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Ion acoustic-like waves triggered by nonlinear circularly polarized waves in the presence of an alpha particle beam

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[1] We consider a fast solar wind-type plasma consisting of electrons, a protons background, and a much more tenuous alpha particle beam. It is shown that such system is unstable against ion acoustic-like waves triggered by finite-amplitude left-hand polarized waves propagating in the direction of the interplanetary magnetic field. The ion acoustic-like waves have similar properties to those found in a plasma with a much denser proton beam (Gomberoff, 2006b). Although the alpha particle beam is much more tenuous than the proton beam, the system is equally able to trigger ion acoustic-like waves. Therefore we believe that this effect should be taken into account in the evolution of the fast solar wind.

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1. Introduction

[2] It has been shown that large-amplitude circularly polarized waves can stabilize (or destabilize further) linear beam plasma instabilities and can also trigger ion acoustic-like instabilities [*Gomberoff*, 2003; *Gomberoff et al.*, 2003, 2004a, 2004b, 2005; *Hoyos and Gomberoff*, 2005; *Gomberoff and Hoyos*, 2005]. In these studies the plasma was assumed to be composed by electrons, a proton core, and a less dense proton beam drifting in the direction of the magnetic field. It was also shown that similar properties hold in a plasma composed by electrons, a proton core, and a very tenuous alpha particle beam [*Gomberoff*, 2006a]. In the work of *Gomberoff* [2006b], it was shown that ion acoustic waves triggered by these finite-amplitude waves have different properties depending on whether the large-amplitude wave is supported by the proton core or by the proton beam. Thus for example, ion acoustic waves triggered by finite-amplitude waves supported by the proton core have a minimum nonzero wave number value, while those supported by the beam always start at zero wave number. Also, the former can only trigger forward propagating waves, while the latter can destabilize forward as well as backward propagating ion acoustic waves. By simulating Landau damping through a collision-like term, it was shown that some of the acoustic-like waves which, according to linear theory, should be strongly damped, are in fact very weakly damped [see *Gomberoff*, 2006b]. It was conjectured that these waves might be the ion acoustic waves observed in regions of the solar wind where linear ion acoustic waves should be damped.

[3] Nonlinear ion acoustic waves have also been discussed by several authors in the presence of electron beams [see, e.g., *Esfandyari-Kalejahi et al.,*, 2006; *Esfandyari et al.*, 2001], in dusty plasmas [*Kourakis and Shukla,*, 2005], and in electron-positron plasmas [*Cattaert et al.*, 2005].

[4] We study here ion acoustic-like waves triggered by left-hand polarized finite-amplitude waves in a system composed of electrons, a proton core, and an alpha particle beam. We consider a very low density alpha particle beam, like those observed in high-speed solar wind streams [see *Marsch*, 1991, and references therein] and show that even for such very low densities, ion acoustic like waves can play an important role in such systems. It is shown that the characteristics of the ion acoustic waves are similar to the case of a proton beam and are as efficient in exciting the ion acoustic waves as proton beams even for alpha particle beam densities as low as those of the fast solar wind.

[5] Since in the turbulent solar wind finite-amplitude circularly polarized waves are of common occurrence [see, e.g., *Spangler*, 1992], it is important to include their effects in the evolution of of the solar wind. Thus for example, it has been argued that they may be responsible for the existence of unstable proton and alpha particle distribution functions within 1 AU [*Marsch and Livi*, 1987; *Tu et al.*, 2004; *Araneda and Gomberoff*, 2004; *Gomberoff*, 2006a]. They may also be responsible for other unresolved issues in the fast solar wind like the enhanced deceleration of protons and alpha particles [*Kaghashvili et al.*, 2003, 2004]. Finally, the observation of ion acoustic waves in the solar wind, in regions where according to linear theory they should be strongly Landau damped [*Gurnett et al.*, 1979; *Gurnett*, 1991], might be the result of the presence of finite-amplitude polarized waves which can trigger ion acoustic-like waves that experience very little damping [*Gomberoff et al.*, 2006b].

[6] The layout of the paper is as follows. In section 2 we discuss the linear and nonlinear dispersion relation of a plasma system composed of electrons, a proton background, and a much more tenuous alpha particle beam. In section 3

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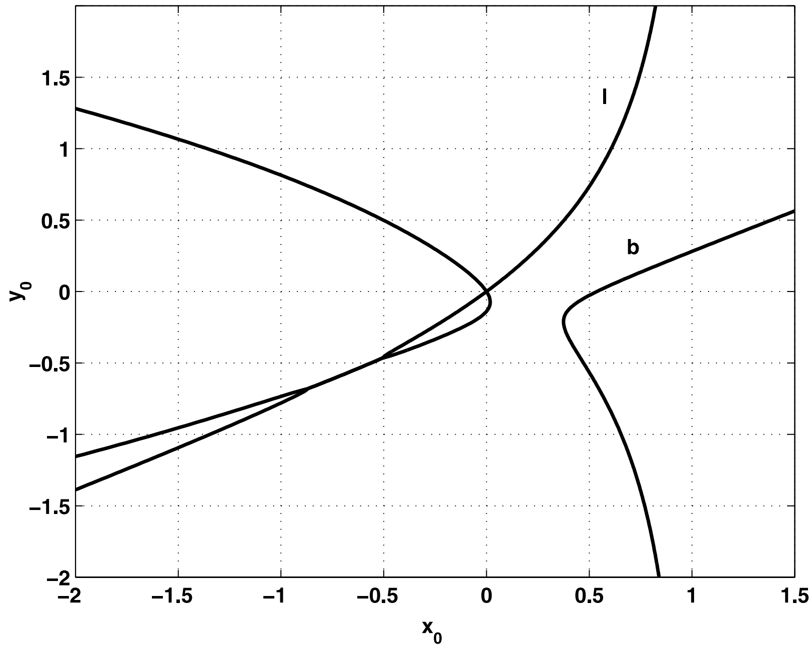

