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Filamentation instability associated with dispersive Alfvén wave and solar coronal heating

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Abstract. This paper presents the nonlinear dynamics of the dispersive Alfvén wave (DAW) in the low-β plasmas ($\beta \ll m_e/m_i$; known as inertial Alfvén waves) applicable to solar corona. The pump DAW is perturbed by a low-frequency slow Alfvén wave (SW). When the ponderomotive nonlinearities are incorporated in the DAW and SW dynamics, the model equations of DAW and SW turn out to be the modified Zakharov system of equations (MZSE) Growth rate and threshold field for modulational (filamentation) instability have been calculated. The dependence of the growth rate on the perturbation wave number and the pump wave parameters such as $k_{0x}\lambda_e$ (inertial) has also been presented. It is obvious from this investigation that DAW can become unstable when it nonlinearly interacts with the SW and modulational instabilities can be triggered. The relevance of these investigations for solar corona has been discussed.

1. Introduction

The heating of the solar coronal plasma is one of the greatest challenges in modern solar physics. Although a large number of mechanisms for the coronal heating have been investigated. Recently, in situ observations from the *Cluster* and *Fast Auroral Snapshot Explorer* (FAST) spacecrafts show that these low-frequencies Alfvén waves (AWs) can be responsible for the energization of plasma particles [1]. These AWs are low-frequency electromagnetic waves in a conducting fluid propagating along magnetic field lines in space and laboratory plasmas and can be converted into kinetic Alfvén waves (KAWs) when propagating outward due to the inhomogeneities, the parameter instability, or nonlinear wave–wave coupling [2–5]. An admixture of inertial Alfvén waves (IAWs) (in low-β plasmas, i.e. $\beta \ll m_e/m_i$, β is thermal to magnetic pressure ratio) and KAWs (in intermediate-β plasmas, i.e. $m_e/m_i \ll \beta \ll 1$) is known as dispersive Alfvén waves (DAWs) [6]. The nonlinear interaction of magnetohydrodynamic (MHD) waves has been considered by many authors [1, 7, 8]. Recent observations show that DAWs can energize the plasma by nonlinear processes and various nonlinear mechanisms are proposed like oscillating two stream instability (OTSI) or filamentation instability, resonant decay, etc.

An important parametric instability is the transverse collapse of slightly perturbed small-amplitude AWs, often referred to as wave filamentation. Champeaux et al. [9] and Laveder et al. [10] studied the filamentation of AWs in the Hall-MHD

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case. The filamentation process (hot spot formation) is also found in plasmas deviating strongly from the almost one fluid state, specifically when electromagnetic beam interact with plasmas [11]. The DAW carries a non-zero parallel electric and magnetic field perturbations that play an important role in accelerating and heating plasma particles. Thus, the DAWs can energize plasma from longer spatial scales to shorter spatial scales [12]. One such means for transferring energy from the large scale to small scale is the transverse collapse leading to the formation of strong magnetic filaments parallel to the ambient field. AW filamentation [13] is a process by which a circularly polarized parallel propagating DAW train undergoes a transverse modulational instability that leads to wave energy concentration in field-aligned magnetic filaments. Starting with the pump AW, propagating along the magnetic field lines, Goldreich and Sridhar [14] have studied the saturated AW spectra involving AW with finite transverse wave number. They have considered the strong turbulence due to nonlinear interactions among shear AWs in an incompressible magnetized fluid. They found that one-dimensional energy spectrum is proportional to $k^{-5/3}$ (anisotropic Kolmogorov scaling).

Shukla et al. [15] studied the nonlinear dynamics of KAW by taking adiabatic and non-adiabatic response of acoustic wave. Growth rate and threshold power also calculated for modulational and filamentational instabilities. Many authors [16–18] studied the saturated spectra of KAW (IAW) and ion-acoustic turbulence by filamentation instability for adiabatic and non-adiabatic case. They found that the spectra approach the Kolmogorov $k^{-5/3}$ scaling. Sharma et al. [19] studied numerically the nonlinear coupling of DAW and transversely propagating magnetosonic wave. They studied the saturated spectra in adiabatic case. They found that the ponderomotive force leads to the formation of intense magnetic filaments of DAW. At higher DAW pump wave amplitude, the spectra approaches near the Kolmogorov $k^{-5/3}$ scaling.

