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Nonlinear magnetoacoustic waves in pair-ion plasma with dust impurity

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Abstract. Nonlinear properties of magnetoacoustic waves are investigated in magnetized pair-ion plasmas with dust impurity. Three-fluid collisionless magneto-hydrodynamic model is considered and reductive perturbation method is employed to derive Korteweg-de Vries equation for magnetoacoustic solitary waves (MASWs). The effects of the charge number of dust particles, magnetic field intensity, and plasma number density are studied on MASWs. It is found that the variation of parameters causes significant changes in solitary structures. The present investigation may be useful to understand formation and propagation of MASW structures in dust pair-ion plasmas.

1. Introduction

In recent years, physics of pair-ion (PI) plasmas consisting of only positive- and negative-charged particles with an equal mass has received a great attention. PI plasma represents a new state of matter with unique thermodynamic properties drastically different from ordinary plasmas. The electron–positron (e-p) plasmas are PI plasmas and exist in astrophysical plasma situations such as active galactic nuclei, neutron stars, quasars, and pulsar magnetospheres (Stenflo et al. 1985; Iwamoto 1993; Zank and Greaves 1995). Although e-p plasmas can be produced experimentally (Zank and Greaves 1995), the short life time of e-p plasmas and the low density production of positrons in laboratory experiments make it difficult to analyze various collective modes. It is necessary for long time-scale plasma to meet the condition that the annihilation time scale is many orders of magnitude larger than the plasma period. In order to overcome the problem of short time scales of e-p pair plasma, Oohara et al. (Oohara and Hatakeyama 2003, 2007; Oohara et al. 2005, 2007) developed a novel method for the generation of PI plasmas by impact ionization of a gas of fullerenes (C_{60}). Many authors have investigated pair plasmas collective modes in pure PI plasma (Dubinov et al. 2006; Moslem et al. 2007; Diver and Laing 2009; Mahmood and Ur-Rehman 2010; Shah et al. 2010; Verheest 2010) as well as nonlinear wave structures in the presence of dust as an impurity (Moslem and Shukla 2006; Sabry 2008; Chatterjee et al. 2009; El-Shamy 2009; Mushtaq et al. 2012; Ur-Rehman 2012).

Magnetoacoustic wave is a fundamental mode in magnetized plasma which propagates in the perpendicular direction of external magnetic field, and both density and magnetic field compression are responsible for the propagation of magnetoacoustic wave (Miller and Wiita 1986). Many authors have investigated magnetoacoustic solitary waves' (MASWs) nonlinear structures in recent years (Hussain and Mahmood 2011a,b, 2012; Liu et al. 2011; Valiulina and Dubinov 2012; Masood et al. 2013; Ruan et al. 2013). However, to the best of our knowledge, the propagation of MASWs in PI plasmas has not been investigated so far. In this paper we derive the Korteweg-de Vries (KdV) equation for the propagation of nonlinear magnetoacoustic waves in magnetized pair-ion–dust (PID) plasmas. In our model, we ignore the inertia of positive and negative ions, whereas the dust is dynamic.

In this study, the magneto-hydrodynamic (MHD) model is applied to investigate the propagating MASWs in PID plasma. The KdV equation is derived by using three-fluid MHD model and the reductive perturbation technique. This paper is organized as follows: In Sec. 2, the basic set of dynamic equations of PID plasma for MASWs is presented. In Sec. 3, the KdV equation is derived using the reductive perturbation method and the solitary solution is obtained. In Sec. 4, the numerical results are presented and discussed. Finally, summary of the work is given in Sec. 5.

2. Governing equations

We consider three-fluid collisionless homogenous magnetized plasma consisting of PI plasma with small fraction of arbitrarily ($s = \pm 1$) charged dust grains, $s = 1(-1)$ for negatively (positively) charged dust grains. The quasi-neutral condition at background is $n_{+0} = n_{-0} + sZ_d n_{d0}$, where n_{+0}, n_{-0}, and n_{d0} are the equilibrium number densities of positive ions, negative ions, and dust, respectively. The positive and negative ion masses are $m_+ = m_- = m$, the external magnetic field is directed along the z-axis, i.e. $\mathbf{B}_0 = B_0\hat{z}$, where $\hat{z}$ is the unit vector in the z-axis. The set of dynamic equations for nonlinear magnetoacoustic waves in plasmas is given as follows:

The continuity and momentum equations for the dust are given by

$$\frac{\partial n_d}{\partial t} + \nabla\cdot(n_d\mathbf{V}_d) = 0, \tag{2.1}$$

$$\frac{\partial \mathbf{V}_d}{\partial t} + (\mathbf{V}_d\cdot\nabla)\mathbf{V}_d = -\frac{sZ_d e}{m_d}\left(\mathbf{E} + \frac{1}{c}(\mathbf{V}_d\times\mathbf{B})\right). \tag{2.2}$$

The continuity and momentum equations for positive ions are described as follows:

$$\frac{\partial n_+}{\partial t} + \nabla\cdot(n_+\mathbf{V}_+) = 0, \tag{2.3}$$

$$0 = \frac{e}{m}\left(\mathbf{E} + \frac{1}{c}(\mathbf{V}_+\times\mathbf{B})\right) - \frac{T_+}{mn_+}\nabla n_+. \tag{2.4}$$

The continuity and momentum equations for negative ions are written as follows:

$$\frac{\partial n_-}{\partial t} + \nabla\cdot(n_-\mathbf{V}_-) = 0, \tag{2.5}$$

$$0 = -\frac{e}{m}\left(\mathbf{E} + \frac{1}{c}(\mathbf{V}_-\times\mathbf{B})\right) - \frac{T_-}{mn_-}\nabla n_-. \tag{2.6}$$

Faraday's law is given by

$$\nabla\times\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}, \tag{2.7}$$

and Ampere's law can be written as

$$\nabla\times\mathbf{B} = \frac{4\pi}{c}\mathbf{j} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t}, \tag{2.8}$$

where V_d, V_+, V_-, T_+, T_-, m_d, m, n_d, n_+, and n_- denote the velocity, temperature, mass, number density of dust, positive ions, and negative ions, respectively, $\mathbf{E}$ is the electric field vector, and $\mathbf{j}$ is the current density.

The normalized set of dynamic equations is given as follow:

$$\frac{\partial n_d}{\partial t} + \nabla\cdot(n_d\mathbf{V}_d) = 0, \tag{2.9}$$

$$\frac{\partial \mathbf{V}_d}{\partial t} + (\mathbf{V}_d\cdot\nabla)\mathbf{V}_d = -sZ_d\mathbf{E} - s\mathbf{V}_d\times\mathbf{B}, \tag{2.10}$$

$$\frac{\partial n_+}{\partial t} + \nabla\cdot(n_+\mathbf{V}_+) = 0, \tag{2.11}$$

$$0 = \mathbf{E} + \frac{1}{Z_d}\mathbf{V}_+\times\mathbf{B} - \frac{\beta}{Z_d n_+}\nabla n_+, \tag{2.12}$$

$$\frac{\partial n_-}{\partial t} + \nabla\cdot(n_-\mathbf{V}_-) = 0, \tag{2.13}$$

$$0 = -\mathbf{E} - \frac{1}{Z_d}\mathbf{V}_-\times\mathbf{B} - \frac{\sigma\beta}{Z_d n_-}\nabla n_-, \tag{2.14}$$

$$\nabla\times\mathbf{E} = -\frac{1}{Z_d}\frac{\partial \mathbf{B}}{\partial t}, \tag{2.15}$$

$$\nabla\times\mathbf{B} = \mathbf{j} + \alpha\frac{\partial \mathbf{E}}{\partial t}, \tag{2.16}$$

and

$$\mathbf{j} = \delta n_+\mathbf{V}_+ - (\delta - s)n_-\mathbf{V}_- - sn_d\mathbf{V}_d.$$