Figure 1. Solution of linear dispersion relation, equation (1), x_0 versus y_0 for η = 0.04 and U = 1.78.

we solve the nonlinear dispersion relation numerically. In section 4 we summarized the results.

2. Dispersion Relation

2.1. Linear Dispersion Relation

[7] The linear dispersion relation of circularly polarized waves triggered by an alpha particle beam moving in the direction of an external magnetic field, in a plasma system composed by electrons, core protons, and the alpha particle beam is [*Gomberoff and Elgueta*, 1991],

$$y_0^2 = \frac{x_0^2}{(1 - x_0)} + \frac{4\eta(x_0 - y_0 U)^2}{(1 - 2(x_0 - y_0 U))}, \tag{1}$$

where $x_0 = \omega_0/\Omega_p$, $y_0 = k_0\, V_p/\Omega_p$, $V_A = B_0/(4\pi n_p M_p)^{1/2}$ is the Alfvén speed where B_0 is the external magnetic field and M_p the proton mass, $U = V\alpha/V_A$ is the normalized alpha beam velocity, $\eta = n_b/n_p$ is the normalized alpha beam density relative to background proton density, n_p, and $\Omega_p = qB_0/cM_p$ is the proton gyrofrequency.

[8] Equation (1) is valid in a current free plasma and in a reference frame where the background protons are at rest. For an alpha particle beam this relation was first derived using kinetic theory in the semicold approximation [*Gomberoff and Elgueta*, 1991]. The dispersion relation given by equation (1) is a polynomial of order three in both y_0 and x_0. Thus for each real value of y_0, equation 1 has three roots. Roots with $Im(x_0) \geq 0$ correspond to linear instabilities. In Figure 1a we show the real part of the three roots of equation (1) for $\eta = 0.04$ and U = 1.78. For η = 0.04 this U values is slightly above instability threshold [see, e.g., *Gnavi et al.*, 1966; *Gomberoff et al.*, 1996; *Gomberoff and Astudillo*, 1998; *Gomberoff et al.*, 2000; *Gary et al.*, 2000, 2001]. We are interested in left-hand polarized waves moving forward relative to the external magnetic field. These waves correspond to the dispersion curves in the first quadrant of Figure 1. The Alfvén branch of the dispersion relation is denoted by “l, and the other curve, denoted by “b, correspond to waves supported essentially by the beam.

3. Nonlinear Dispersion Relation

[9] Assuming each plasma species satisfies the fluid equations, in a system composed by electrons, background protons, proton beam, and a finite-amplitude left-hand polarized wave propagating in the direction of the proton beam, *Hollweg et al.* [1993] derived the following dispersion relation:

$$\begin{aligned} &L_+L_-D + L_+R_-B_{-cc} + L_+R_{-\alpha}B_{-cc\alpha} + L_-R_+B_+ - L_-R_\alpha B_{+\alpha} \\ &\quad + (B_{-cc}B_\alpha - B_{-cc\alpha}B_+)(R_-R_{+\alpha} - R_+R_{-\alpha})D = 0. \end{aligned} \tag{2}$$

where

$$L_\pm = y_\pm^2 - x_\pm^2/\psi_\pm - 4\eta x_\pm^2/\psi_{\pm\alpha}$$

$$R_\pm = y_\pm\left(x_0 - \frac{yx_0^2}{y_0 x} + \frac{x_\pm}{\psi_\pm}\right)/2\psi_0$$

$$R_{\pm\alpha} = 2\eta y_\pm\left(x_{0\alpha} - \frac{yx_{0\alpha}^2}{y_0 x_\alpha} + \frac{x_{\pm\alpha}}{\psi_{\pm\alpha}}\right)/\psi_{0\alpha}$$

$$D = \beta_e'\Delta\eta r_\alpha x^2 + \beta_e'\Delta_\alpha r x_\alpha^2 - \Delta\Delta_\alpha(xx_\alpha)^2$$

$$B_+ = -2\beta_e' B_{+\alpha l}\eta r x x_\alpha + B_{+l}x^2\left(\beta_e'\eta r_\alpha - \Delta_\alpha x_\alpha^2\right)$$

$$B_{+\alpha} = -\beta_e' B_{+l} r_\alpha x x_\alpha/2 + B_{+\alpha l}x_\alpha^2\left(\beta_e' r - \Delta x^2\right)$$

