velocity relative to the protons, a new instability region appears very close to the proton gyrofrequency. As the drift velocity increases, the two instability regions approach each other, while the growth rate of both branches increases until the growth rate of the low frequency branch starts to decrease. Finally, both branches merge into just one branch, and the maximum growth rate decreases very fast with increasing drift velocity.

[19] When the effect of proton absorption is taken into account, the high-frequency branch of the unstable spectrum is either partially stabilized, like in Figures 2, 5, and 6, or completely stabilized, like in Figures 3 and 4, depending, of course, on the values of the parameters. In the latter case we have proposed on the basis of energy conservation that the energy that would trigger the proton-cyclotron waves is absorbed directly by the protons. In other words, the protons should be heated without the generation of proton-cyclotron waves.

[20] The drift velocity affects also the absorption spectrum of the system. One of these effects is the displacement of the absorption frequency to higher frequencies [see, e.g., *Gomberoff and Elgueta*, 1991; *Tu and Marsch*, 1999]. We have not included these effects here because they are not relevant to our problem.

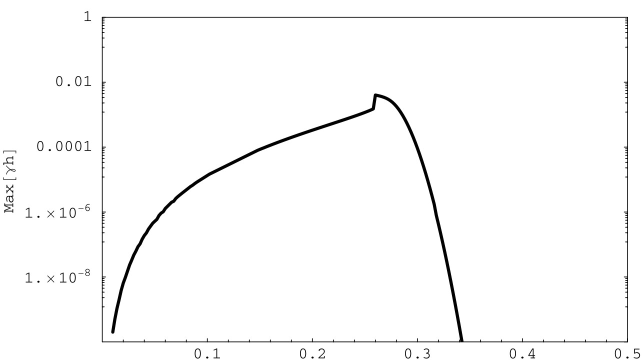

Figure 7. The maximum ion cyclotron growth rate of the high frequency instability as a function of U, with $\beta_{||O^{+6}} = 0.0004$. The jump around U = 0.26 corresponds to the critical drift velocity when the lower frequency branch merges with the high frequency instability.

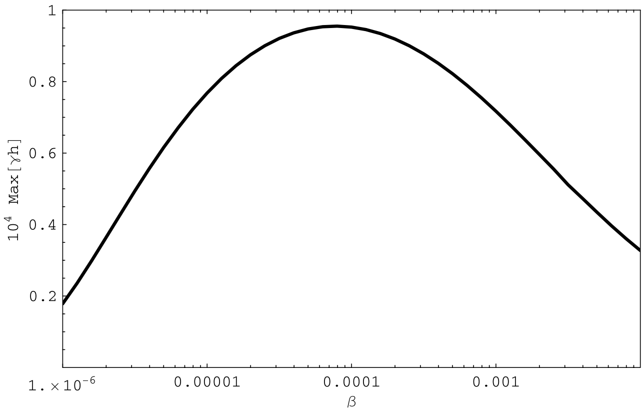

Figure 8. The maximum ion cyclotron growth rate of the high frequency instability as a function of $\beta_{||O^{+6}}$, with U = 0.15.

[21] Clearly, the growth rate of the proton cyclotron waves depends on η and on the heavy ion thermal anisotropy. As it follows from equation (3), the larger these two parameters are, the larger the growth rate is. The large thermal anisotropy of O^{+5} can be an indication of large thermal anisotropies of other heavy ion species such as O^{+6} ions. The O^{+6} ion density is at least two orders of magnitude larger than the O^{+5} ions and, as is argued here, they can lead to relatively strong proton-cyclotron waves. These waves can then be absorbed by the protons owing to cyclotron resonant damping, leading to proton heating and proton thermal anisotropy. Since there are a large number of many minor heavy ion species in the solar corona, the addition of all of them can lead to a significant effect. The maximum growth rate of the high frequency instability also depends on $\beta_{||O^{+6}}$ as it is shown in Figure 8 for the same parameters as before but with U = 0.15.

[22] As pointed out in section 1, in order to determine the amount of energy deposited on the protons by the mechanism considered here, one requires either a quasi-linear theory or simulation experiments. Although this is beyond the scope of the present work, it is a relevant problem that should be addressed.

[23] The effect of proton thermal anisotropy as well as the effect of a second abundant heavy ion species such as alpha particles will be published elsewhere. Both of these effects will reduce the proton absorption leading thereby to proton-cyclotron wave propagation.

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