Here in (2.9)–(2.16), the plasma number density is defined as $n_j = \frac{n_j}{n_{j0}}(j = +,-,d)$, velocity is normalized by dust Alfven speed $V_{dA}(V_{dA} = \frac{B_0}{\sqrt{4\pi m_d n_{d0}}})$, magnetic field is normalized by B_0, electric field is normalized by $\frac{m_d V_{dA}\Omega_d}{e}$, $\Omega_d = \frac{Z_d e B_0}{m_d c}$ is the dust gyro-frequency, and c is the speed of light. The dust acoustic speed is defined as $V_{sd} = \sqrt{\frac{Z_d T_+}{m_d}}$. The normalization of space and time is defined as $r = \frac{r\Omega_d}{V_{dA}}$ and $t = t\Omega_d$. The temperature ratio of negative ions to positive ions is defined as $\sigma = \frac{T_-}{T_+}$. The other parameters such as $\beta = \frac{V_{sd}^2}{V_{dA}^2}$, $\delta = \frac{n_{+0}}{Z_d n_{d0}}$, and the ratio of Alfven velocity to the velocity of light in free space is defined as $\alpha = Z_d\frac{V_{dA}^2}{c^2}$. The wave propagation for magnetoacoustic waves is taken along the x-axis only, i.e. $\nabla = (\frac{\partial}{\partial x}, 0, 0)$.

3. Derivation of the KdV equation

In order to derive the KdV equation, we use the reductive perturbation technique (Washimi and Taniuti 1966):

$$\xi = \varepsilon^{1/2}(x - \lambda t), \tau = \varepsilon^{3/2}t. \tag{3.1}$$

The physical quantities n_j, V_{jx}, V_{jy}, B, and E can be expanded as a power series in ε as follows:

$$\begin{aligned} n_j &= 1 + \varepsilon n_j^{(1)} + \varepsilon^2 n_j^{(2)} + \cdots, \\ V_{jx} &= \varepsilon V_j^{(1)} + \varepsilon^2 V_j^{(2)} + \cdots, \\ V_{jy} &= \varepsilon^{3/2} U_j^{(1)} + \varepsilon^{5/2} U_j^{(2)} + \cdots, \\ B_z &= 1 + \varepsilon B^{(1)} + \varepsilon^2 B^{(2)} + \cdots, \\ E_x &= \varepsilon^{3/2} E^{(1)} + \varepsilon^{5/2} E^{(2)} + \cdots. \end{aligned} \tag{3.2}$$

Substituting (3.1) and (3.2) into (2.9)–(2.16) and collecting the lowest order ($\varepsilon^{3/2}$) terms of momentum and continuity equations, we have

$$V_+^{(1)} = V_-^{(1)} = V_d^{(1)} = \lambda n_+^{(1)} = \lambda n_-^{(1)} = \lambda n_d^{(1)} = \lambda B^{(1)}. \tag{3.3}$$

$$\begin{aligned} &E^{(1)} = C_0\frac{\partial B^{(1)}}{\partial \xi}, U_+^{(1)} = C_+\frac{\partial B^{(1)}}{\partial \xi}, U_-^{(1)} = C_-\frac{\partial B^{(1)}}{\partial \xi}, \\ &U_d^{(1)} = C_d\frac{\partial B^{(1)}}{\partial \xi}. \end{aligned} \tag{3.4}$$

$$\lambda = \sqrt{\frac{Z_d(1 + \delta\beta + \sigma\delta\beta - s\sigma\beta)}{Z_d + \alpha}}, \tag{3.5}$$

where $C_0 = -\frac{\lambda^2}{Z_d+\alpha}$, $C_+ = \frac{Z_d\lambda^2}{Z_d+\alpha} + \beta$, $C_- = \frac{Z_d\lambda^2}{Z_d+\alpha} - \sigma\beta$, and $C_d = (\frac{Z_d}{Z_d+\alpha} - s)\lambda^2$, and λ is the phase speed of the magnetoacoustic wave.

From the terms of order $\varepsilon^{5/2}$ we obtain the following:

$$\frac{\partial n_d^{(1)}}{\partial \tau} - \lambda\frac{\partial n_d^{(2)}}{\partial \xi} + \frac{\partial}{\partial \xi}(n_d^{(1)}V_d^{(1)}) + \frac{\partial V_d^{(2)}}{\partial \xi} = 0,$$

$$\frac{\partial V_d^{(1)}}{\partial \tau} - \lambda\frac{\partial V_d^{(2)}}{\partial \xi} + V_d^{(1)}\frac{\partial V_d^{(1)}}{\partial \xi} + sZ_dE^{(2)} + sZ_dU_d^{(2)}$$