$$B_{-cc\alpha} = -\beta_e' B_{-ccl} r_\alpha x x_\alpha/2 + B_{-cc\alpha l}x_\alpha^2\left(\beta_e' r - \Delta x^2\right)$$

$$B_{+(\alpha)l} = -\frac{A\psi_{-(\alpha)}\left(y_+\psi_{+(\alpha)}x_{0(\alpha)}^2 - y_0\psi_{0(\alpha)}x_{+(\alpha)}\right)}{y_0 y_+ x_{(\alpha)}}$$

$$B_{-cc(\alpha)l} = \frac{A\psi_{+(\alpha)l}\left(y_-\psi_{-(\alpha)}x_{0(\alpha)}^2 - y_0\psi_{0(\alpha)}x_{-(\alpha)}^2\right)}{y_0 y_- x_{(\alpha)}}$$

$$B_{-cc} = -2\beta_e' B_{-cc\alpha l}\eta r_\alpha x x_\alpha + B_{-ccl}x^2\left(\beta_e' r_\alpha - \Delta_\alpha x_\alpha^2\right),$$

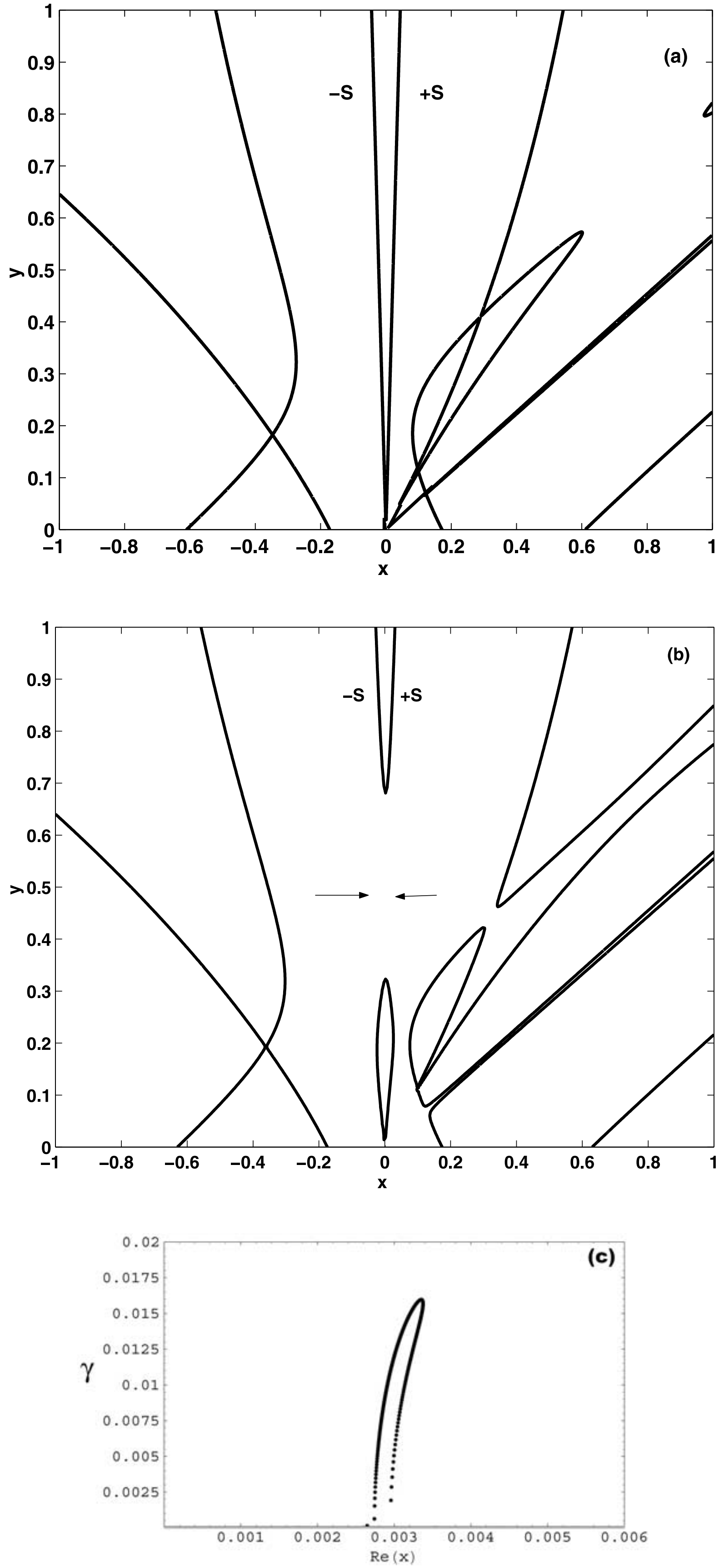

Figure 2. (a) Solution of the nonlinear dispersion relation, equation (2), x versus y for $x_0 = 0.1$, $\eta = 0.04$, $\beta_{(e,p,b)} = 0.001$, and $U = 1.78$ for $A = 0$. (b) Same as Figure 2a but for $A = 0.1$. (c) Growth rate γ versus $Re(x)$ for the instability of Figure 2b.

