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Dissipative dust acoustic solitary waves in an electron depleted dusty plasma with superthermal ions

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Abstract

Dust acoustic (DA) solitary waves are investigated in an unmagnetized dusty plasma comprising of fluid warm dust particles and kappa distributed ions. We assume the electron number density to be sufficiently depleted in this fluid model, i.e., $n_e << n_d$. We consider the usual *ad hoc* damping term, involving the damping rate ν due to the dust–neutral collisions; and derived the modified dispersion relation of DA waves. It is found that there is a critical wave number, which should have $k > k_{crit}$, otherwise overdamping occurs. The critical value of the wave number increases with ν, while it decreases with κ. Also, a modified Korteweg-de-Vries (mKdV) equation was derived for description of DA solitary wave. We found that the amplitude, width and velocity of DA solitary waves are modified in the presence of damping term. As the amplitude and velocity of solitary DA wave decreases with τ, the width of soliton spreads. Also, it is found that the polarity of soliton changes from positive to negative at special value of κ.

Keywords*:* Dust acoustic wave; Nonlinear wave; Kappa distribution; Standard reductive perturbation method

1. Introduction

Dusty plasma, i.e., a plasma consisting of electrons, positive ions, and negatively charged heavy dust grains, which are present in space environments as well as in laboratory plasmas have attracted a great deal of attention in the last few decades [1-7]. The presence of dust particles modifies the existing wave spectra, and also introduces new eigenmodes, such as dust acoustic mode [8-12], dust ion acoustic mode [13], dust lattice mode [14-18], dust cyclotron mode [19] and dust drift mode [8, 20-22]. Rao *et al.* [8] first predicted the existence of a new low- frequency DA waves in a multi-component dusty plasma. Subsequently, Barkan *et. al.*, [11] experimentally observed DA waves in laboratory experiments. These waves arise due to the restoring force provided by the plasma thermal pressure (electrons and ions) while the inertia comes from dust mass. Furthermore, in a real dusty plasma, the dust charge may fluctuate and therefore become a new dynamical variable. It must be noted that the DA phase velocity is much smaller than the electron and ion thermal speeds. The nonlinear properties of the DA waves have been studied by a number of authors due to their fundamental importance both in laboratory, astrophysical and space environments [23-29]. In a fully ionized (collisionless) dusty plasma where ions are assumed to behave as a fluid, background neutral pressure is completely negligible, while the experimental conditions [30-32] show that the modes are often excited when there is a significant background pressure of neutrals. It has also been estimated that under such experimental conditions [30, 31] the ion-neutral and the dust–neutral collisional mean free paths may be comparable or even shorter than the typical wavelengths of the excited modes. Thus, in a dusty plasma with a significant background neutral pressure, one cannot use the collisionless plasma limit to study such modes. Rosenberg investigated the ion- dust streaming instability in a dusty plasma with a significant background neutral pressure and the ion streaming effect. DA instability in a collisional dusty plasma with a constant dc electric field has been studied by D'Angelo and Merlino [33]. Xie and Yu investigated DA waves in a strongly coupled dissipative plasma [34]. They considered some effects with similar time scale, such as dust-charge variation, elastic electron and ion collisions with dust and neutral particles, and showed that the dispersion properties of the DA waves were determined by a sensitive balance of the effects of collisional relaxation and strong dust coupling. Moreover, the influence of several dissipative

