Ion acoustic instability triggered by finite amplitude polarized waves in the solar wind

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Received 28 September 2004; revised 9 November 2004; accepted 18 February 2005; published 4 June 2005.

[1] It is shown that ion-acoustic waves propagating along an external magnetic field and generated by parametric decays of circularly polarized finite amplitude waves have the properties of ion-acoustic waves observed in the solar wind.

Citation: Gomberoff, L., J. Hoyos, and A. L. Brinca (2005), Ion acoustic instability triggered by finite amplitude polarized waves in the solar wind, *J. Geophys. Res.*, *110*, A06101, doi:10.1029/2004JA010810.

1. Introduction

[2] Electrostatic ion-acoustic instabilities have been observed in several space plasma environments. In some cases they have been positively identified as ion-acoustic waves because all the conditions for their generation, according to linear theory, have been properly identified. These conditions are their free energy source and small Landau damping effects, $T_e \gg T_p$. However, in some instances like, e.g., in the solar wind, ion-acoustic waves seem to be present under conditions where both the nature of the free energy source of the instability and the condition for small damping are not consistent with the theory [see, e.g., *Marsch*, 1991; *Gurnett*, 1991, and references therein].

[3] It is shown here that electrostatic waves generated from parametric decays of large-amplitude left-hand polarized waves might be responsible for ion-acoustic waves observed in the solar wind. It is also shown that the instability can also be triggered by right-hand polarized waves for any frequency, provided that $\omega \ll \Omega_e$, where $\Omega_e = eB_0/cm_e$ is the electron cyclotron frequency. Using a collisional-like term in the fluid equations and the linear Landau damping expression obtained from kinetic theory, we show that the instability does not depend on the relative ratio between T_e/T_i, where T_e and T_i are the electron and ion temperature, respectively, and depends only on the total temperature of the system, $T_e + T_i$. It is also shown here that the instability is almost monochromatic and the growth rate decreases with increasing $\beta_e + \beta_i$, where $\beta_l = (v_{th.l}/v_A)^2 < 1$, $v_{th.l} = \sqrt{2kT_l/M_l}$ is the thermal velocity of species l and v_A is the Alfvén velocity. It has been observed that the number of events and the growth rate increases with decreasing β values [see, e.g., *Gurnett*, 1991, and references therein]. In other words, the instability is much more frequent closer to the Sun. Therefore the properties of these waves can help to explain some of the events involving ion-acoustic waves in the solar wind.

2. Dispersion Relation

[4] Assuming that the system consists of a magnetized plasma composed of protons and massless electrons and also that it is current-free, the dispersion relation in the proton rest frame is given by

$$y_0^2 = \frac{x_0^2}{(1 \mp x_0)}, \tag{1}$$

where $y_0 = k_0 v_A/\Omega_p$, $x_0 = \omega_0/\Omega_p$, $v_A = (B_0/(4\pi n_p m_p))^{1/2}$, $\Omega_p = qB_0/cm_p$ is the proton gyrofrequency, and B_0 is the external magnetic field.

[5] Equation (1) is the dispersion relation satisfied by circularly polarized waves. The minus (plus) sign refers to left-handed (right-handed) waves. The dispersion relation is valid for $\omega_0 \ll \Omega_e$.

[6] Assuming now that the system consists of protons, electrons, and a large-amplitude wave satisfying equation (1) and propagating in the direction of the external magnetic field, the nonlinear dispersion relation can be written in the following form [see, e.g., *Wong and Goldstein*, 1986; *Jayanti and Hollweg*, 1993a, 1993b; *Hollweg*, 1994; *Gomberoff*, 2000],

$$L_-(L_+D + R_+B_+) + L_+R_-B_- = 0, \tag{2}$$

where

$$L_\pm = y_\pm^2 - x_\pm^2/\xi_\pm, \tag{3}$$

$$R_\pm = \frac{y_\pm}{2\xi_0}\left(x_0 - \frac{yx_0^2}{y_0 x} + \frac{x_\pm}{\xi_\pm}\right), \tag{4}$$