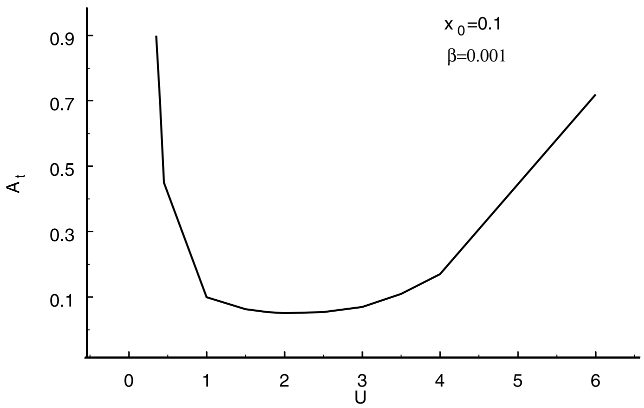

Figure 3. Threshold amplitude A_t versus drift velocity U for $x0 = 0.1$ and $\beta_i = 0.001$.

and

$$\Delta = A + r\left(1 - \beta_p y^2/x^2\right),$$

$$\Delta_\alpha = A + r_\alpha\left(1 - \beta_\alpha y^2/4x_\alpha^2\right),$$

$$A = (B/B_0)^2,$$

$$r_{(\alpha)} = \psi_{0(\alpha)}\psi_{+(\alpha)}\psi_{-(\alpha)},$$

$$\psi_0 = 1 - x_0,$$

$$\psi_{0\alpha} = 1 - 2x_{0\alpha},$$

$$\psi_\pm = 1 - x_\pm,$$

$$\psi_{\pm\alpha} = 1 - 2x_{\pm\alpha},$$

$$x_\pm = x_0 \pm x,$$

$$y_\pm = y_0 \pm y,$$

$$x_\alpha = x - yU,$$

$$x_{0\alpha} = x_0 - y_0 U,$$

$$x_{\pm\alpha} = x_\pm - y_\pm U,$$

$$\beta_i = 4\pi n_p \gamma K T_i/B_0^2, i = e, p, \alpha$$

$$\beta'_e = \beta_e y^2/(1 + 2\eta),$$

where B is the magnetic field of the finite-amplitude wave, and the symbol "(α)," in some of the definitions, means with the alpha particle beam when alpha is without the brackets, and without alpha particles when alpha has the brackets. The nonlinear dispersion relation, equation (2), is a polynomial of order ten in both x and y, where $x = \omega/\Omega_p$, $y = kV_A/\Omega_p$.

[10] The solutions of equation (2) for $A = 0$, $L_\pm = 0$, and $D = 0$ give the various branches of the nonlinear dispersion relation. The crossings between the solutions give the position and nature of the possible wave couplings in the system. The solutions of the nonlinear dispersion relation equation (2) are invariant under a rotation through an angle of 180°. Therefore it is sufficient to analyze the solutions in the upper half (x,y) plane [see, e.g., *Hollweg et al.*, 1993; *Gomberoff et al.*, 1994, 1995a, 1995b]. Note that for A = 0 only the ion acoustic waves depend on β_i (i = electrons (e), protons (p), beam (b)). The nonlinear wave is characterized by x_0 and y_0, and it is located at the origin of the (x,y) coordinate system [*Longtin and Sonnerup*, 1986]. For zero wave amplitude, A = 0, equation (2) reduces to $L_- L_+ D = 0$. The solutions of $L_\pm = 0$ correspond to the linear dispersion relation given by equation (1) but for upper and side band waves, respectively. The solution $D = 0$ corresponds to linear electrostatic ion acoustic waves. For $\eta \ll 1$, the roots of $D = 0$ are given by

$$x = \pm\left(\beta_e + \beta_p\right)^{1/2} y, \tag{3}$$

$$x - yU = \pm(\beta_b)^{1/2} y. \tag{4}$$

Equation (3) corresponds to ion acoustic waves supported mainly by the proton core, and propagate forward and backward relative to the magnetic field which is also in the