$$+ sU_d^{(1)}B^{(1)} = 0,$$

$$\frac{\partial n_+^{(1)}}{\partial \tau} - \lambda\frac{\partial n_+^{(2)}}{\partial \xi} + \frac{\partial}{\partial \xi}(n_+^{(1)}V_+^{(1)}) + \frac{\partial V_+^{(2)}}{\partial \xi} = 0,$$

$$Z_dE^{(2)} + U_+^{(2)} + U_+^{(1)}B^{(1)} - \beta\frac{\partial n_+^{(2)}}{\partial \xi} + \beta n_+^{(1)}\frac{\partial n_+^{(1)}}{\partial \xi} = 0,$$

$$\frac{\partial n_-^{(1)}}{\partial \tau} - \lambda\frac{\partial n_-^{(2)}}{\partial \xi} + \frac{\partial}{\partial \xi}(n_-^{(1)}V_-^{(1)}) + \frac{\partial V_-^{(2)}}{\partial \xi} = 0,$$

$$Z_dE^{(2)} + U_-^{(2)} + U_-^{(1)}B^{(1)} + \sigma\beta\frac{\partial n_-^{(2)}}{\partial \xi} - \sigma\beta n_-^{(1)}\frac{\partial n_-^{(1)}}{\partial \xi} = 0,$$

$$\frac{\partial B^{(1)}}{\partial \tau} - \lambda\frac{\partial B^{(2)}}{\partial \xi} + \frac{\partial V_+^{(2)}}{\partial \xi} + \frac{\partial}{\partial \xi}(V_+^{(1)}B^{(1)}) = 0,$$

$$\frac{\partial B^{(2)}}{\partial \xi} + \delta U_+^{(2)} + \delta U_+^{(1)}n_+^{(1)} - (\delta - s)U_-^{(2)} - (\delta - s)\delta U_-^{(1)}n_-^{(1)}$$

$$- sU_d^{(2)} - sU_d^{(1)}n_d^{(1)} + \frac{\alpha}{Z_d}\frac{\partial V_+^{(1)}}{\partial \tau} - \frac{\alpha\lambda}{Z_d}\frac{\partial}{\partial \xi}(B^{(1)}V_+^{(1)})$$

$$- \frac{\alpha\lambda}{Z_d}\frac{\partial V_+^{(2)}}{\partial \xi} = 0. \quad (3.6)$$

The next higher order terms of ε, i.e. ($\sim \varepsilon^2$) are described as follows:

$$-s\lambda\frac{\partial U_+^{(1)}}{\partial \xi} = V_d^{(2)} - V_+^{(2)},$$

$$V_+^{(2)} + 2V_+^{(1)}B^{(1)} = 0,$$

$$V_-^{(2)} + 2V_-^{(1)}B^{(1)} = 0, \quad (3.7)$$

$$\delta V_+^{(2)} + \delta V_+^{(1)}n_+^{(1)} - (\delta - s)V_-^{(2)} - (\delta - s)V_-^{(1)}n_-^{(1)}$$

$$- sV_e^{(2)} - sV_e^{(1)}n_e^{(1)} - \alpha\lambda\frac{\partial E^{(1)}}{\partial \xi} = 0.$$

Now by eliminating $n_+^{(2)}$, $n_-^{(2)}$, $n_d^{(2)}$, $V_+^{(2)}$, $V_-^{(2)}$, $V_d^{(2)}$, $U_+^{(2)}$, $U_-^{(2)}$, $U_d^{(2)}$, and $E^{(2)}$, one can finally obtain

$$\frac{\partial B^{(1)}}{\partial \tau} + PB^{(1)}\frac{\partial B^{(1)}}{\partial \xi} + Q\frac{\partial^3 B^{(1)}}{\partial \xi^3} = 0. \quad (3.8)$$