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processes on the plasma wave properties have been investigated by a number of authors [35-39]. Note that such processes play a vital role both in determining the dispersive/damping properties and in maintaining the equilibrium state of the system of the plasma fluctuations. Low frequency DA waves in low temperature collisional plasmas containing impurity charge fluctuations have been discussed by Ostrikov et al [38]. They derived and analyzed the generalized dispersion relation (which described the propagation and damping) of the DA waves. Ivlev and Morfill [39] studied acoustic modes in a collisional dusty plasma with dust charge fluctuations. Ghosh et al [40] supposed that the ion hydrodynamical time scale was much smaller than that of the ion-dust collision, and showed that the damping of the nonlinear ion-acoustic wave is caused by ion- dust collision. Fedila and Djebli [41] investigated the influence of dust- neutral collision on small amplitude DA waves in a plasma with positively charged dust grains. El-Labany et al studied [42] head-on collision between two DA dark solitons. They derived the phase shift and the trajectories of these solitons. Bacha and Tribeche [43] studied DA waves in a nonextensive dusty plasma with dust charge fluctuations. Their results reveal that the amplitude, strength and nature of the nonlinear DA solitons as well as shock waves are significantly sensitive to the degree of ion nonextensivity. Also, they showed that the dust charge fluctuations lead to more spiky solitary structures. It must be noted that when a dusty plasma is cooled down to an extremely low temperature, such that the de Broglie wavelength of the dust particles become comparable to the dimension of the system, the quantum mechanical effects appear and play an important role. Shukla and Ali studied DA waves in a quantum dusty plasma [44]. Dust- ion acoustic solitary waves in an unmagnetized nonplanar quantum dusty plasma have been studied by Khan et al [45]. They showed that their results were completely different from one-dimensional planar solitary waves. Furthermore, Khan et al investigated dust-ion acoustic waves in a magnetized quantum dusty plasma with polarity effects [46]. Ali et al discussed the nonlinear electrostatics waves in a two dimensional quantum dusty plasma [47].

Although most of these studies have been confined to the Maxwell-Boltzmann distributed electrons and ions, observations indicate that astrophysical and space plasmas have particle distribution functions which are quasi-Maxwellian up to the mean thermal velocities, and possess non-Maxwellian suprathermal tails at the high velocities or energies. Such distributions may be accurately modeled using a kappa or generalized Lorentzian distribution. The behavior of superthermal ions modifies the existence domain of nonlinear structures, which are not observed in dusty plasma with isothermal ions [48-51]. Such superthermal ions are often present in space and astrophysical plasma environments, viz., the ionosphere, mesosphere, magnetosphere, lower atmosphere, magneto-sheet, terrestrial plasma-sheet, radiation belts and auroral zones [52-56].

Baluku and Hellberg [57] discussed the influence of kappa distributed electrons and/or ions on the formation of DA solitary waves in dusty plasma systems. They showed that their results reveal important differences from those found when one of the plasma components has a diferent nonthermal distribution, such as Cairns distribution. Rubab and Murtaza considered the influence of suprathermal ions on DA oscillations [58]. [See also Refs. 59-62]. Recently, Shahmansouri and Tribeche have studied DA solitary waves in electron depleted superthermal dusty plasmas with two-temperature ion species [63]. They showed that the superthermality effects significantly modify the spatial patterns as well as the nature of DA solitary waves and double-layers. Also, the influence of dust charge fluctuations on the DA solitary structure in a superthermal dusty plasma has been discussed in Refs. [64, 65]. Thus, it is expected that deviation from Maxwell-Boltzmann distribution leads to the appearance of significant effects in the study of the nonlinear features of dusty plasma systems, rather than the Maxwell-Boltzmann distributions.

In the DA time scale, we discuss the propagation properties of DA solitary waves in a superthermal dusty plasma in the presence of dust-neutral collisions. We assume the electron number density to be sufficiently depleted in this fluid model, i.e. $n_e << n_d$. The standard method of reductive perturbation is used to study the propagation properties of solitary waves.

2. Model equations

Here we consider the propagation properties of nonlinear DA waves in dusty plasma consisting of kappa distributed ion species. We assume that the electron number density is sufficiently depleted in fluid model, i.e. $n_e << n_d$, such type of plasma is often present in Saturn's F-ring [66-69]. Also, collision between dust and neutral particles are considered via damping term ν in fluid equations. In consequence of the fact that the typical dust charging time scale is longer than DA time scale, it is anticipated that the dust charge fluctuations have no essential effect on DA mode [70], and so we assume that the dust charge is constant. Thus, one dimensional dynamics of DA solitary waves is governed by the following basic normalized equations:

$$\frac{\partial n_d}{\partial t}+\frac{\partial (n_d u_d)}{\partial x}=0, \quad (1)$$

$$\frac{\partial u_d}{\partial t}+\nu u_d+u_d\frac{\partial u_d}{\partial x}-\frac{\partial \phi}{\partial x}+3\sigma n_d\frac{\partial n_d}{\partial x}=0, \quad (2)$$

