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Stabilization of electromagnetic ion beam instabilities by finite amplitude Alfvén waves revisited

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In the upstream regions of the interplanetary and astrophysical shocks, quasi-coherent Alfvén waves are excited by the reflected ions or cosmic ray streaming. The energy ratio between inward and outward propagating Alfvén waves are considerable for the diffusive shock acceleration (DSA) to operate, since it affects the heating and transportation of the charged particles. Lucek and Bell claimed that in a presence of energetic plasma beam (streaming cosmic rays), wave magnetic perturbations are drastically amplified, and these magnetic perturbations can enhance the acceleration efficiency of galactic cosmic rays. On the other hand, the recent progress of the analytical and numerical models on electromagnetic ion-beam instability (R-mode instability) declares that the R-mode instability can be stabilized by the presence of finite amplitude Alfvén waves. While such new knowledge on ion-beam instability should be considerable for the DSA process, physical processes have not been discussed in detail yet. In the present short paper, we demonstrate that the dependence of the ion-beam instabilities on the amplitude of the left-hand polarized Alfvén waves. Further, we report on a new instability, which seems to be different from the instabilities reported in the past works. Other issues on ion beam instability are also discussed in the last section.

Keywords: MHD waves, ion beams, solar wind, foreshock, cosmic rays

1. Introduction

The physics of beam-plasma interactions is an important topic in space plasma physics[1, 2, 3]. In the upstream regions of the interplanetary and astrophysical shocks, quasi-coherent Alfvén waves are excited by the reflected ions or cosmic ray streaming. The energy ratio between inward and outward propagating Alfvén waves are considerable for the diffusive shock acceleration (DSA) to operate[4], since it affects the heating and transportation of the charged particles[5, 6]. Lucek and Bell[7] claimed that in the presence of energetic plasma beam components (streaming cosmic rays), wave magnetic perturbations are drastically amplified, and that the amplified magnetic perturbations can enhance the acceleration efficiency of galactic cosmic rays.

On the other hand, it is recently found that the electromagnetic ion beam instability (the "R-mode" or "resonant" instability[8, 9, 10, 11, 12]) could be stabilized or strongly decrease in the presence of large-amplitude Alfvén waves[13, 14]. Gomberoff[13] and his colleagues[15, 16, 17, 18, 19, 20] addressed the proton-proton instability in the presence of the finite amplitude Alfvén waves using the analytical model, which was the modified model of the dispersion relation on parametric instabilities of Alfvén waves in a plasma composed of massless electrons, protons, and alpha particles[21].

In the present short paper, we demonstrate the dependence of the ion beam instability on the wave amplitude, which has not clearly been shown in the past studies. We also discuss a new instability and the ion Landau damping effects. In section 2, the analytical models discussed in the present paper are briefly discussed. In section 3, we numerically discuss the growth rates of electromagnetic ion beam instabilities. The results and the future issues are discussed in section 4.

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2. Dispersion relation

In the present short paper, we discuss the electromagnetic ion beam instability in the presence of the monochromatic finite amplitude Alfvén waves. By assuming the charge-neutrality, the fluid description for each plasma species (core protons, beam protons, and massless electrons) satisfies the fluid equation, and the spatial dependence and the background magnetic field are only in the longitudinal (x) direction, we obtain the dispersion relations as follows[13, 15, 17]:

$$\begin{aligned} L_+L_-D + L_+R_-B_{-cc} + L_+R_{-b}B_{-ccb} \\ +L_-R_+B_+ + L_-R_{+b}B_{+b} \\ +(B_{-cc}B_{+b} - B_{-ccb}B_+) \\ (R_-R_{+b} - R_{-b}R_+)/D = 0, \end{aligned} \tag{1}$$

where

$$L_\pm = y_\pm^2 - \frac{x_\pm^2}{\psi_\pm} - \frac{\eta x_{\pm b}^2}{\psi_{\pm b}}$$