Marklund et al. [20] studied that the large amplitude DAW can cause important nonlinear effects, parametric instabilities and the formation of envelope solitons. They have investigated the modulational instability of DAW and shown that the spectral broadening of the AWs gives rise to modulational instability growth rate. Recently, Kumar and Sharma [21] have studied the nonlinear dynamics of fast AW with DAW in the low-β as well as intermediate-β plasmas and calculated the growth rate of the instabilities. In the present paper, we discuss the parametric instability associated with DAW and slow Alfvén waves (SW). We derive the nonlinear dynamical equations of this interaction. The growth rate of this instability is calculated and the relevance of this instability in coronal heating is pointed out.

The organization of this paper is as follows: the model equations appropriate for SW and DAW in a low-β plasma are presented in Sec. 2 and Sec. 3, respectively. Nonlinear dispersion relations for the study of the instability have been obtained in the same section. Finally, in the Sec.4 we provide discussion and conclusion.

2. Basic theory

We consider the propagation of an incident high-frequency wave (DAW) in the magnetized plasma having static magnetic field along the z-axis, i.e. $\vec{B}_0 = B_0\hat{z}$. A low-frequency SW (also propagating in the x–z plane) is assumed to be nonlinearly

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interacting with this wave to give filamentation instability or modulation instability. For that we have set up the dynamical equations for the SW and DAW as follows.

2.1. Slow Alfvén Wave (SW) Dynamics

The dynamical equation for SW can be obtained as follows in the model equations.

(i) Equation of motion:

$$\frac{\partial \vec{v}_j}{\partial t} = \frac{q_j}{m_j}\vec{E} + \frac{q_j}{cm_j}(\vec{v} \times \vec{B}_0) - \frac{\gamma_j k T_j}{m_j}\vec{\nabla}\frac{n_j}{n_0} + \frac{\vec{F}_j}{m_j}, \tag{1}$$

(ii) The continuity equation:

$$\frac{\partial n}{\partial t} + \vec{\nabla}.(n\vec{v}) = 0, \tag{2}$$

(iii) Faraday's law:

$$(\vec{\nabla} \times \vec{E}) = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}, \tag{3}$$

where v_j the velocity of species $j = i, e$ ($i =$ ions, $e =$ electrons), m_j and T_j are the masses and temperature of ions and electrons, respectively, c is speed of light in vacuum and $\vec{F}_j = \left[m_j(\vec{v}_j.\vec{\nabla})\vec{v}_j - \left(\frac{q_j}{c}\right)(\vec{v}_j \times \vec{B}_0)\right]$ is the ponderomotive force on account of DAW.

Putting the values of $\vec{v}_j$ in wave equation and taking x, y and z-components of that, one can have the x-component of the equations:

$$\frac{\partial^2 E_x}{\partial z^2} - \frac{\partial^2 E_z}{\partial x \partial z} - \frac{1}{V_A^2}\frac{\partial^2 E_x}{\partial t^2} = -\beta\frac{m_e}{e}\omega^2\frac{\partial}{\partial x}\left(\frac{n_e}{n_0}\right) + \frac{4\pi ne}{c^2}\left[\frac{\omega^2 F_{ex}}{\omega_{ce} m_e} - \frac{i\omega F_{ey}}{\omega_{ce} m_e}\right], \tag{4}$$

where $V_A = \left(B_0^2/4\pi n_0 m_i\right)^{1/2}$ is the Alfvén speed, n_e is the modified electron density, n_0 is the unperturbed plasma number density and $\beta = 8\pi N_0 T_e/B_0^2$. Here, T_e is electron temperature. Similarly, y and z-components of wave equation can be derived and are given as follows:

$$\frac{\partial^2 E_y}{\partial x^2} - \frac{\partial^2 E_y}{\partial z^2} - \frac{1}{V_A^2}\frac{\partial^2 E_y}{\partial t^2} = \frac{4\pi n T_e}{cB_0}\frac{\partial^2}{\partial x \partial t}\left(\frac{n_e}{n_0}\right) + \frac{4\pi ne}{c^2}\left[\frac{\omega^2}{\omega_{ce}^2}\frac{F_{ex}}{m_e} - \frac{i\omega}{\omega_{ce}}\frac{F_{ey}}{m_e}\right], \tag{5}$$