$$\frac{\partial^2 \phi}{\partial x^2}=n_d-n_i, \quad (3)$$

$$n_i=(1+\frac{\phi}{\kappa-3/2})^{-\kappa+1/2}. \quad (4)$$

The following normalization $x\to\omega_{pd}x/\lambda_{Dim}$, $t\to\omega_{pd}t$, $n_j\to n_j/n_{j0}$, $u_d\to u_d/C_d$, $\phi\to e\phi/k_BT_i$, and $\nu=\nu_n/\omega_{pd}$ have been applied in Eqs. (1)-(4). Where, the dust plasma frequency is $\omega_{pd}=\sqrt{n_{d0}Z_d^2e^2/m_d\varepsilon_\circ}$, the dust fluid speed is $C_d=\sqrt{Z_dk_BT_i/m_d}$ and Debye length is $\lambda_{Dim}=\sqrt{k_BT_i\varepsilon_\circ/Z_dn_{d0}e^2}$, and $\sigma=T_d/T_i$. Furthermore, the charge equilibrium condition of system takes the form of $Z_dn_{d0}=n_{i0}$.

2.1. Linear dispersion relation

In the linear regime, the dispersion relation of DA waves can be obtained as follows,

$$\omega(\omega+i\nu)=3\sigma k^2+\frac{k^2}{k^2+c_1}, \quad (5)$$

where $c_1=(2\kappa-1)/(2\kappa-3)$, this relation is the same as Eq. (7) of Ref. [8]. The above equation (5) necessitates that

$$k>k_{crit}=\sqrt{\frac{\nu^2/4-1-3\sigma c_1}{6\sigma}+\sqrt{\frac{\nu^2c_1}{12\sigma}+(\frac{\nu^2/4-1-3\sigma c_1}{6\sigma})^2}}, \quad (6)$$

otherwise over-damping happens. Dispersion relation for different values of ν and κ is plotted in Fig. 1. It is found that an increase in κ leads to decrease of k_{crit}, while it grows with ν.

3. Soliton solution

In order to derive the KdV equation we adopt the following stretched coordinates

$$\xi=\varepsilon^{1/2}(x-M_qt),\ \tau=\varepsilon^{3/2}t, \quad (7)$$

where ε is a small parameter that measures the strength of nonlinearity, and M is the DA solitary wave velocity normalized by the DA speed C_d. The dependent variables are expanded as