The nonlinear and dispersive coefficients P and Q in (24) are given as

$$P = \frac{Z_d[3\lambda^2 + (\delta - s)C_- - \delta C_+ - sZ_dC_0]}{Z_d + \alpha},$$

$$Q = \frac{sZ_dC_d\lambda}{2(Z_d + \alpha)}.$$

In order to find the solution of (24), we use the transformation $\eta = \xi - u_0\tau$ for a comoving frame with velocity u_0 of the nonlinear structure, and used the boundary conditions, i.e. $B^{(1)} \to 0$ and $\frac{\partial B^{(1)}}{\partial \xi}$, $\frac{\partial^2 B^{(1)}}{\partial \xi^2}$, $\frac{\partial^3 B^{(1)}}{\partial \xi^3} \to 0$ as $\eta \to \infty$ for the localized solution. We obtain the following soliton solution:

$$B^{(1)} = \phi sech^2\left(\frac{\eta}{\triangle}\right), \quad (3.9)$$

where u_0 is the velocity of the soliton, and ϕ and $\triangle$ represent the amplitude and width of soliton, respectively,

$$\phi = \frac{3u_0}{P}, \triangle = \sqrt{\frac{4Q}{u_0}}. \quad (3.10)$$

4. Results and discussion

In this section we will investigate the dependence of MASWs on relevant plasma parameters such as the charge number Z_d, magnetic field, and plasma density. We present the numerical results by choosing some laboratory parameters, i.e. $n_+ = 1\times10^7 \sim 2\times10^8$ cm^{-3}, $B_0 = 10^3 \sim 10^4$ G, $T_+(T_-) = 0.3 \sim 0.5$ eV (Oohara and Hatakeyama 2003, 2007; Oohara et al. 2005, 2007), and $m_d \sim 2\times10^{-18}$ kg (DAngelo 2001; Chabrier et al. 2002), to investigate the effects of different plasma parameters on MASWs in PID plasmas.

First of all we investigate the effect of dust charge number (Z_d) of the ($s = 1$) charged dust particles on solitary wave structures. Figure 1 shows increase in the amplitude of the solitary wave as the dust charge number is raised, while the width of the structure remains the same.

The external magnetic field intensity variation has an impact on the solitary wave structure of MASWs in PID plasmas as shown in Figs. 2 and 3. It can be seen evidently from Fig. 2 that by increasing the magnetic field intensity B_0, the amplitude of the structure increases and the width decreases for negatively charged dust particles. However, it is observed from Fig. 3 that by increasing the value of magnetic field intensity B_0, both amplitude and width of solitary wave increase for positively charged dust particles in PID plasma.

We have studied the variation of MASWs structures with increasing plasma number density. In Fig. 4, the amplitude of MASWs decreases and the width increases by increasing positive ions number density n_{+0}, while the width of solitary waves remains the same. It can be easily seen from Fig. 5 that the amplitude and width of solitary wave increase by enhancing the value of dust number density, n_{d0}.

5. Summary and conclusions

To summarize, we have studied the nonlinear properties of magnetized PID plasmas using the three-fluid