$$\frac{\partial^2 E_z}{\partial x^2} - \frac{\partial^2 E_x}{\partial z \partial x} - \frac{1}{c^2}\frac{\partial^2 E_z}{\partial t^2} - \frac{\omega_{pe}^2}{c^2}E_z = \frac{4\pi i n T_e}{c^2 m_e}\frac{\partial}{\partial z}\left(\frac{n_e}{n_0}\right) - \frac{4\pi ne}{c^2}\left[\frac{F_{ez}}{m_e}\right], \tag{6}$$

where the ions are assumed to be cold and $\omega \ll \omega_{cj}$. The electric field components are related to each other as follows (6):

$$E_y = \frac{-iD}{(S - \eta^2)}E_x, \qquad E_z = \frac{\eta^2 \cos\theta \sin\theta}{(P - \eta^2 \sin^2\theta)}E_x,$$

$$\eta = k^2c^2/\omega^2, \quad S = 1 - \sum_j \omega_{pj}^2/\left(\omega_0^2 - \omega_{cj}^2\right) \quad \text{and} \quad D = \sum_j \omega_{cj} \times \frac{\omega_{pj}^2}{\left(\omega_0^2 - \omega_{cj}^2\right)}.$$

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The equation of continuity yields

$$\frac{\partial}{\partial t}\left(\frac{n_e}{n_0}\right) = -\frac{\partial}{\partial x}(v_{ex}) - \frac{\partial}{\partial z}(v_{ez}). \tag{7}$$

The components of ponderomotive force can be written as follows:

$$F_{jx} = -\frac{q_j^2}{4m_j\omega^2}\frac{\partial}{\partial x}\langle|E_z|^2\rangle + \frac{q_j^2}{m_j\omega^2}\left[E_z^*\frac{\partial}{\partial z}E_x\right] \tag{8}$$

and

$$F_{jy} = \frac{iq_jc}{cB_0}\left[E_z^*\frac{\partial}{\partial z}E_x\right]. \tag{9}$$

Using (7) and (9) and putting E_y, E_z in (4), one can obtains

$$\left[\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}-\frac{1}{V_A^2}\frac{\partial^2}{\partial t^2}\right)\left(\frac{\partial^2}{\partial z^2}-\frac{1}{V_A^2}\frac{\partial^2}{\partial t^2}\right)+\frac{\beta}{V_A^2}\left(\frac{\omega_{pe}^2}{\omega_{ce}^2}-\frac{c^2}{V_{Te}^2}\right)\frac{\partial^4}{\partial x^2\partial t^2}\right]\left(\frac{n_e}{n_0}\right)$$

$$= \frac{2\omega_{pe}^2}{\omega_{ce}^2B_0^2}\frac{\partial}{\partial x}\left[\left(\frac{\partial B_{0y}}{\partial x}\right)\left(\frac{\partial^2 B_{0y}}{\partial z^2}\right)\right] - \frac{c^2}{4\omega_{ce}^2B_0^2V_A^2}\frac{\partial^4}{\partial x^2\partial t^2}\left|\frac{\partial B_{0y}}{\partial x}\right|^2, \tag{10}$$

where $V_{Te}(=\sqrt{T_e/m_e})$ is the electron thermal speed and $\omega_{pe}=(4\pi n_0e^2/m_e)^{1/2}$.

Taking the Fourier transform of left-hand side and putting the right-hand side (driver term) of the above equation equal to zero, we get

$$\left[\left(k^2-\frac{\omega^2}{V_A^2}\right)\left(k_\parallel^2-\frac{\omega^2}{V_A^2}\right)+\beta k_x^2\left(\frac{\omega_{pe}^2}{\omega_{ce}^2}\frac{\omega^2}{V_A^2}-\frac{c^2}{V_{Te}^2}\frac{\omega^2}{V_A^2}\right)\right]\left(\frac{n_e}{n_0}\right)=0. \tag{11}$$