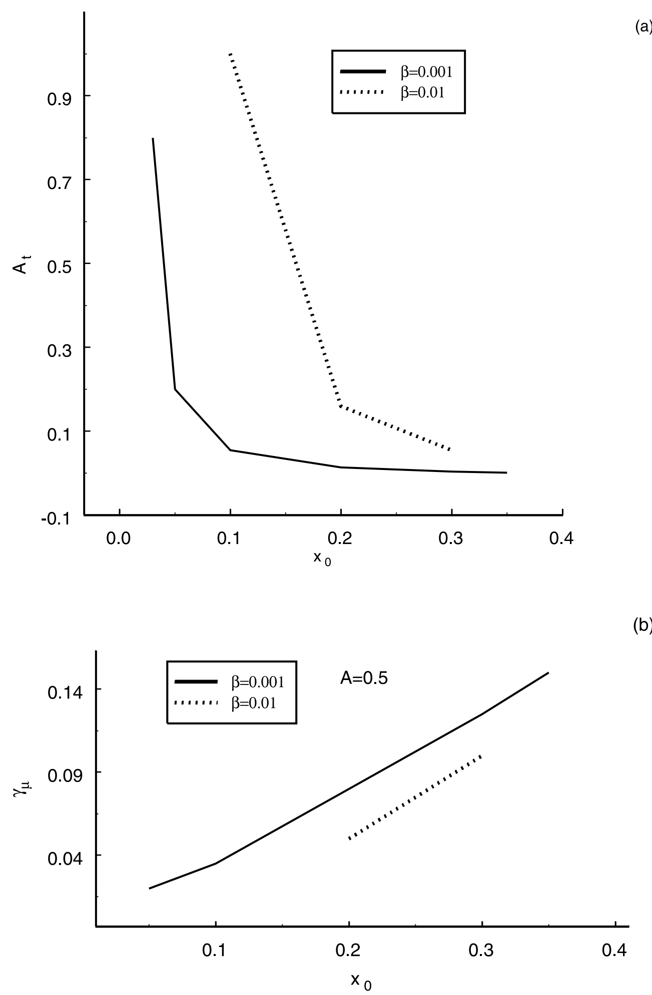

Figure 4. (a) Threshold amplitude A_t versus finite-amplitude wave frequency x_0 for β_i = 0.001, 0.01. (b) Maximum growth rate γ_m versus finite-amplitude wave frequency x_0, for $A = 0.5$ and two values of $\beta_i = 0.001, 0.01$.

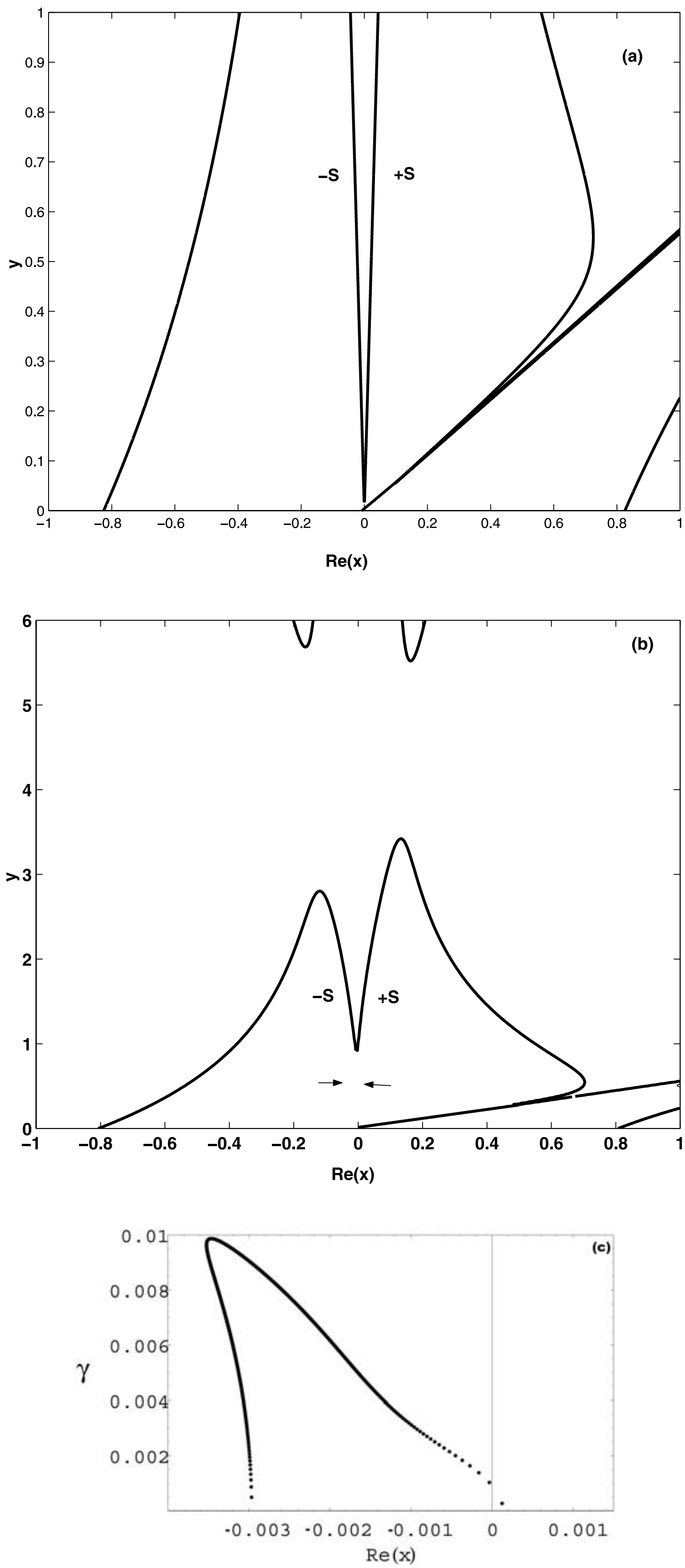

Figure 5. (a) Solution of the nonlinear dispersion relation, equation (2), x versus y, for $x_0 = 1.1$, $\eta = 0.04$, $\beta_i = 0.001$, $U = 1.78$, and $A = 0$. (b) Same as Figure 5a but for $A = 2 \times 10^{-5}$. (c) Growth rate γ versus $Re(x)$, for the instability of Figure 5b but for $A = 3 \times 10^{-5}$.