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

$$
\begin{aligned}
R_{\pm b} &= \frac{\eta y_{\pm}}{2\psi_{0b}}\left(x_{0b} - \frac{y x_{0b}^2}{y_0 x_b} + \frac{x_{\pm b}}{\psi_{\pm b}}\right)\\
D &= \beta_e' \Delta \eta r_b x^2 + \beta_e' \Delta_b r x_b^2 - \Delta\Delta_b (x x_b)^2\\
B_{+} &= -\beta_e' B_{+b1}\eta r x x_b + B_{+1} x^2(\beta_e' \eta r_b - \Delta_b x_b^2)\\
B_{+b} &= -\beta_e' B_{+1} r_b x x_b + B_{+b1} x_b^2(\beta_e' r - \Delta x^2)\\
B_{-cc} &= -\beta_e' B_{-ccb1}\eta r x x_b + B_{-cc1} x^2(\beta_e' \eta r_b - \Delta_b x_b^2)\\
B_{-ccb} &= -\beta_e' B_{-cc1} r_b x x_b + B_{-ccb1} x_b^2(\beta_e' r - \Delta x^2)\\
B_{+(b)1} &= -A\frac{\psi_{-(b)}(y_{+}\psi_{+(b)}x_{0(b)}^2 - y_0\psi_{0(b)}x_{+(b)}^2)}{y_0 y_{+} x_{(b)}}\\
B_{-cc(b)1} &= -A\frac{\psi_{+(b)}(y_{-}\psi_{-(b)}x_{0(b)}^2 - y_0\psi_{0(b)}x_{-(b)}^2)}{y_0 y_{-} x_{(b)}}\\
\Delta &= A + r\left(1 - \beta_c \frac{y^2}{x^2}\right)\\
\Delta_b &= A + r_b\left(1 - \beta_b \frac{y^2}{x_b^2}\right)\\
x_{(0)b} &= x_{(0)} - y_{(0)}U\\
x_{\pm b} &= x_{\pm} - y_{\pm}U\\
A &= \left(\frac{B}{B_0}\right)^2\\
r_{(b)} &= \psi_{0(b)}\psi_{+(b)}\psi_{-(b)}\\
\psi_{0(b)} &= 1 - x_{0(b)}\\
\psi_{\pm(b)} &= 1 - x_{\pm(b)}\\
x_{\pm} &= x_0 \pm x\\
y_{\pm} &= y_0 \pm y\\
\beta_e' &= \frac{\beta_e y^2}{(1+\eta)}\\
\beta_l &= \frac{4\pi n_c \gamma_l K_B T_l}{B_0^2}(l = e, c, b)
\end{aligned}
$$

and $y = kV_{Ap}/\Omega_{cp}$ is the normalized wave number, $x = \omega/\Omega_{cp}$ is the normalized frequency, $V_{Ap} = B_0/\sqrt{4\pi n_p m_p}$, $\Omega_{cp} = eB_0/m_p c$, $U = V_{0xb}/V_{Ap}$, V_{0xp} is the bulk speed of the beam protons, $\eta = n_b/n_c$, B is the amplitude of the parent Alfvén wave, K_B is the Boltzmann constant, c is the speed of light, e and m_p are the proton charge and the proton mass, T_l and n_l are the temperature and the number density of background plasmas (where $l = e, c, b$ indicate massless electrons, core protons, and beam protons, respectively), γ_l $(l = e, c, b)$ is the ratio of the specific heats, and 0 and $\pm$ in subscripts indicate that the variables relate to the parent wave and the sideband waves, respectively. Eq.(1) is for the reference in which the protons have no zeroth-order drift ($V_{0xc} = 0$). The current-free condition for the longitudinal component is satisfied from the charge neutrality. The normalized frequency and the wave number of the parent Alfvén wave (x_0 and y_0) satisfy the linear dispersion relation

$$L_0 = y_0^2 - \frac{x_0^2}{\psi_0} - \frac{\eta x_{0b}^2}{\psi_{0b}} = 0. \qquad (2)$$

We here briefly remark on Eq.(1). First, in Eq.(1),

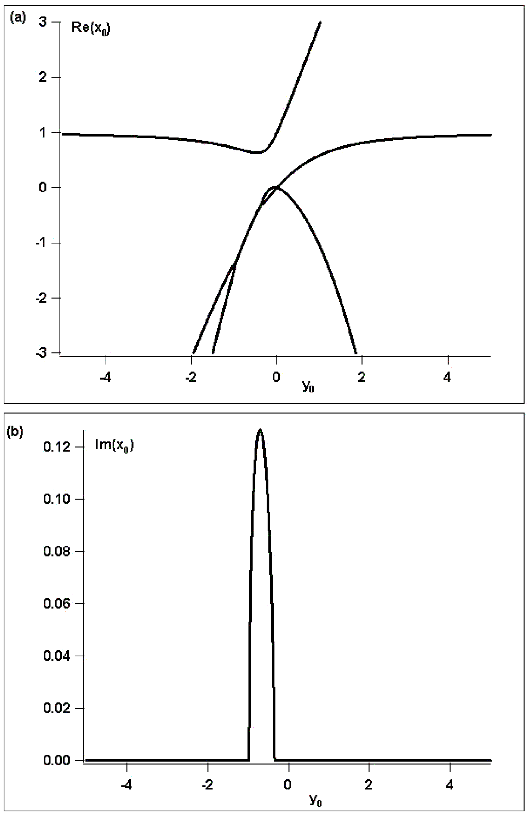

Fig. 1 (a)Linear dispersion relation and (b)growth rates obtained from Eq.(2) with $\eta = 0.2$ and $U = 2.0$.