For $\beta=0$, we recover the usual two modes of the cold plasma, namely slow and fast modes, respectively, given by

$$\omega = k_\parallel V_A \quad \text{(SW)} \quad \text{and}$$

$$\omega = kV_A \quad \text{(FW)}.$$

3. Dispersive Alfvén Wave (DAW) dynamics

The dynamical equation for nonlinear DAW propagating in x–z plane, having ambient magnetic field B_0 along the z-axis, is governed by [2, 16, 22–25]

$$\frac{\partial^2\tilde{B}_y}{\partial t^2} = \Gamma_1\lambda_e^2\frac{\partial^4\tilde{B}_y}{\partial x^2\partial t^2} - \Gamma_2V_{Te}^2\lambda_e^2\frac{\partial^4\tilde{B}_y}{\partial x^2\partial z^2} + V_A^2\left(1-\frac{n_e}{n_0}\right)\frac{\partial^2\tilde{B}_y}{\partial z^2}, \tag{12}$$

where $\Gamma_1=1$ and $\Gamma_2=0$ for low-β plasmas ($\beta\ll m_e/m_i$) and $\Gamma_1=0$ and $\Gamma_2=1$ for intermediate-β plasmas ($m_e/m_i\ll\beta\ll1$), $\lambda_e=(\sqrt{c^2m_e/4\pi n_0e^2})$ is the collisionless electron skin depth.

Consider the plane wave solution of (12) as

$$\tilde{B}_y = B_y(x,z)\,e^{i(k_{0x}x+k_{0z}z-\omega t)}. \tag{13}$$

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Using (12) and (13), one gets the dynamical equation

$$-2i\omega\left(1+\Gamma_1 k_{0x}^2\lambda_e^2\right)\frac{\partial B_y}{\partial t}-\left(2i\Gamma_1 k_{0z}V_A^2+2i\Gamma_2 k_{0z}k_{ox}^2\lambda_e^2V_{Te}^2\right)$$

$$\times\frac{\partial B_y}{\partial z}-\left(\Gamma_1 V_A^2+\Gamma_2 k_{0x}^2V_{Te}^2\lambda_e^2\right)\frac{\partial^2 B_y}{\partial z^2}+\left(\Gamma_1\lambda_e^2\omega^2-\Gamma_2 V_{Te}^2\lambda_e^2k_{0z}^2\right)\frac{\partial^2 B_y}{\partial x^2}$$

$$+2ik_{0x}\lambda_e^2\left(\Gamma_1\omega^2-\Gamma_2V_{Te}^2k_{0z}^2\right)\frac{\partial B_y}{\partial x}-k_{0z}^2V_A^2n_eB_y=0. \tag{14}$$

The above dynamical equation for DAW has been studied by many authors numerically [18, 26] and analytically [27–28] by taking the appropriate value of n_e in adiabatic and non-adiabatic cases, when the low-frequency perturbing wave is ion-acoustic- wave. In our present case, n_e is due to the low-frequency SW as given by (10). One can write down the system of (10) and (14) in dimensionless form as follows:

$$\left[\frac{\partial^2 n_e}{\partial z^2}-\zeta_1\frac{\partial^2 n_e}{\partial t^2}\right]=-|B_{0y}|^2-\zeta_2\frac{\partial^2}{\partial x^2}|B_{0y}|^2 \tag{15}$$

and

$$+i\frac{\partial B_y}{\partial t}\mp i\frac{\partial B_y}{\partial x}+i\frac{\partial B_y}{\partial z}+\zeta_3\frac{\partial^2 B_y}{\partial z^2}+n_eB_y=0, \tag{16}$$

where the lower sign in two sign convention (hereafter also unless specified) corresponds to plasmas with low-β ($\beta\ll m_e/m_i$) with

$$\zeta_1=\frac{\omega^2}{k_{0x}^2V_A^2}\frac{(k_{0x}\lambda_e)^4}{\left(1+k_{0x}^2\lambda_e^2\right)^2},\quad \zeta_2=\frac{c^2\omega^2k_{0x}^2}{2\omega_{pe}^2k_{0z}^2V_A^2}$$

and $\zeta_3=k_{0x}^2\lambda_e^2$ and upper sign to intermediate-β ($m_e/m_i\ll\beta\ll1$) plasmas with

$$\zeta_1=\frac{\omega^2}{k_{0x}^2V_A^2}\left(k_{0x}\lambda_e\frac{V_{Te}}{V_A}\right)^4,\quad \zeta_2=\frac{c^2\omega^2k_{0x}^2}{4\omega_{pe}^2k_{0z}^2V_A^2}\quad\text{and}\quad \zeta_3=\left(k_{0x}\lambda_e\frac{V_{Te}}{V_A}\right)^2.$$

