Effect of ion-fluid temperature on dust-ion-acoustic solitons with non-thermal electrons

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Abstract

We have investigated the properties of dust-ion-acoustic (DIA) solitons using the reductive perturbation method in an unmagnetized dusty plasma, whose constituents are adiabatic ion-fluid, nonthermally distributed electrons and static dust particles. We have also derived the korteweg-de Vries (KdV) equation with its stationary solution analyzed. KdV equation of the present paper reduces to the Kdv equation of Sayed and Mamun [18] if we set the nonthermal parameter β equal to zero.

Keywords: Dust-ion-acoustic solitons, non-thermal electrons.

Resumen

Hemos investigado las propiedades de solitones de polvo-iónico-acústico (DIA) utilizando el método de perturbación reductora en un plasma de polvo magnetizado, cuyos componentes son fluidos-iones adiabáticos, los electrones y las partículas de polvo estático son distribuidos no termalmente. También hemos obtenido la ecuación de Korteweg-de Vries (KDV) con su solución estacionaria analizada. La ecuación KDV del presente trabajo se reduce a la ecuación KDV de Sayed y Mamun [18] si fijamos el parámetro no térmicos β igual a cero.

Palabras claves: Solitones de polvo-acústicu de iones, los electrones no térmicos.

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I. INTRODUCTION

Linear as well as nonlinear collective processes in dusty or complex plasmas have received special attention due to the realization of their occurrence in heliospheric and astrophysical plasma, and in laboratory and technological applications [1, 2]. Dusty plasma physics studies the properties of heavier charged dust in the presence of traditional electrons and ions. In the commonly used charging model, the dust grains would be essentially charged by the capture of the more mobile electrons; hence, photoionization or secondary electron emission, as is assumed to be the case in the outer part of the rings of Saturn, cometary tails and Jupiter's magnetic sphere [3].

Wave propagation in such complex systems is expected to be substantially different from that in ordinary two-component plasmas and the presence of charged dust can have a strong influence on the characteristics of the usual plasma wave modes, even at frequencies where the dust grains do not participate in the wave motion. The presence of static charged dust grains had been found to modify the existing plasma wave spectra [2]. While dust dynamics has been discovered to introduce new eigen modes such as dust-acoustic (DA) mode, Dust Lattice (DL) mode etc. [4, 5, 6, 7]. Of all the modified dusty modes discussed in the literature, the dust-ion-acoustic (DIA) solitary wave has received wide attention as well as experimental confirmation in several low-temperature dusty plasma devices [1, 2, 8, 9, 10, 11, 12, 13, 14, 15].

Shukla and Silin [16], were the first to theoretically consider negatively charged static dust thereby showing that due to the conservation of equilibrium charge density $n_{eo}e + n_{d0}z_d e - n_{i0}e = 0$ couple with strong inequality $n_{e0} << n_{i0}$ (where n_{s0} is the particle number density of the species s with s = e, i, d for electrons, ions, dust, z_d is the number of electrons residing onto the dust grain surface, and e is the magnitude of the electronic charge) a dusty plasma with negatively charged static dust grains supports low-frequency dust-ion-acoustic (DIA) wave with phase speed much larger (smaller) than ion (electron) thermal speed. The dispersion relation of the linear DIA waves for the cold ion limit was given by [16] as

$$\frac{\omega^2}{k^2} = \frac{c_i^2}{\left[1-\alpha \quad 1+k^2\lambda_{D_i}^2\right]},\ \text{where}\ c_i = \left(\frac{K_B T_{e0}}{m_i}\right)^{\frac{1}{2}}\ \text{is}$$

the ion-acoustic speed (with T_{e0} being the electron temperature atquilibrium and m_i being the ion mass, k_B being the Boltzmann constant), $\lambda_{D_e} = \left(\frac{k_B T_{e0}}{4\pi n_{e0} e^2}\right)^{\frac{1}{2}}$ is the electron Debeye radius and

$$\alpha = \frac{z_d n_{d0}}{n_{i0}}.$$

Recently, Mamun *et al*. [17] have studied the combined effects of the adiabaticity of electrons/ions and negatively charged static/mobile dust on the basic features (polarity, speed, amplitude and width) of small as well as arbitrary amplitude DIA and DA (Dust-acoustic) solitary waves. They found out that, the combined effects of the adiabaticity of electrons/ions and negatively charge static/mobile dusts significantly modify the basic features (polarity, speed, amplitude and width) of the DIA and DA solitary waves. Likewise a theoretical investigation of recent, has been carried out by [18] to study the effect of ion-fluid temperature on DIA solitary structures in a dusty plasma containing adiabatic ion-fluid, Boltzmann electron and static dust particles.