$$n_d=1+\varepsilon n_d^{(1)}+\varepsilon^2n_d^{(2)}+\cdots, \quad (8a)$$

$$u_d=\varepsilon u_d^{(1)}+\varepsilon^2u_d^{(2)}+\cdots, \quad (8b)$$

$$\phi=\varepsilon\phi^{(1)}+\varepsilon^2\phi^{(2)}+\cdots. \quad (8c)$$

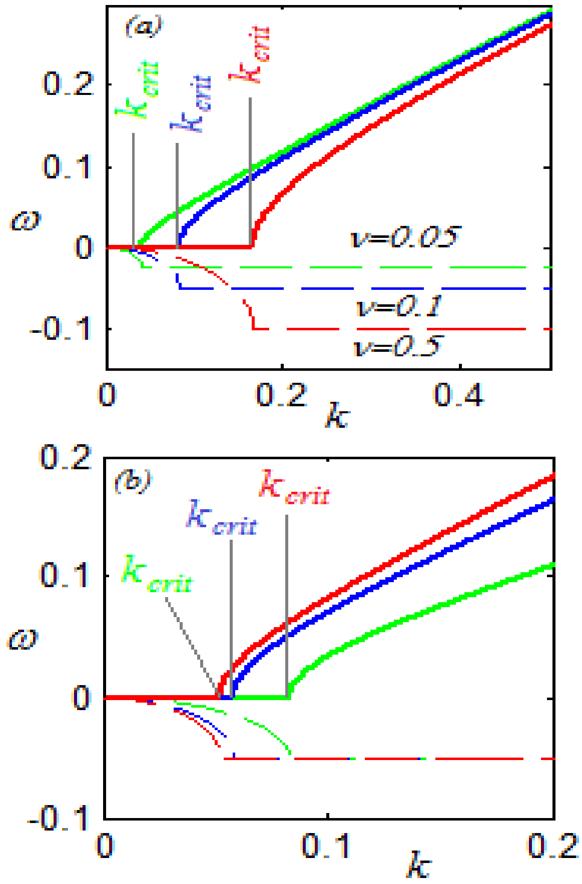


Fig. 1. Dispersion relation of dust acoustic waves, (a) for different values of ν, $\nu=0.05$ (green line), $\nu=0.1$ (blue line), $\nu=0.5$ (red line), and $\kappa=2$, (b) for different values of κ, $\kappa=2$ (green line) $\kappa=4$ (blue line), $\kappa=10$ (red line), and $\nu=0.1$. Solid lines refer to real part of frequency and dotted lines to imaginary part, where $\sigma=0.01$.

Substituting the set of Eqs (8) into Eqs. (1)–(4) and collecting the terms in the different powers of ε, one can obtain to the lowest order

$$n_d^{(1)}=-c_1\phi^{(1)}, \quad (9)$$

$$u_d^{(1)}=-c_1M_q\phi^{(1)}. \quad (10)$$

By introducing (9) and (10) into Poisson's equation, the dispersion relation of the system takes the form of

$$M_q^2 - 3\sigma = \frac{1}{c_1}. \tag{11}$$

At the next power of ε, eliminating the second-order quantities along with the Eq. (11), we can obtain the mKdV equation in the following form

$$\frac{\partial \phi^{(1)}}{\partial \tau} + A\phi^{(1)}\frac{\partial \phi^{(1)}}{\partial \xi} + B\frac{\partial^3 \phi^{(1)}}{\partial \xi^3} + \frac{\nu}{2}\phi^{(1)} = 0, \tag{12}$$

where

$$A = \frac{-3c_1^3(\sigma + M_q^2) + 2c_2}{2M_q c_1^2}, \tag{13}$$

$$B = \frac{1}{2M_q c_1^2}. \tag{14}$$

Equation (12) is the mKdV equation for small amplitude DA solitary waves. If one neglects the interparticles collision, Eq. (12) can be reduced to the ordinary KdV equation. There is a solitary wave solution for Eq. (12) of the form

$$\phi^{(1)} = \phi_m \sec h^2\left(\frac{\eta}{L}\right), \tag{15}$$

where $\eta = \xi - M_0\tau$ and the amplitude, width and velocity of solitary wave are defined as $\phi_m = 3M_0 / A$, $L = \sqrt{12B / A\phi_m}$ and $M_0 = 4B\exp(-2\nu\tau/3)$, respectively. This shows that the soliton amplitude decreases with ν.

Figure 2 indicates the behavior of nonlinear coefficient of mKdV equation. This Fig. shows that the sign of this coefficient changes at a critical value of kappa κ_{crit}. It means that the polarity of soliton solution changes from positive to negative at this critical value of kappa.

Variations of the electrostatic potential $\phi^{(1)}$ in the plane of (ξ,τ) are depicted in Fig. 3, for $\kappa = 2$ and $\nu = 0.1$. This Fig. shows how the amplitude and velocity of soliton change with time in space. The high value of ν has been chosen to emphasize the qualitative effect of damping on propagation of DA wave. Also, the behavior of $\phi^{(1)}$ as a function of ξ, is plotted in Fig. 4 for different values of τ. It is found that the influence of damping on the soliton profile for smaller values of kappa is larger (than higher values).

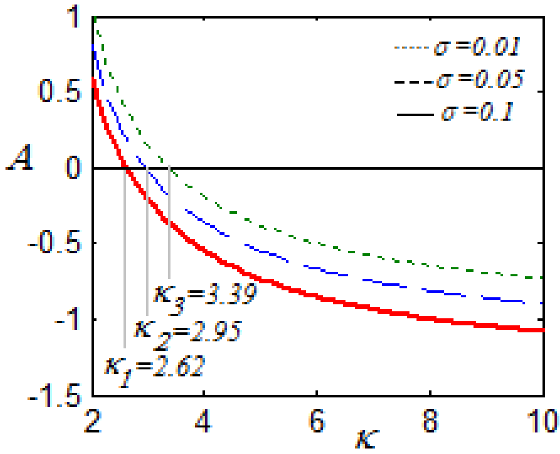


Fig. 2. Variation of the coefficient of nonlinear term in mKdV equation against κ, for different values of σ