$$D = r\beta_e y^2 - x^2\Delta, \tag{5}$$

$$B_\pm = \pm\frac{Ax\xi_\mp\left(\xi_\pm y_\pm x_0^2 - y_0\xi_0 x_\pm^2\right)}{y_0 y_\pm}, \tag{6}$$

$$\Delta = A + r\left(1 - \beta_p\frac{y^2}{x^2}\right), \tag{7}$$

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0148-0227/05/2004JA010810

with the definitions

$$A = \left(\frac{B}{B_0}\right)^2,$$

$$r = \xi_0 \xi_+ \xi_-,$$

$$\xi_0 = 1 - x_0,$$

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

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

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

$$\beta_{e,p} = \frac{4\pi n_p \gamma_{e,p} k T_{e,p}}{B_0^2}.$$

[7] In the last relations, k is Boltzmann's constant and $\delta p/p_0 = \gamma \delta n/n_0$, with γ the adiabaticity coefficient. When $A = 0$, the nonlinear dispersion relation reduces to

$$L_+ L_- D = 0, \tag{8}$$

which corresponds to the sideband waves and the ion-acoustic modes. In particular, for $A = 0$, the acoustic modes are given by $D = 0$, namely

$$x^2 = (\beta_e + \beta_p) y^2. \tag{9}$$

3. Numerical Solutions

[8] In Figure 1a we show the numerical solution of equation (2) for $x_0 = 0.1$, $\beta = 0.02$, and $A = 0$. The lines denoted by $\pm S$ correspond to the ion acoustic waves propagating forward, $+S$, and backward, $-S$, relative to the external magnetic field. The line denoted by $-F$ corresponds to a backward propagating left-hand polarized wave. In Figure 2b, we show the same as in Figure 1a, but for $A = 0.3$. At the point A there is a parametric decay instability involving an ion acoustic sound wave, $+S$, and a backward propagating left-hand polarized wave belonging to the lower sideband waves, $-F$. The instability ends up at point B, where it is mostly electrostatic. The instability threshold of the parametric instability occurs at a very low value of $A \simeq 0.0001$.

[9] In Figure 2a we have plotted the threshold behavior of A_t as a function of the left-hand polarized finite amplitude frequency, x_0, for $\beta = 0.1, 0.2, 0.3$. As shown in the figure, the threshold amplitude decreases with increasing frequency for $\beta \leq 0.1$. For $\beta \geq 0.1$ a similar behavior is observed until it reaches a value such that for frequencies above this value, the system is stable. For $\beta > 0.5$ and $x_0 = 0.1$ the growth rate becomes very small. Likewise, in Figure 2b we have plotted A_t versus right-hand polarized forward propagating finite amplitude wave frequency, for $\beta = 0.01, 0.1, 0.3, 0.4, 0.5$. Here again the system is unstable, and A_t decreases for increasing x_0. As before, the system is stable for $\beta \geq 0.5$, but there is no frequency limit for the unstable cases except that $\omega_0 \ll \Omega_e$.