However, in real dusty plasma, the effect of finite ion temperature cannot be neglected and the electron behaviour can be strongly modified by nonlinear potential of the localized DIA structures by generating a population of fast energetic electrons. Consequently, the present paper is devoted to see how finite ion temperature combined with electron non-thermality effects can be expected to modify the result arrived at in [18]. This generalization involves a little increase in algebraic complexity of the relevant formulas. But, the basic principles do, not change. It is worth noting that some recent theoretical work focused on the effects of non-thermal electrons and ions which are common in space plasmas [20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34].

This paper is organized as follows. In the next section, we present the basic equation of the model. Our analytical results are presented in section III. While in section IV, we discuss and conclude our findings.

II. BASIC EQUATIONS

We consider an unmagnetized dusty plasma consisting of adiabatic ion-fluid, non-thermal electrons and immobile negatively charged dust grains of density n_i, n_e and n_d respectively. The basic equation for one-dimensional DIA waves can be expressed in terms of normalized variables as:

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}\left(n_i V_i\right) = 0, \tag{1}$$

$$n_i \frac{\partial V_i}{\partial t} + n_i V_i \frac{\partial V_i}{\partial x} = -n_i \frac{\partial \psi}{\partial x} - \alpha \frac{\partial p}{\partial x}, \tag{2}$$

$$\frac{\partial p}{\partial t} + V_i \frac{\partial p}{\partial x} + 3p\frac{\partial V_i}{\partial x} = 0, \tag{3}$$

$$\frac{\partial^2 \psi}{\partial x^2} = \mu n_e - n_i + (1-\mu), \tag{4}$$

where $\mu = \frac{n_{e0}}{n_{i0}} = 1 - \frac{z_d n_{d0}}{n_{i0}}$ and $\alpha = \frac{T_i}{T_e}$. The subscript stands for equilibrium values. The electrostatic potential ψ, the ion fluid speed v_i and the ion number density n_i are normalized respectively by $\frac{k_B T_e}{e}, c_i = \left(\frac{k_B T_e}{m_i}\right)^{\frac{1}{2}}$, *and* n_{i0}. The time and the space variables are in units of the ion plasma period $\omega_{pi}^{-1} = \left(\frac{m_i}{4\pi n_{i0} e^2}\right)^{\frac{1}{2}}$ and the Debye radius $\lambda_D = \left(\frac{K_B T_e}{4\pi e^2 n_{i0}}\right)^{\frac{1}{2}}$. P is the ion-thermal pressure normalized by $n_{i0}\ K_B\ T_i$. To model the fast non-thermal electron distribution; we consider the BGK solution of [20] which solves the electron Vlasov equation. Hence, we choose

$$f_e\left(x, V_d\right) = \frac{n_{e0}}{1+3\alpha_1}\left(\frac{m_e}{2\pi T_e}\right)^{\frac{1}{2}}\left\{1 + 4\alpha_1\left(\frac{m_e V_e^2/2 - e\phi}{T_e}\right)^2\right\} \exp\left(-\frac{m_e V_e^2/2 - e\phi}{T_e}\right). \tag{5}$$

Here α_1 is a parameter determining the number of non-thermal electrons present in our plasma model with the distribution of equation (5), we obtain

$$n_e\left(\phi\right) = \int_{-\infty}^{+\infty} f_e(x, V_e)\,dV_e = n_{e0}\left\{1 - \beta\frac{e\phi}{T_e} + \beta\frac{e^2\phi^2}{T_e^2}\right\}\exp\left(\frac{e\phi}{T_e}\right), \tag{6}$$

where

$$\beta = \frac{4\alpha_1}{1+3\alpha_1}. \tag{7}$$

The Poisson's equation (4) now reduces to:

$$\frac{\partial^2\psi}{\partial x^2} = \mu\exp(\psi)\ 1-\beta\psi+\beta\psi^2\ -n_i+\ 1-\mu\ . \qquad (8)$$

III. DUST-ION-ACOUSTIC SOLITARY WAVES

For the study of small but finite amplitude DIA solitary waves, we employ the reductive perturbations technique by first introducing the stretched variables [19] $\xi = \in^{\frac{1}{2}}\ \ x - V_0 t$ and $\tau = \in^{\frac{3}{2}} t$, where $\in$ is the expansion parameter, measuring the amplitude of the wave or the weakness of the wave dispersion. V_0 is the phase speed of the DIA waves normalized by c_i.