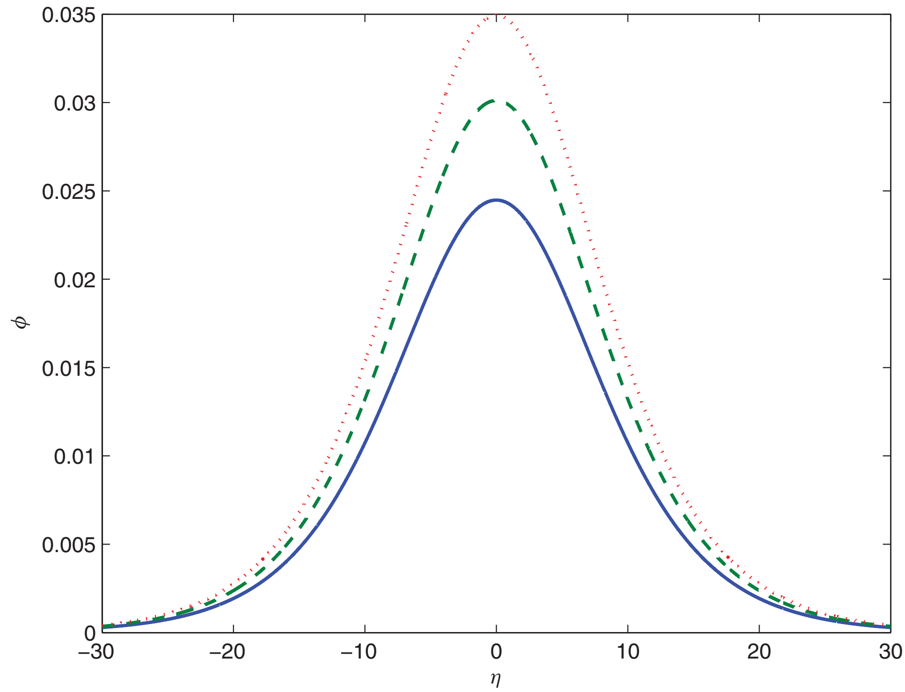

Figure 1. (Colour online) Variation of MASWs with increase in the charge number of the negatively ($s = 1$) charged dust particles. $Z_d = 3$ (solid curve), $Z_d = 4$ (dashed curve), and $Z_d = 5$ (dotted curve). The other parameters are $n_{+0} = 2 \times 10^8$ cm^{-3}, $n_{d0} = 1 \times 10^7$ cm^{-3}, $B_0 = 3 \times 10^3$ G, $T_+ = T_- = 0.3$ eV.

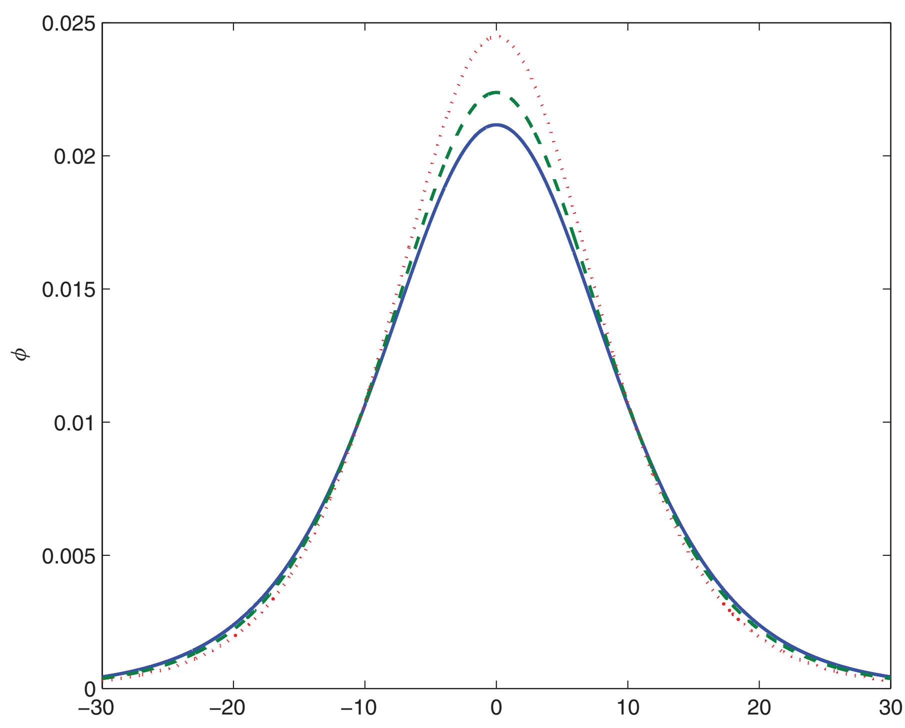

Figure 2. (Colour online) Variation of MASWs with increase in the value of external magnetic field intensity. $B_0 = 1 \times 10^3$ G (solid curve), $B_0 = 2 \times 10^3$ G (dashed curve), $B_0 = 3 \times 10^3$ (dotted curve). The other parameters are $n_{+0} = 2 \times 10^8$ cm^{-3}, $n_{d0} = 1 \times 10^7$ cm^{-3} , $T_+ = T_- = 0.3$ eV, s = 1.

collisionless MHD model and the reductive perturbation theory. The effects of variation of the charge number of dust, magnetic field, plasma species number densities on MASWs in a PID plasma are investigated. It is found from the numerical results that variation in the values of the charge number of dust, magnetic field intensity, and plasma densities has strong impact on the amplitude of dust MASW structures. However, the width of MASWs remains the same by increasing the charge number of dust and dust number density. The present investigation