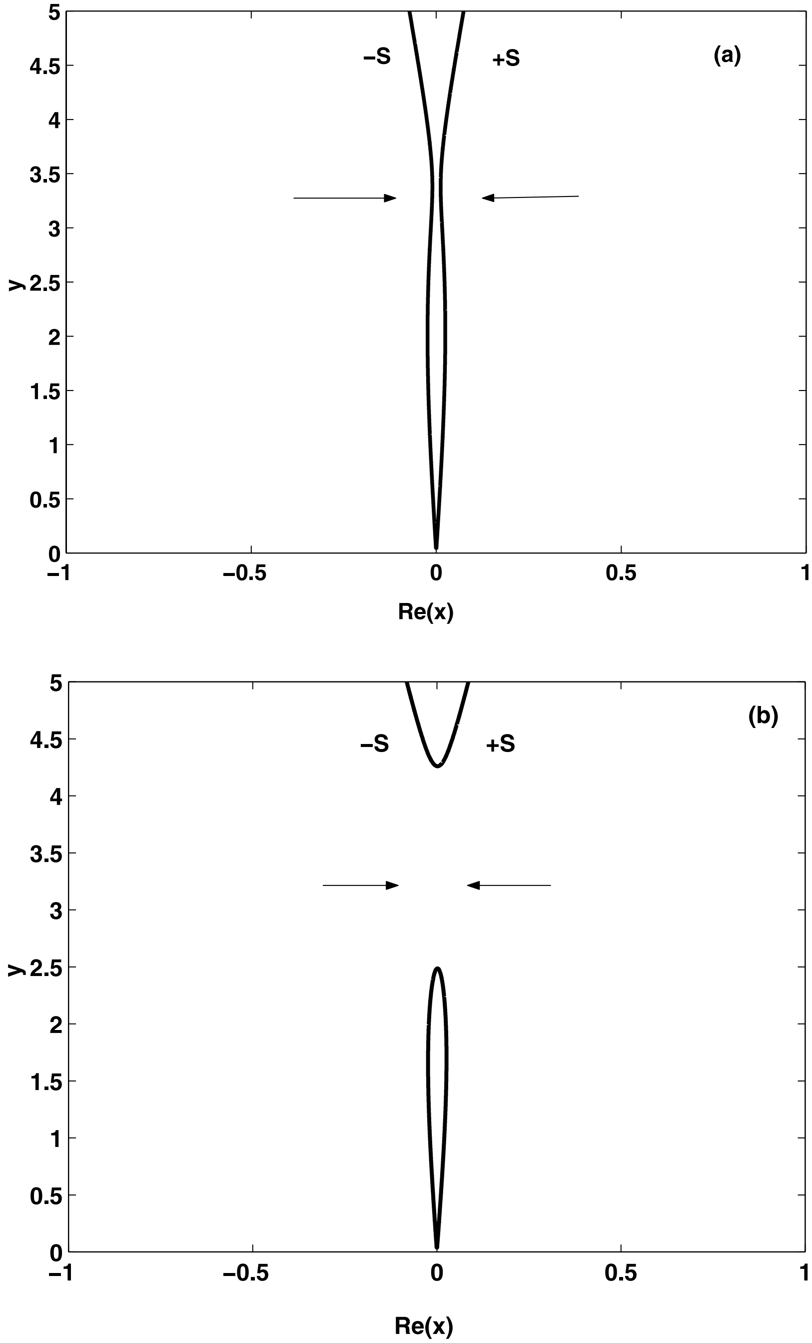

Figure 6. (a) Same as Figure 5a, but for $x_0 = 7$ and $A = 5.8 \times 10^{-3}$. (b) Same as Figure 6a but for $A = 6.3 \times 10^{-3}$. (c) Same as Figure 6a but for $A = 8.5 \times 10^{-3}$.

beam direction. Equation (4) describes ion acoustic waves supported mainly by the alpha particle beam and propagate forward and backward relative to the alpha particle beam. The ion acoustic waves appearing in the nonlinear dispersion relation come from longitudinal perturbation, i.e., along the beam direction, of the fluid equations in the presence of the large-amplitude wave [*Hollweg et al.*, 1993].

4. Numerical Analysis

[11] In this section we solve equation (2) numerically in order to illustrate the various effects of interest. In order to do this, we use the method first developed by *Longtin and Sonnerup*, [1986].