Equations (1) – (3) and (8) can now be expressed in terms of ξ and τ as follows:

$$\in^{\frac{3}{2}}\frac{\partial n_i}{\partial\tau} - V_0\in^{\frac{1}{2}}\frac{\partial n_i}{\partial\xi} + \in^{\frac{1}{2}}\frac{\partial v_i}{\partial\xi} + V_i\in^{\frac{1}{2}}\frac{\partial n_i}{\partial\xi} = 0, \qquad (9)$$

$$\in^{\frac{1}{2}} n_i\frac{\partial V_i}{\partial\tau} - V_0\in^{\frac{1}{2}} n_i\frac{\partial V_i}{\partial\xi} + n_i V_i\in^{\frac{1}{2}}\frac{\partial V_i}{\partial\xi} = -\in^{\frac{1}{2}} n_i\frac{\partial\psi}{\partial\xi} - \in^{\frac{1}{2}}\alpha\frac{\partial p}{\alpha\xi}, \quad (10)$$

$$\in^{\frac{3}{2}} n_i\frac{\partial p}{\partial\tau} - V_0\in^{\frac{1}{2}}\frac{\partial p}{\partial\xi} + V_i\in^{\frac{1}{2}}\frac{\partial p}{\partial\xi} + 3p\in^{\frac{1}{2}}\frac{\partial V_i}{\partial\xi} = 0, \qquad (11)$$

$$\in\frac{\partial^2\psi}{\partial\xi^2} = \mu\left\{\left(1+\psi+\frac{1}{2}\psi^2+\ldots\right)\ 1-\beta\psi+\beta\psi^2\ \right\} - n_i + (1-\mu). \quad (12)$$

Expanding the variables n_i, V_i, p and ψ in a power series of $\in$ as follows;

$$n_i = 1+\in n_i^1 + \in^2\ n_i^2 + \ldots, \qquad (13)$$

$$V_i = 0+\in V_i^1 + \in^2\ V_i^2 + \ldots, \qquad (14)$$

$$p = 1+\in\ p^1 + \in^2\ p^2 + \ldots, \qquad (15)$$

$$\psi = 0+\in\psi^1 + \in^2\ \psi^2 + \ldots. \qquad (16)$$

Substituting equations (13) - (16) into equations (9) – (12) and considering the coefficients of $\in^{\frac{3}{2}}$ from equations (9) – (12) and $\in$ from equation (12), we have

$$V_i^1 = \frac{V_0\psi'}{V_0^2 - 3\alpha'}, \qquad (17)$$

$$p^1 = \frac{3\psi'}{V_0^2 - 3\alpha}, \qquad (18)$$

$$n_i^1 = \frac{\psi'}{V_0^2 - 3\alpha}, \qquad (19)$$

$$V_0 = \sqrt{\frac{1}{\mu\ 1-\beta} + 3\alpha}. \qquad (20)$$

Similarly, substituting equations (13) – (16) into equations (9) – (12) and taking the coefficient of $\in^{\frac{5}{2}}$ from equations (9) – (12) and $\in^2$ from equation (12), we obtain

$$\frac{\partial n_i^1}{\partial\tau} - V_0\frac{\partial n_i^2}{\partial\xi} + \frac{\partial}{\partial\xi}\left[V_i^2 + n_i^1 V_i^1\right] = 0, \qquad (21)$$

$$\frac{\partial V_i^1}{\partial\tau} - V_0 n_i^1\frac{\partial V_i^1}{\partial\xi} - V_0\frac{\partial V_i^2}{\partial\xi} + V_i^1\frac{\partial V_i^1}{\partial\xi} = n_i^1\frac{\partial\psi}{\partial\xi} - \frac{\partial\psi^2}{\partial\xi} - \alpha\frac{\partial p^2}{\partial\xi}, \quad (22)$$

$$\frac{\partial p^1}{\partial\tau} - V_0\frac{\partial p^2}{\partial\xi} + V_i^1\frac{\partial p^1}{\partial\xi} + 3p^1\frac{\partial V_i^1}{\partial\xi} - \frac{3\partial V_i^2}{\partial\xi} = 0, \qquad (23)$$

$$\frac{\partial^2\psi^1}{\partial\xi^2} = \mu\psi^2 + \frac{1}{2}\mu\left[\psi^1\right]^2 - \mu\beta\psi^2 - n_i^2. \qquad (24)$$

Eliminating n_i^2, V^2, p^2 and ψ^2 by making use of equations (17) – (20), we obtain, finally the following expression:

$$\frac{\partial\psi^1}{\partial\tau} + A\psi^1\frac{\partial\psi^1}{\partial\xi} + B\frac{\partial^3\psi^1}{\partial\xi^3} = 0, \qquad (25)$$

where the linear coefficient A and the dispersion coefficient B are given by

$$A = \frac{\left[3\mu\ 1-\beta\ ^2 - 1 + 12\alpha\mu^2\ 1-\beta\ ^3\right]B\mu}{1-\beta}, \qquad (26)$$

and

$$B = \frac{1}{2\mu\sqrt{\mu\ 1-\beta\ \left[1+3\alpha\mu\ 1-\beta\ \right]}}, \qquad (27)$$

The k-dv equation describing the nonlinear propagation of DIA waves in an unmagnetized dusty plasma consisting of adiabatic ion-fluid, non-thermal electron distribution, and static negatively charged dust grains is given as equation (25).