the frequency of the parent Alfvén waves (x_0) is treated as the real constant[21]. Thus, the modes unstable to the ion-beam instability should be irrelevant to the parent Alfvén waves, while some past studies considered the unstable modes as the parent waves[15, 17]. Second, the definition of β_l in Eq.(1) is different from the one used in general (=thermal pressure/background magnetic pressure). In some past studies[13, 15, 17], the conditions $\beta_e = \beta_c = \beta_b$, which also indicate that $\gamma_e T_e = \gamma_c T_c = \gamma_b T_b$, is used. In the present paper, we consider the case $\gamma_e = 1$ and $\gamma_c = \gamma_b = 3$ in the fluid systems[22]. Namely, the conditions $\beta_e = \beta_c = \beta_b$ indicate that $T_c = T_b = \gamma_e T_e/\gamma_c = T_e/3$. We also remark that Eq.(1) is different from the dispersion relation in some previous works, which discussed the electron - proton - heavy ion plasmas[21, 23, 24].

To discuss the ion Landau damping effects of ion acoustic waves, we introduce a kinetic expression for γ_c and γ_b as a function of ξ_l, where $\xi_c = x/yV_{th,c}$, $\xi_b = x_b/yV_{th,b}$, and $V_{th,l} = \sqrt{2K_B T_l/m_p}$ $(l = c, b)$, in the form[24, 25, 26]

$$\gamma_l = 2\left(\xi_l^2 - \frac{1}{Z_l'}\right), \qquad (3)$$

where $Z_l' = -2(1 + \xi_l Z(\xi_l))$, and $Z(\xi_l)$ is the plasma dispersion function. While the some past

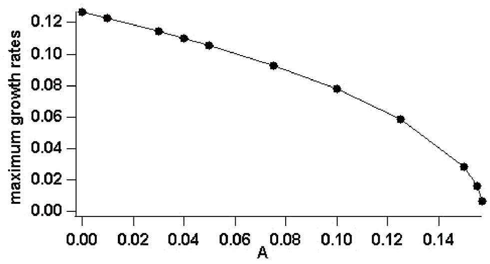

Fig. 2 The maximum growth rates of the R-mode instability for $y_0 = 0.27$ $x_0 = 0.211$ as a function of A.

studies[20, 27] introduce the damping effect through a collision-like term in the longitudinal component of the fluid equations of motion, numerical results using the model using a collision-like term do not agree with those using the exact Landau damping formulation (Eq.(3))[26]. Thus, we use Eq.(3) to discuss the ion Landau damping effects in the present study.

3. Numerical results

We numerically solve Eq.(1) with $\gamma_b = \gamma_c = 3$, $\beta_l = 0.01$, $\eta = 0.2$, $U = 2.0$, $y_0 = 0.27$, and $x_0 > 0$ (the forward propagating left-hand polarized waves). Fig. 1 shows the numerical solutions of Eq.(2). We first discuss the case that a normal left-hand polarized mode ($x_0 = 0.211$) is given. As shown in Fig. 1(a) and (b), the R-mode instability is observed in this set of parameters with $A = 0$. On the other hand, the maximum growth rates of this instability decrease with increasing A, and finally this instability is completely stabilized at a certain value $A_t \sim 0.16$ (Fig. 2)[13]. When A is relatively small, the relation between A and the maximum values of $Im(x)$ is almost linear, while when A is close to A_t, $Im(x)$ rapidly decreases.

Next we discuss the beam mode ($x_0 = 1.5$) (Fig. 1(a)), which is the same parameters in Gomberoff and Hoyos[18]. Fig. 3(a) and (b) are reproduction of Fig.2(a)(b) and Fig.3 in Gomberoff and Hoyos[18], respectively. As seen in Fig. 3(b), the stabilization of the R-mode instability occur at much smaller value of A than the previous case. However, the excitation of a new instability (Fig. 4), which are not distinctly mentioned in Gomberoff and Hoyos[18] along with the stabilization of the R-mode instability. The stabilization point of the R-mode instability (Fig. 3(b)) and the destabilization point of a new instability (Fig. 4) are surrounded by a circle in Fig. 3(a). It is also observed in Fig.2(a) of Gomberoff and Hoyos[18]. We remark that a new instability associates with the ion acoustic waves supported by the beam protons, while the R-mode instability only associate with the transverse wave modes. Thus, it seems to be different from the instabilities reported in the past works[20, 23].