[12] Thus in Figure 2a we show the solutions of the nonlinear dispersion relation equation (2) x versus y, for $\eta = 0.04$ [*Neugebauer*, 1981; *Marsch*, 1991], $\beta_i = \beta_{(e,p,b)} = 0.001$, $x_0 = 0.1$, $U = 1.78$, and $A = 0$. In Figure 2b we have raised $A = 0.1$. The gap shown by the arrows corresponds to the ion acoustic-like instability between the ion acoustic waves denoted by $\pm$ S because the frequency there is complex. The instability region occurs between $0.32 \leq x_0 \leq 0.38$. In Figure 2c we show the growth, γ versus Re(x), of the instability of Figure 2b. Note that the instability has a lower y bound at $y \simeq 0.32$. This is a property for all ion

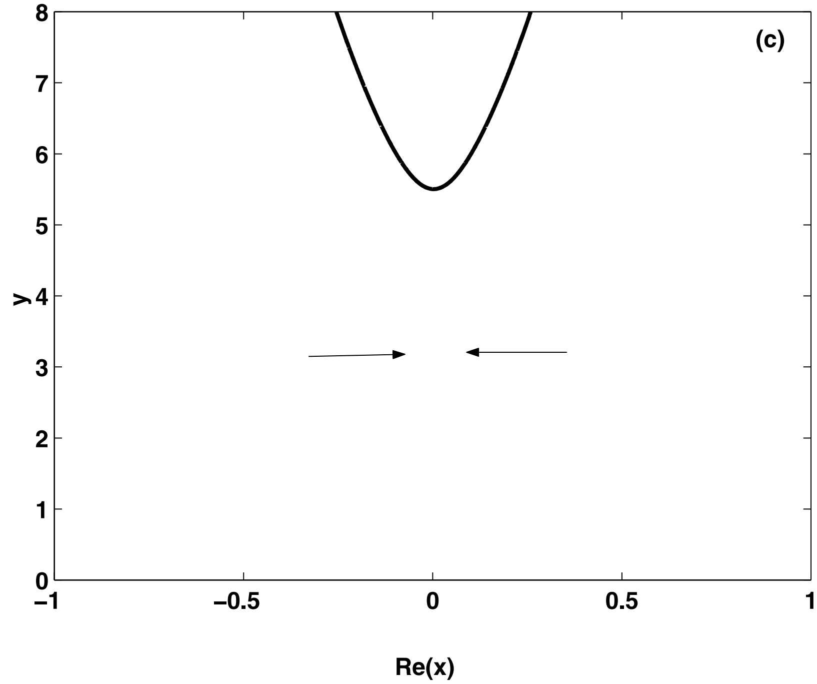

Figure 6. (continued)

acoustic-like instabilities triggered by large-amplitude waves belonging to the Alfvén branch of the dispersion relation (l-waves). Also, only positive frequencies can be destabilized by waves belonging to this branch. A similar situation was found in the case of a proton beam [*Gomberoff*, 2006b].

[13] Note that we are using a rather large beam drift velocity, $U = 1.78$ which is slightly above the threshold for linear magnetosonic instability [see, e.g., *Gnavi et al.*, 1966]. However, the ion acoustic like instability triggered by finite-amplitude forward propagating left-hand polarized waves can occur for beam drift speeds as low as $U \simeq 0.3$, as illustrated in Figure 3, or even less depending on the finite wave frequency, x_0. It follows from this figure that the ion acoustic-like instability threshold becomes larger than 0.9 for $U < 0.3$ and similarly for $U > 6.5$. Thus we could have used a smaller beam drift velocity with similar results. We want to note that although for $A = 0$, there is a linear magnetosonic instability, for $A = 0.1$ the instability is completely stabilized by the large-amplitude wave. Therefore these two instabilities do not interfere with each other.

[14] In Figure 4a we illustrate the behavior of the threshold amplitude for ion acoustic-like instability, A_t, as a function of finite-amplitude frequency, x_0, for $\beta_i = 0.001$ and $\beta_i = 0.01$. For $\beta_i = 0.001$, the system is unstable for frequencies starting at $x_0 \simeq 0.03$ up to $x_0 \simeq 0.35$. Beyond this frequency, there is a new regime which is stable against ion acoustic-like instabilities. For $\beta_i = 0.01$, the unstable frequency range is much shorter, going from $0.1 \leq x_0 \leq 0.3$. For $\beta_i \geq 0.1$ the system is stable. In Figure 4b we show the behavior of γ_m as a function of x_0 for $\beta_i = 0.001$ and $\beta_i = 0.01$, for $A = 0.5$.

[15] Large-amplitude waves belonging to the beam branch of the dispersion relation (b-waves) with frequencies between $0.5 \leq x_0 \leq 1.03$ do not destabilize ion acoustic-like instabilities. Starting from $x_0 \simeq 1.03$ the system is unstable against ion acoustic-like instabilities. In Figure 5a we solve the nonlinear dispersion, x versus y, for $x_0 = 1.1$, $U = 1.78$, $\beta_i = 0.001$, and $A = 0$. The lines denoted by $\pm S$ correspond to the acoustic modes. In Figure 5b, $A = 2 \times 10^{-5}$. The region between the origin and $y \simeq 0.8$ is now unstable. In Figure 5c we show the growth rate γ versus $Re(x)$ for the instability of Figure 5b but for $A = 3 \times 10^{-5}$. In contrast to the Alfvén branch of the dispersion relation (l-branch), the minimum bound of the unstable y-region is $y = 0$. The threshold amplitude for instability increases with increasing frequency, until $x_0 \simeq 4$ where a new regime is encountered. This is illustrated in Figure 6 for $x_0 = 7$. In Figure 6a, $A = 2.2 \times 10^{-3}$. There is an strangulation between the two ion acoustic modes at $x \simeq 3.3$ shown by the arrows. In Figure 6b A has been increased to $A = 6.3 \times 10^{-3}$. The ion acoustic-like instability develops between $2.5 \leq y \leq 4.4$, corresponding to the region shown by the arrows. This situation is similar to that of Figure 2b. However, in this case as A increases, the lower y-bound of the instability goes to zero. This is illustrated in Figure 6c for $A = 8.5 \times 10^{-3}$.