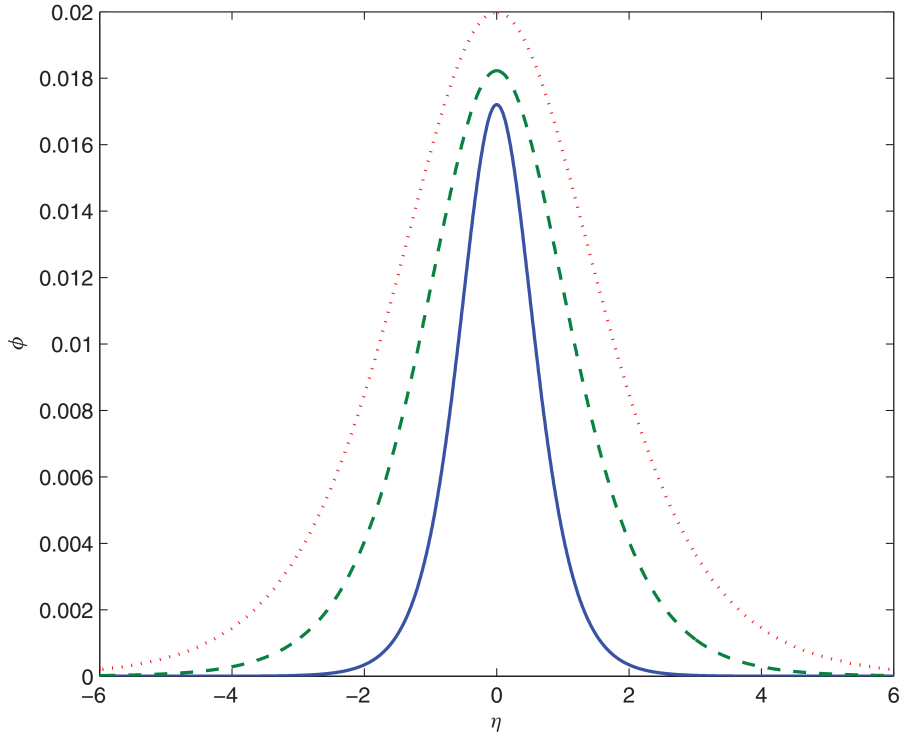

Figure 3. (Colour online) Variation of MASWs with increase in the value of external magnetic field intensity. $B_0 = 1 \times 10^3$ G (solid curve), $B_0 = 2 \times 10^3$ G(dashed curve), $B_0 = 3 \times 10^3$ G(dotted curve). The other parameters are $n_{+0} = 2 \times 10^8$ cm^{-3}, $n_{d0} = 1 \times 10^7$ cm^{-3} , $T_+ = T_- = 0.3$ eV, s $= -1$.