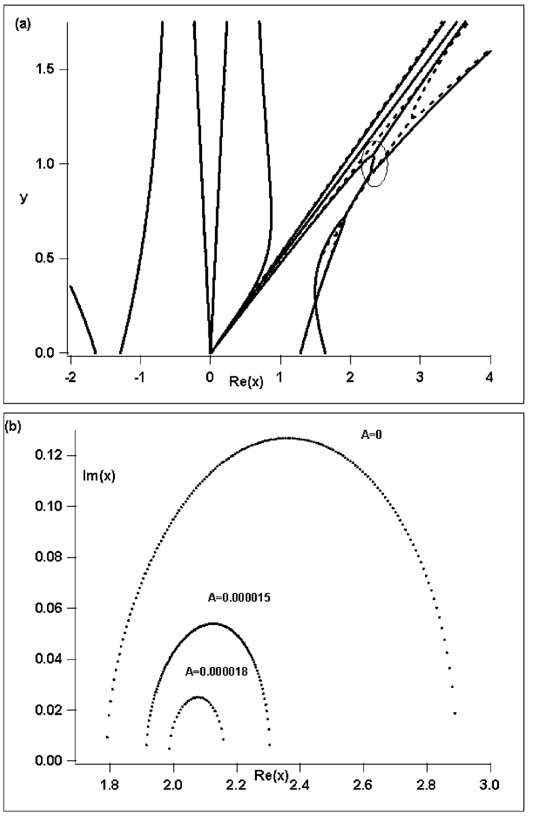

Fig. 3 (a)Dispersion relations (1) for $A = 0$ (dotted lines) and $A = 1.5 \times 10^{-5}$ (bold lines). (b)Growth rates of the R-mode instability for the corresponding A (same as Fig.3 in Gomberoff and Hoyos[18]).

Finally, we discuss the kinetic model (Eq.(1) with Eq.(3)). As shown in Fig. 4, while the exact Landau damping formulation is used, the growth rate of the R-mode instability in the kinetic model is almost same as one in the fluid model, and the growth rate of a new instability is not so much affected by the ion Landou damping effect.

4. Summary and discussion

In the present short paper, we have discussed the stabilization of the electromagnetic ion beam instability by finite amplitude left-hand polarized Alfvén waves. We have confirmed the responsibility of some results in the past studies, and demonstrated that the dependence of the growth rate of the ion-beam instabilities on the amplitude of the left-hand polarized Alfvén waves. Further, we have reported on a new instability, which seems to be different from the instabilities reported in the past works.

The recent study also declares that in the nonlinear stage of the ion-beam instabilities, parallel and quasi-parallel propagating waves convert their energy into quasi-perpendicular waves through wave-wave interactions (“nonlinearly-driven” filamentation

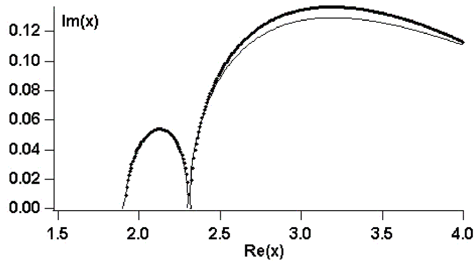

Fig. 4 Growth rates of the R-mode instability and a new instability for $A = 1.5 \times 10^{-5}$. Thick and thin lines indicate the fluid model ($\gamma_p = \gamma_c = 3$) and the kinetic model (3), respectively.

instability)[12]. We remark that it is important for the DSA process, since the quasi parallel propagating waves, which are considered as the "scatterer" of the DSA process, are possibly dissipated, and quasi-perpendicular wave modes are excited. However, only a few numerical studies discussed the nonlinear evolution of the ion-beam instability in the presence of finite amplitude Alfvén waves[14, 28].

The past studies also reported the other new instabilities such as parametric instabilities and electrostatic instabilities[21, 20, 23]. However, to our knowledge, numerical simulations on these instabilities have also not been carried out yet. Recently, Araneda *et al.*[30] discussed the generation of the proton beam components by the modulational instability of the left-hand polarized Alfvén wave. A comprehensive study on the instabilities in proton core - proton beam - electron plasmas will be reported in our future publications.

The acceleration and heating of the heavy ions are also considerable in the solar wind[1, 24, 29]. We note that the characteristics of the velocity distributions of plasmas observed by *in situ* measurements give the *constraint* to declare the acceleration and heating processes of the solar wind and the solar corona.

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