In our case, we get modified Zakharov system of equations (MZSE) (see (15) and (16)). The normalizing parameters for low-β plasma are

$$x_n=1/k_{0x}\simeq2.6\times10^3\,\text{cm},\quad z_n=1/2k_{0z}k_{0x}^2\lambda_e^2\simeq2.5\times10^7\,\text{cm},$$

$$n_N=4n_0k_{0x}^2\lambda_e^2\simeq4\times10^4\,\text{cm}^{-3},\quad B_n=8Bk_{0x}\lambda_e\simeq2.56G,$$

$$t_n=\left(1+k_{0x}^2\lambda_e^2\right)/2\omega k_{0x}^2\lambda_e^2\simeq0.362\ \text{sec}.$$

The actual numerical values of ζ_1, ζ_2 and ζ_3 can be calculated from the parameters given in Sec. 3. Here, we have considered $\partial_xB_y\ll k_{0x}B_y$in writing (16). Taking the space as well as time dependence of the wave amplitude as $\sim\exp[i(k_xx+\alpha z-\omega t)]$ and following the standard techniques [29], the system of (15) and (16) gives the following dispersion relation for low-β plasmas:

$$\zeta_1\omega^4+\{\zeta_1(2k_x+2\alpha)\}\omega^3+\left\{\zeta_1\left(k_x^2+\alpha^2-2k_x\alpha-\zeta_0\alpha^4\right)+\alpha^2\right\}\omega^2$$

$$-\left\{\alpha^2(2k_x-2\alpha)\right\}\omega-\alpha^2\left(k_x^2+\alpha^2-2k_x\alpha-\zeta_0\alpha^4\right)+2\zeta_0\alpha^2\left(\zeta_3k_x^2-1\right)B_{0y}=0, \tag{17}$$

where B_{0y} is the pump DAW amplitude, $k_x$and α are the perpendicular and parallel wave numbers of perturbation, respectively. The values of ζ_1, ζ_2 and ζ_3 can be

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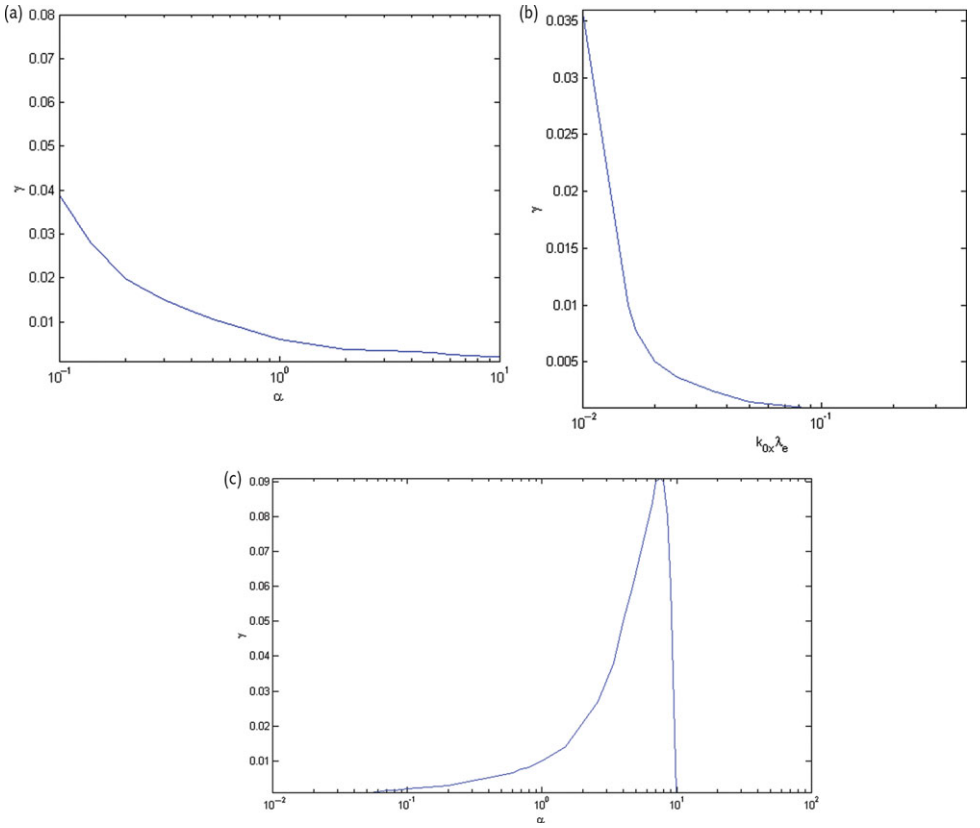