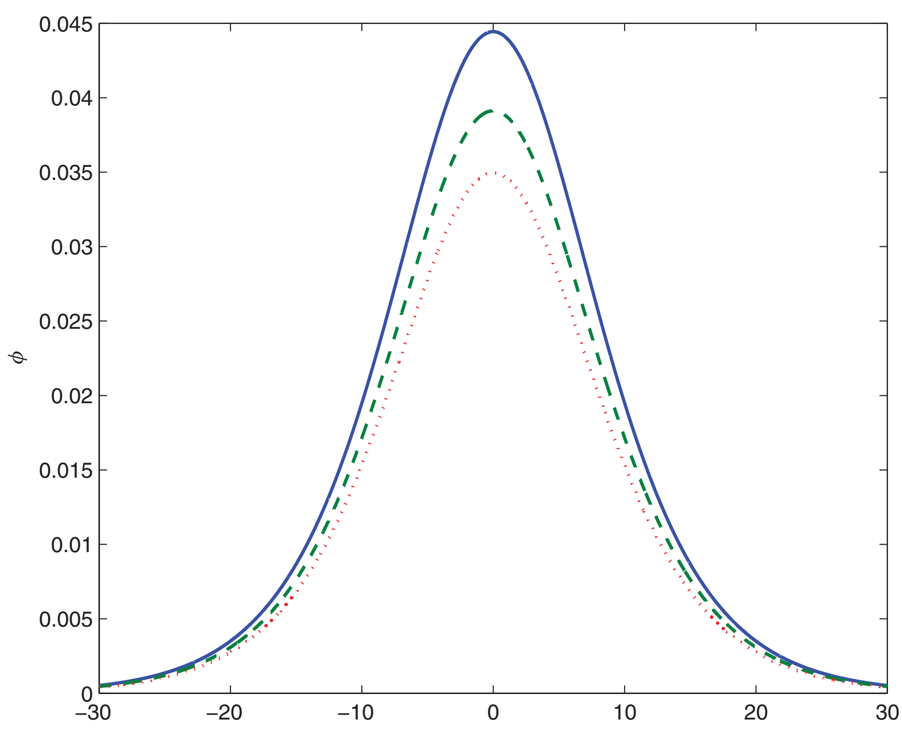

Figure 4. (Colour online) Variation of MASWs with positive ions number density. $n_{+0} = 0.8 \times 10^8$ cm^{-3} (solid curve), $n_{+0} = 1 \times 10^8$ cm^{-3} (dashed curve), and $n_{+0} = 1.2 \times 10^8$ cm^{-3} (dotted curve). The other parameters are $n_{d0} = 1 \times 10^7$ cm^{-3}, $B_0 = 3000$ G, $Z_d = 3$, $T_+ = T_- = 0.5$ eV, s $= 1$.

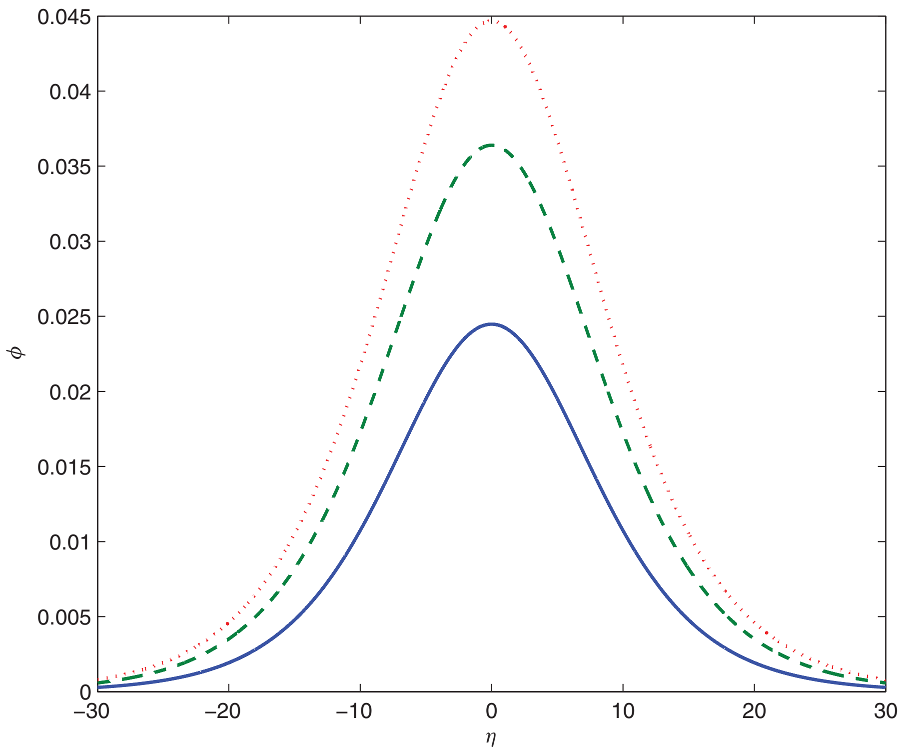

Figure 5. (Colour online) Variation of MASWs with the dust number density: $n_{d0} = 1 \times 10^7$ cm^{-3} (solid curve), $n_{d0} = 2 \times 10^7$ cm^{-3} (dashed curve), and $n_{d0} = 3 \times 10^7$ cm^{-3} (dotted curve). The other parameters are $n_{+0} = 2 \times 10^8$ cm^{-3}, $B_0 = 3000$ G, $Z_d = 3$, $T_+ = T_- = 0.5$ eV, s = 1.

may be useful to understand formation and propagation of MASW structures in PID plasmas.

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