Although the K-dV equation can be solved analytically for an arbitrary initial value with the help of inverse scattering method, we rather present here the stationary solution by transforming the independent variables from ξ to $\zeta = \xi\text{-}u_0\tau$ and τ to $\tau = \tau$, where u_0 is a constant speed normalized by c_i and by imposing the appropriate boundary conditions for localized perturbation:

$\psi^1 \to 0$, $\frac{\partial \psi^1}{\partial \xi} \to 0$, $\frac{\partial^2 \psi^1}{\partial \xi^2} \to 0$ at $\xi \to \pm\infty$. Hence, the solution of the K –dV equation is given as

$$\psi^1 = \psi_m \sec h^2\left(\frac{\xi}{\Delta}\right), \tag{28}$$

whose the amplitude ψ_m (normalized by $K_B\ T_e/e$) and the width Δ (normalized by λ_D) are given by

$$\psi_m = \frac{3u_0}{A}, \tag{29}$$

and

$$\Delta = \sqrt{\frac{4B}{u_0}}. \tag{30}$$

IV. DISCUSSION AND CONCLUSION

It is obvious from equation (26) that there exists positive (negative) solitary potential profiles if $A > 0 \quad A < 0$. We have investigated the basic properties of small but finite amplitude DIA solitary waves for an unmagnetized dusty plasma system consisting of static negatively charged dust particles, adiabatic ion-fluid and nonthermally distributed electrons. For us to interpret our analytical results, we express equation (29) as:

$$\psi_m = \frac{12(1-\beta)}{\left[3\mu(1-\beta)^2 - 1 + 12\alpha\mu^2(1-\beta)^3\right]\Delta^2\mu},$$

where

$$\Delta = \left(\sqrt{\frac{2}{u_0}}\right)\mu^{-\frac{3}{4}}\ (1-\beta)(1+3\alpha\mu(1-\beta)^{-\frac{1}{4}}.$$

Hence, with constant values of μ, α and β, the amplitude decreases with increasing width which is an established feature of K-dV solitons, while for the width (Δ), it decreases by increasing the values of α, μ and β. Numerical analysis of these properties will be investigated in subsequent write-ups.

If the nonthermal parameter β is set to zero, in order to have Boltzmann distribution for electrons, above expression reduces to

$$\psi_m = \frac{12}{\left[\mu\Delta^2(3\mu - 1 + 12\alpha\mu^2)\right]},$$

and

$$\Delta = \left(\sqrt{\frac{2}{u_0}}\right)\mu^{-\frac{3}{4}}(1+3\alpha\mu)^{-\frac{1}{4}}.$$

It can be observed that; with β set to zero, our expression for solitary width (Δ) as $\left(\sqrt{\frac{2}{u_0}}\right)\mu^{-\frac{3}{4}}(1+3\alpha\mu)^{-\frac{1}{4}}$ is exactly what is obtained by [18]. While for ψ_m (solitary amplitude) we have

$$\psi_m = \frac{12}{\left[\mu\Delta^2(3\mu - 1 + 12\alpha\mu^2)\right]},$$

which is different from ψ_m as obtained by [18] as:

$$\psi_m = \frac{12}{\left[\mu^2\Delta^2(3\mu - 1 + 12\alpha\mu^2)\right]}.$$

We strongly feel that, the proper thing should be our result as:

$$\psi_m = \frac{12}{\left[\mu\Delta^2(3\mu - 1 + 12\alpha\mu^2)\right]},$$

with the following reasons if $\Delta = \sqrt{\frac{4B}{u_0}}$ is evaluated from the result of [18], we should have

$$\Delta = \left(\sqrt{\frac{2}{u_0}}\right)\mu^{-\frac{5}{4}}(1+3\alpha\mu)^{-\frac{1}{4}}.$$

We have extended the recent work of Sayed and Mamun [18] to see how the electron non-thermality effect will modify the results of their analysis. In particular, it may be noted that the present dusty plasma model may admit positive and negative solitary potential profiles which is to be considered in subsequent paper. We stress that our results should be useful in the understanding of DIA solitons in dusty plasma (which is made-up of adiabatic ion-fluid, nonthermal electrons and negatively charged static dust particles) that is relevant in laboratory experiments and space.

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