Figure 1. (Colour online) (a) Variation in growth rate temporal γ against α for low-β plasmas. (b) Variation in growth rate temporal γ against $k_{0x}\lambda_e$ for low-β plasmas. Here, the frequency normalization has been used corresponding to $k_{0x}\lambda_e = 0.01$. (c) Variation in growth rate (spatial) γ against α for low-β plasmas.

estimated from the low-β plasmas parameters. The above equation is a fourth-order equation in ω that is very difficult to solve analytically. Therefore, we have solved this equation numerically by using root finding algorithm in MATLAB. We have four roots ofω for a given k_{0x}, α and B_{0y}. In order to study the dependence of growth rate on perturbation wave number α, we have plotted a curve of growth rate γ with respect to α but keeping B_{0y} and k_x fixed, as shown in Fig. 1(a). It is clear from the figure that, as we increase α, the growth rate decreases to zero from its maximum value. The homogeneous threshold field for solar corona parameters comes out to be $B_{0y}/B_N = 0.015$. We have also plotted a curve of growth rate γ against $k_{0x}\lambda_e$ keeping B_{0y} and k_x fixed, as shown in Fig. 1(b). It is also clear from the figure that, as we increase $k_{0x}\lambda_e$, the growth rate decreases to zero from its maximum value.

Taking the space dependence of the wave amplitudes as $\sim\exp[i(k_x x + \alpha z)]$ and following the standard procedure (15) and (16) give the following dispersion relation for low-β plasmas:

$$\left(1 + 2\zeta_2\zeta_3 B_{0y}^2\right) k_x^2 - 2\alpha k_x + \alpha^2 - \zeta_2\alpha^4 - 2\zeta_2 B_{0y}^2 = 0. \tag{18}$$

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Equation (18) is second-order equations in k_x and these equations give two roots of k_x. Linear growth rate of the instability, for given ζ_0, ζ_2, ζ_3, α and B_{0y} can be calculated numerically. Keeping B_{0y} fixed, the variation in spatial growth rate against α is shown in Fig. 1(c) for low-β. It is clear from the figure that, as we increase α, the growth rate of the instability first increases gradually and then decreases after attaining maximum value. The homogeneous threshold field for the spatial case comes out to be $B_{0y}/B_N = 0.003$.

For application purpose in low-β plasmas, the typical parameters in solar coronal holes [9] are $B_0 \approx 32G$, $n_0 \approx 10^8\,\mathrm{cm}^{-3}$, $T_e = 0.4 \times 10^6\,\mathrm{K}$ and $T_i = 0.2 \times 10^6\,\mathrm{K}$. Using these values, one finds that $V_A \approx 7 \times 10^8\,\mathrm{cm\,s}^{-1}$, $V_{Te} = 2.5 \times 10^8\,\mathrm{cm\,s}^{-1}$, $\omega_{ci} \approx 3 \times 10^5$ Hz and $\beta \approx 2 \times 10^{-4}$. For $\omega = 13.8 \times 10^3$ Hz and $k_{0x}\lambda_e = 0.01$, we get $k_{0x} = 1.9 \times 10^{-4}\,\mathrm{cm}^{-1}$, $k_{0z} = 2 \times 10^{-5}\,\mathrm{cm}^{-1}$. For these typical parameters, we find $x_n \simeq 2.6 \times 10^3\,\mathrm{cm}$, $z_n \simeq 2.5 \times 10^7\,\mathrm{cm}$, $t_n \simeq 0.362\,\mathrm{s}$, $n_N \simeq 4 \times 10^4\,\mathrm{cm}^{-3}$ and $B_N/B_0 \simeq 9.48 \times 10^{-2}$.