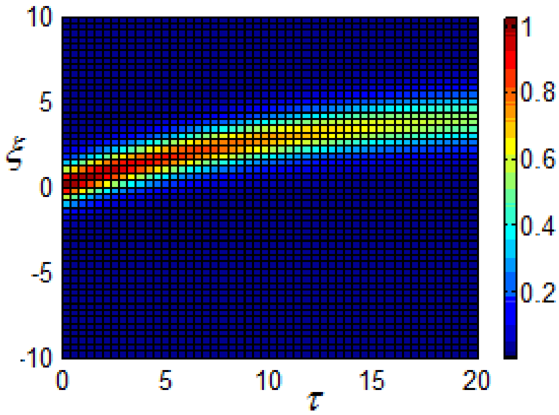
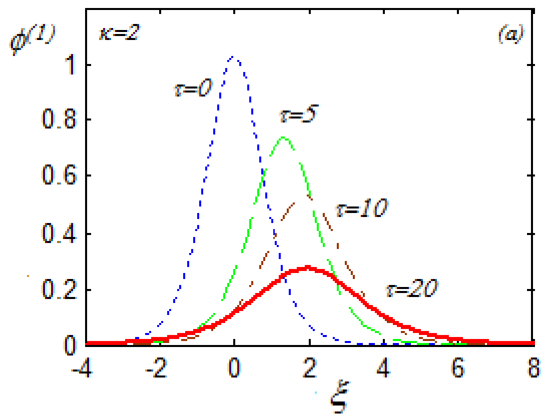


Fig. 3. The behavior of $\phi^{(1)}$ in plane of (ξ,τ), for $\sigma = 0.01$, $\kappa = 2$ and $\nu = 0.1$



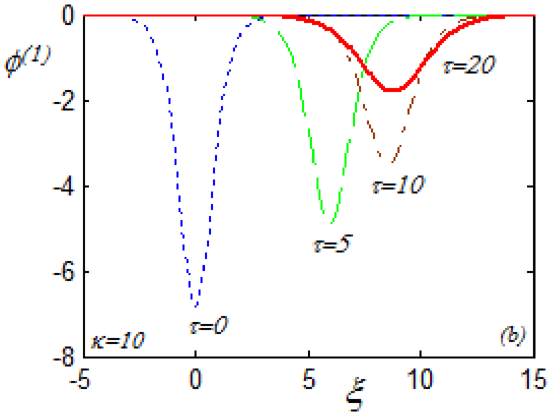


Fig. 4. Influence of damping on the soliton profile at different times, for parameters $\nu = 0.1$ and $\sigma = 0.01$, for (a) $\kappa = 2$ and (b) $\kappa = 10$

4. Conclusions

To conclude, we presented a theoretical model to show the existence of DA solitary waves in an unmagnetized dusty plasma with a high energy-tail ion distribution and consisting of dust-neutral collision. It is found that there is a critical wave number, below which overdamping occurs. An increase of ν leads to increase of k_{crit}, while it decreases with κ.

We found that a mKdV equation describes the evolution of DA solitary waves. It is shown that the amplitude, width and velocity of DA solitary wave are modified in the presence of damping term. As the amplitude and velocity of solitary DA wave decreases with τ, the width of soliton spreads. The results of a qualitative study are shown in Figs. 3 and 4. It is found that damping plays an important role in the smaller values of kappa.

Numerical studies show that the sign of A changes at a critical value of κ. We see that for larger values of σ, A becomes zero at smaller values of κ. The critical value of κ is derived for three different values of σ, as follows: (σ, κ_{crit}) = [(0.01,3.39) , (0.05,2.95) and (0.1,2.62)]. These pairs indicate the conditions at which the polarity of soliton changes from positive to negative.

According to definition of the soliton width and properties of Eq. (15), it is required that $B / M_0 > 0$. It means that both B and M_0 should have the same sign, thus depending on whether B is positive or negative, supersonic or subsonic solitons may be appear in the system, respectively. In this model B is always positive, thus M_0 is limited to the positive values. As a result, here only supersonic solitons can be excited in this model.

The results of this paper would be useful in understanding the basic nonlinear features of DA wave propagates in laboratory and space dusty plasmas, especially to dusty plasma existing in Saturn F-ring's region.

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