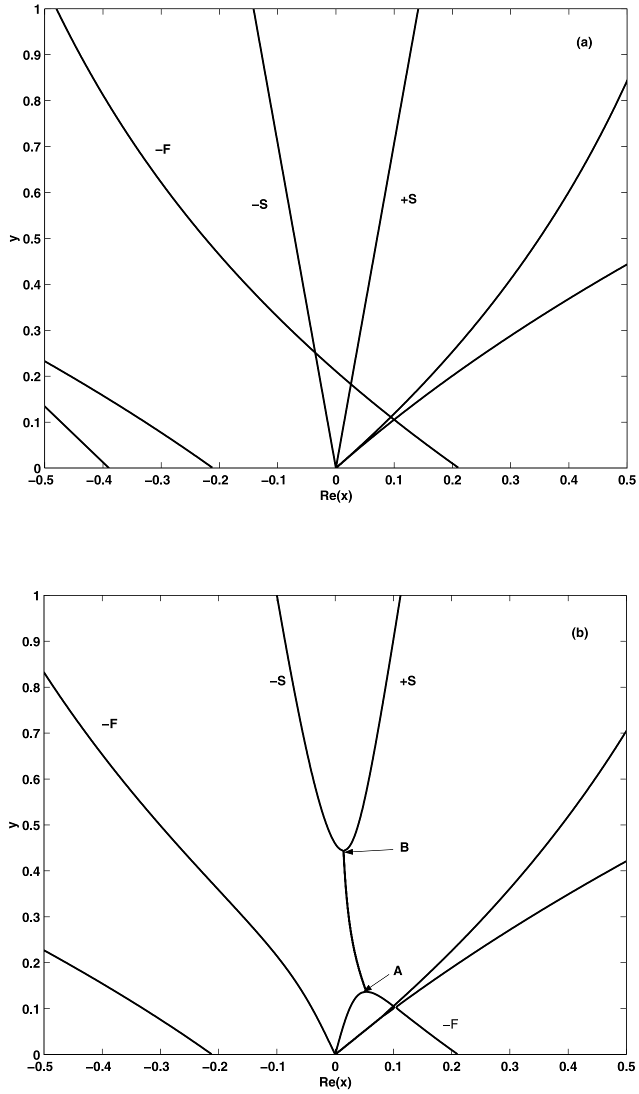

Figure 1. Nonlinear dispersion relation y versus $Re(x)$, $x_0 = 0.1$, $\beta = 0.02$ for (a) $A = 0$ and (b) $A = 0.3$.

[10] In order to simulate Landau damping in the ion-acoustic modes, we introduce a collisional-like term in the direction of the external magnetic field, $\vec{B}_0$ of the fluid equations [*Gomberoff*, 2000; *Gomberoff et al.*, 2001],

$$\left(\frac{\partial}{\partial t} + V \cdot \nabla\right)\vec{V} = \frac{q}{m}\left(\vec{E} + \frac{1}{c}\vec{V} \times \vec{B}\right) - \frac{\vec{\nabla} p}{mn} - \nu \vec{V}, \tag{10}$$

where ν is the damping rate.

[11] After linearization of equation (10), the new term adds a contribution $i\nu$ to ω in the left-hand side of the equation. It is simple to show that the effect of this term on the nonlinear dispersion relation, equation (2), is equivalent

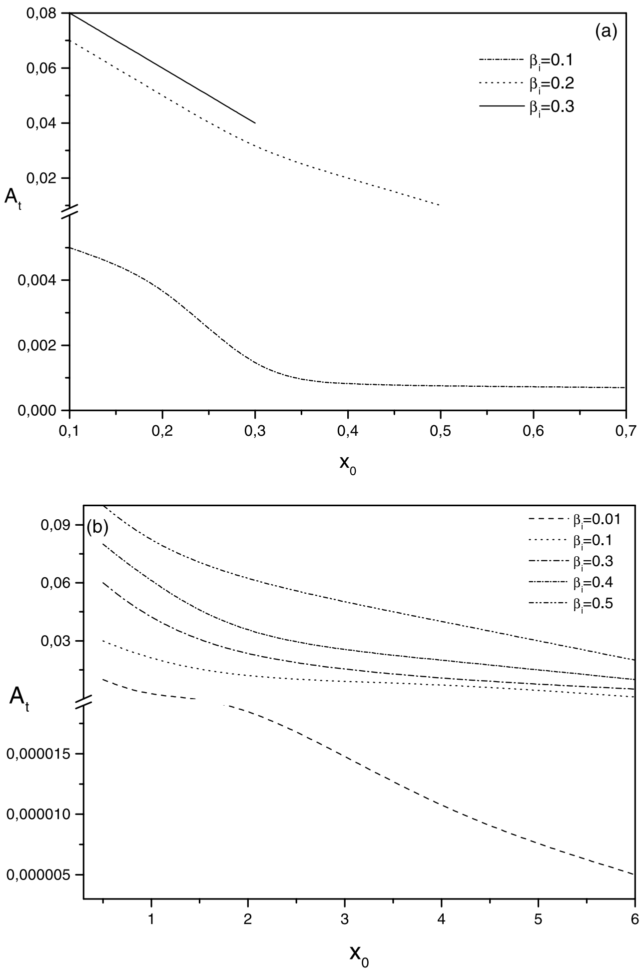

Figure 2. Threshold A_t versus x_0 for (a) left-hand polarized finite amplitude waves for β = 0.1, 0.2, 0.3, and (b) right-hand polarized large amplitude waves for β = 0.01, 0.1,0.3, 0.4, 0.5.

to replacing x^2 by $x(x + i\bar{\nu})$ in the expression for D, equation (5), with $\bar{\nu} = \nu/\Omega_p$.