4. Discussion and conclusion

To summarize, we have presented an investigation of the modulational and filamentational instabilities associated with DAW in a low-β when pump DAW is perturbed by a low-frequency SW. The model equations of DAW and SW turn out to be the MZSE when the ponderomotive nonlinearities are included in the DAW and SW dynamics. The dependence of the growth rate on the perturbation wave number and the pump wave parameters like $k_{0x}\lambda_e$ (intertial) has also been presented. It is obvious from this investigation that DAW can become unstable when it nonlinearly interacts with the SW; therefore, modulational and filamentation instabilities can be triggered.

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References

[1] Wu, D. J. and Yang, L. 2006 *Astron. Astrophys.* **452**, L7–L10.
[2] Shukla, A. and Sharma, R. P. 2001 *Phys. Plasmas* **8**, 3759.
[3] Shukla, A., Sharma, R. P. and Malik, M. 2004 *Phys. Plasmas* **7**, 2738.
[4] Voitenko, Y., Goossens, M., Sirenko, O. and Chian, A. C. L. 2003 *Astron. Astrophys.* **409**, 331.
[5] Voitenko, Y. and Goossens, M. 2004 *Nonl. Proc. Geophys.* **11**, 535.
[6] Shukla P. K. and Stenflo, L. 2005 *Phys. Plasmas* 1**2**, 084502.
[7] Shukla, P. K., Bingham, R., Eliasson, B., Dieckmann M. E. and Stenflo, L. 2006 *Plasma Phys. Control Fusion* **48**, B249–B255.
[8] Shukla, P. K. and Stenflo, L. 2005 *Astrophys. J.* **629**, L93–L95.
[9] Champeaux, S., Passot, T. and Sulem, P. L. 1999 Alfven wave filamentation and plasma heating. In: *Proc. Workshop on Nonlinear MHD Waves and Turbulence, Nice, France,*

https://doi.org/10.1017/S0022377811000122 Published online by Cambridge University Press

1 December–4 December 1998, (ed. T. Passot and P. L. Sulem), New York: Springer-Verlag, pp. 55–82.
[10] Laveder, D., Passot, T. and Sulem, P. L. 2001 *Physica* D **152–153**, 694–704.
[11] Kruer, W. L. 1988 *The Physics of Laser Plasma Interactions.* Reading, MA, USA: Addison-Wesley-Longman.
[12] Tsiklauri, D., Sakai, J. I. and Saito, S. 2005 *Astron. Astrophys.* **435**, 1105.
[13] Passot, T. and Sulem, P. L. 2003 *Phys. Plasmas* **10**, 3914.
[14] Goldreich, P. and Sridhar 1995 *Astrophys. J.* **438**.
[15] Shukla, P. K., Stenflo, L. and Bingham, R. 1999 *Phys. Plasmas* **6**, 1677.
[16] Sharma, R. P., Singh, H. D. and Malik M. 2006 *J. Geophys. Res.* **111**, A12108.
[17] Singh, H. D. and Sharma, R. P. 2007 *Phys. Plasmas* **14**, 102304.
[18] Malik, M., Sharma, R. P. and Singh, H. D. 2007 *Sol. Phys.* **241**, 317.
[19] Sharma, R. P., Kumar, S. and Singh, H. D. 2009 *Phys. Plasmas* **16**, 032901.
[20] Marklund, M., Shukla, P. K., Stenflo, L. and Lundin, J. 2006 *Phys. Scr.* **74**, 373–376.
[21] Kumar, S. and Sharma, R. P. 2010 *Phys. Plasmas* **17**, 1.
[22] Bellan, P. M. and Stasiewicz, K. 1998 *Phys. Rev. Lett.* **80**, 3523.
[23] Shukla, P. K. and Stenflo, L. 1999 *Phys. Plasmas* **6**, 4120.
[24] Shukla, P. K. and Stenflo, L. 2000 *Phys. Plasmas* **7**, 2738.
[25] Shukla, A. and Sharma, R. P. 2000 *J. Geophys. Res.* **107**, 1338.
[26] Sharma, R. P., Kumar, S. and Singh, H. D. 2008 *Phys. Plasmas* **15**, 082902.
[27] Singh, H. D. and Sharma, R. P. 2006 *Phys. Plasmas* **13**, 012902.
[28] Shukla, A. and Sharma, R. P. 2002 *J. Atmos. Sol. Terr. Phys.* **64**, 661.
[29] Shen, M. M. and Nicholson D. R. 1987 *Phys. Fluids* **30**, 1096.

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