[16] Finally, in Figure 7 we have plotted the threshold amplitude of the finite-amplitude wave required to trigger ion acoustic waves, as a function of the drift velocity U, for $\beta_i = 0.001$ and $x_0 = 1.5$. A comparison with Figure 3 shows that a much smaller amplitude is required to trigger the ion acoustic-like waves when the finite-amplitude wave belongs to the beam branch of the dispersion relation (b-waves). It can also be shown that maximum growth rates for fix A are larger for this branch of the dispersion relation. This branch is unstable for β_i values as large as $\beta_i \simeq 1.0$.

5. Summary

[17] We have shown that ion acoustic-like waves supported mainly by the core protons can be triggered by large-

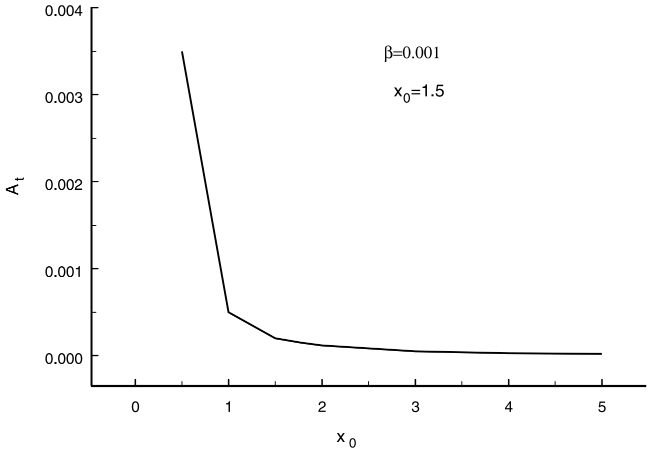

Figure 7. Threshold amplitude A_t versus drift speed U for x_0 = 1.5 and β_i = 0.001.

amplitude left-hand polarized waves moving in the direction of the external magnetic field. The properties of these waves are very similar to the case of a proton beam [*Gomberoff*, 2006a]. Finite-amplitude waves belonging to the Alfvén branch of the dispersion relation (l-waves), trigger ion acoustic-like instability having a lower bound in the wave number instability range. The lower bound remains almost unchanged as a function of A for fix β_i and x_0. In contrast, finite-amplitude waves belonging to the b-branch of the dispersion relation have a zero wave number instability bound. However, at $x_0 \simeq 4$ a new regime develops where the unstable y-spectrum region shows again a lower wave number bound different form zero. In this case the lower bound tends to zero as A increases. The unstable spectrum of ion acoustic waves triggered by finite-amplitude waves belonging to the l-branch of the dispersion relation contains only positive frequencies. In the case of finite-amplitude waves belonging to the b-branch, the unstable frequency spectrum as a function of A, for fix β_i and frequency x_0, contains purely negative frequencies for low A values, but as A increases the spectrum shifts to positive frequencies. This means that for intermediate A-values the unstable spectrum contains waves moving forward and backward relative to the external magnetic field.

[18] Although as pointed out above, the situation is very similar to the case of a proton beam, it is to be noticed that in the present case the density of the alpha particle beam is very low, η = 0.04, and yet the system is as efficient to trigger ion acoustic waves due to the presence of finite-amplitude waves [see *Gomberoff et al.*, 1996], as a proton beam with η = 0.2.

[19] It is important to note that the ion acoustic-like waves supported by the core protons depend on the sum of $\beta_e + \beta_p$, not on each of them separately. Therefore considering $\beta_e = \beta_p$ does not affect the fact that in the fast solar wind they are different, with T_p/T_e >1 [see, e.g., *Marsch*, 1991, and references therein]. Also, owing to the variation of the interplanetary magnetic field, the β values can be very small, $\beta \ll 1$ in coronal holes, while reaching values of the order of 1 at 1 AU [see, e.g., *Marsch*, 1991; *Gomberoff and Elgueta*, 1991; *Gomberoff and Valdivia*, 2002, 2003]. Therefore our parameter study covers a large range of heliocentric distances from coronal holes to 1 AU. Moreover, in the fast solar wind, protons are anisotropic. They have $T_\perp/T_\parallel$ of the order of 3 to 4 [*Marsch*, 1991] The thermal anisotropy has not been considered here, but it is not expected to have any important effect on the ion acoustic waves because they depend only on the total temperature, $T = (T_\parallel + 2T_\perp)/3$. The bounds for threshold amplitudes to trigger nonlinear ion acoustic waves are such that this type of waves are to be expected in the fast solar wind between the solar corona and 1 AU.

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