[12] Using the analytic fit to the exact Landau damping solution [*Chen*, 1984; *Gomberoff*, 2000],

$$-\frac{Im\omega}{Re\omega} = 1.1\theta^{7/4}\exp(-\theta) = f(\theta), \tag{11}$$

valid for $1 < \theta < 10$, where $\theta = T_e/T_p$, From the equations (9) and (11) and denoting by $\beta = \beta_e + \beta_p$, it follows that

$$(Im(x))^2 = \frac{\beta y^2 f^2}{1 + f^2/4} \simeq \beta y^2 f^2. \tag{12}$$

Therefore using equation (12), equation (11) can be written in the form

$$|\bar{\nu}| \simeq (\beta)^{1/2} y f(\theta)$$

because $f^2/4 \ll 1$ even for the maximum of $f(\theta)$ which occurs for $\theta = 1.75$. Replacing this value of $\bar{\nu}$ in equation (5), we obtain an expression of the damping rate in terms of y, θ, and β.

[13] In Figure 3 we have plotted $\gamma = Im(x)$ as a function of y for $x_0 = 0.1$, $A = 0.3$, and $\beta = 0.1$. We have done it for $\theta = 0$ (no damping, see equation (11)) and for $\theta = 1.75$. Note that $\theta = 1.75$ maximizes the Landau damping, equation (11). From the figure it follows that the growth rate is almost the same for zero damping (thick line) and for maximum damping (thin line). For smaller β values, Landau damping is completely negligible. Therefore the instability does not depend on the relative value between T_e and T_p. It depends only on the total β value of the plasma. The maximum growth rate increases with decreasing β. For $A = 0.3$, the maximum growth rate approaches the value $\gamma = 0.05$ as β tends to zero. The behavior of the growth rate of the ion-acoustic instability for finite amplitude right-hand polarized waves is similar. The emissions are very narrow in frequency. The frequency width of the instability (see Figure 1a) is in this case $x_A - x_B \leq 10^{-2}$ and becomes smaller as closer to the point B where the instability becomes mostly electrostatic.

[14] This procedure to simulate Landau damping works very well both numerically and analytically. For a comparison between the results obtained using this approximation and the exact kinetic theory along the direction of the external magnetic field see it *Araneda* [1998] and *Gomberoff and Araneda* [2001]. This method yields results which are in agreement with those of *Inhester* [1990] and *Vasquez* [1995] obtained by using simulation techniques [*Gomberoff*, 2000; *Gomberoff and Araneda*, 2001; *Gomberoff et al.*, 2001].

4. Summary and Conclusions

[15] By solving graphically the nonlinear dispersion relation equation (2) [*Longtin and Sonnerup*, 1986], we have shown that the forward propagation ion acoustic waves involved in the parametric decay of a large-amplitude circularly polarized wave experience negligible Landau damping. The growth rate of the instability does not depend on the relative value of T_e and T_p but on the total $\beta = \beta_e + \beta_p$. In other words, they are almost unaffected by linear Landau damping. To illustrate the effect, we have chosen $\beta = 0.1$ in

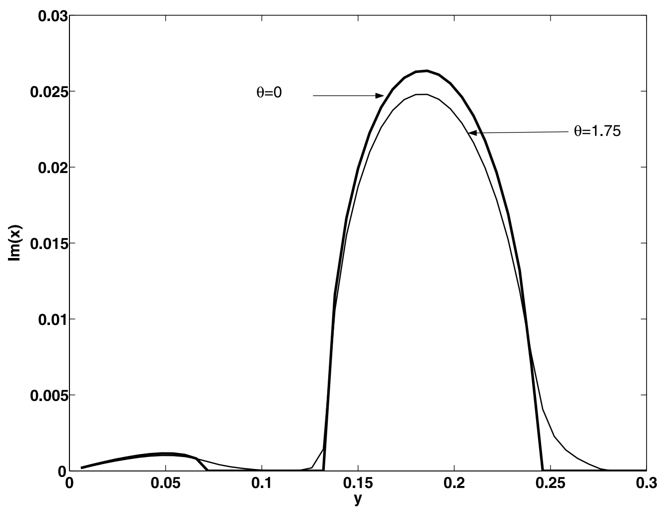

Figure 3. Growth rate γ versus y, for $x_0 = 0.1$, $\beta = 0.1$, $A = 0.3$, $\theta = 0$ (thick line), and $\theta = 1.75$ (thin line).

Figure 3. In the same way it is simple to show that for smaller beta values, Landau damping becomes even smaller. For larger β values, $\beta \geq 0.3$, Landau damping increases, but it is still too small to damp the electrostatic modes. For even larger β, $\beta \geq 0.7$, the system is stable. Although we have considered here plasma systems in the absence of ion beams, these parametric instabilities as well as new nonlinear ion-acoustic instabilities have been shown to exist in the presence of beams [see *Gomberoff et al.*, 2004].

[16] These instabilities can account for observations in the solar wind which point at ion-acoustic instabilities under conditions which are not consistent with linear ion-acoustic instability theory [see, e.g., *Gurnett*, 1991; *Marsch*, 1991, and references therein]. They occur in environments where $T_e/T_p \leq 1$. Under these conditions the ion-acoustic waves should be strongly damped. Also, assuming that the waves detected by Helios are indeed ion-acoustic waves, it is not clear what is the energy source of these instabilities. It is well known that upstream of the Earth's bow shock ion-acoustic waves are closely associated with energetic, 1 to 10 keV, proton beams originated at the bow shock [*Scarf et al.*, 1970]. However, no definite relationship has been established in the interplanetary medium between ion beams an ion acoustic waves [*Gurnett*, 1991]. In a few of the cases analyzed by, e.g., *Dum et al.* [1980] and *Marsch* [1991], waves were seen when the ion-acoustic mode was found to be stable. Measurements from Voyager 2 show that the ion-acoustic waves consist of nearly monochromatic emissions [*Kurth et al.*, 1979], which is also consistent with the ion-acoustic waves triggered by finite amplitude circularly polarized waves [*Gomberoff et al.*, 2004]. Ion acoustic waves detected by HELIOS show enhanced wave activity which tends to be more frequent and intense closer to the Sun [*Gurnett et al.*, 1979]. This fact is in agreement with the behavior of the growth rate of the instability, which has been shown to increase with decreasing β values. The instability does not occur in the absence of a large-amplitude wave, and they can occur even in the presence of ion beams. This situation is similar to that where electromagnetic ion-beam plasma linear instabilities in the solar wind are stable for beam velocities such that, in the absence of a large-amplitude wave, should be unstable [*Araneda and Gomberoff*, 2004].

[17] It is important to note that large-amplitude Alfvénic fluctuations have been observed in a number of space environments. These include the solar wind where they dominate the fast and a fraction of the slow solar wind [see., e.g., *Marsch and Tu*, 1990, 1993; *Cranmer*, 2002], the Earth's bow shock [see, e.g., *Spangler*, 1992], and in comets [see, e.g., *Tsurutani*, 1991]. Finally, since the calculations have been performed in the proton rest frame, i.e., in the solar wind frame, the ion-acoustic frequencies must be Doppler shifted by an amount proportional to the solar wind velocity [see, e.g., *Gurnett*, 1991].

[18] **Acknowledgments.** This work has been partially supported by FONDECYT grants 1020152 and 7020152. One of us (J. H.) thanks MECESUP for a doctoral fellowship.

[19] Shadia Rifai Habbal thanks two referees for their assistance in evaluating this paper.

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