PRAMANA
— journal of
physics

© Indian Academy of Sciences

Vol. 80, No. 2
February 2013
pp. 295–306

Dust-acoustic solitons in quantum plasma with kappa-distributed ions

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MS received 24 February 2012; revised 26 June 2012; accepted 24 July 2012

Abstract. Arbitrary amplitude dust-acoustic (DA) solitary waves in an unmagnetized and collisionless quantum dusty plasma comprising cold dust particles, kappa (κ)-distributed ions and degenerate electrons are investigated. The influence of suprathermality and quantum effects on the linear dispersion relation of DA waves is investigated. Then, the effect of κ-distributed ions and degenerate electrons on the existence domain of solitons is discussed in the space of (M, f). The comparison of the existence domain for higher and lower values of κ shows that suprathermality results in propagation of solitons with lower values of Mach number, and the quantum effects, lead to a higher values of Mach number. The existence domain of solitons for nondegenerate κ-distributed electrons is considered for comparison with effect of degenerate electrons. Also, we found that the Sagdeev potential well becomes deeper and wider as $\varepsilon_{\mathrm{F}-i}$ decreases, as for lower κ values, the influence of quantum effects on the Sagdeev pseudopotential profile is smaller.

Keywords. Dust-acoustic waves; quantum plasma; kappa distributions.

PACS Nos 52.27.Lw; 52.35.Mw; 52.35.Sb

1. Introduction

The basic role of dust particles in the study of astrophysical and space environments, has resulted in the propagation of linear and nonlinear electrostatic excitations in dusty plasmas, attracting much attention in the last few decades [1–7]. Furthermore, it has been shown that in dusty plasmas, the dust charge dynamics introduce new eigenmodes such as dust-acoustic mode [8–13], dust ion-acoustic mode [14,15], dust cyclotron mode [16,17], dust drift mode [8,18–20] and dust lattice mode [21–23].

Nonlinear dust-acoustic (DA) waves have been studied by many [24–35]. It is expected that quantum effects play a vital role in the collective processes of plasma such as intense laser–solid interaction [36–39], microelctronics [40], ultra-cold plasmas [41] and dense astrophysical environments [42–44]. The three well-known mathematical formulations for describing the quantum plasmas dynamics are: the Schrödinger–Poisson model, the

Wigner–Poisson model and the quantum hydrodynamic (QHD) model. Propagation of nonlinear sound waves in quantum plasma has been extensively studied [45–53]. Shukla and Ali [54] studied the quantum dust-acoustic (QDA) wave (also see ref. [46]). Misra and Chowdhury [55] investigated dust-acoustic waves in a self-gravitating dusty plasma with degenerate electrons and also performed linear stability analysis. El-Taibany and Wadati [56] have studied the QDA waves in a nonuniform dusty plasma. The importance of their studies was the diagnostics of charged dust impurities in ultra-small micro- and nanoelectronic devices. Quantum dust-acoustic waves in cylindrical quantum dusty plasma was discussed by Wang and Zhang [57]. Recently, Ayub *et al* have investigated DA waves in a self-gravitating dusty plasma comprising cold fluid dust grains, Maxwellian ions and degenerate electrons [58].

Most papers on DA solitary waves are based on Maxwell–Boltzmann distributed electrons and ions, while the simulation studies of Winske *et al* on dust-acoustic waves indicates deviations from the Boltzmann ion distribution [59]. Such distributions may be accurately modelled using a κ or generalized Lorentzian distribution. Such ion behaviour modifies the existence domain of nonlinear structures, which are not observed in dusty plasma with isothermal ions [60–63]. Superthermal ions are often present in space and astrophysical plasma environments, viz., the ionosphere, mesosphere, magnetosphere, lower atmosphere, magnetosheet, terrestrial plasma sheet, radiation belts and auroral zones [64–68]. Effect of ion suprathermality on propagation of DA waves is discussed in refs [69,70]. Baluku and Hellberg [71] have discussed the influence of κ-distributed electrons and/or ions on the formation of DA solitary waves in dusty plasma system. More recently, DA solitons as well as double layers have been studied in a superthermal electron-depleted dusty plasma [72].

To the best of our knowledge, the simultaneous influence of quantum effects and non-Maxwellian behaviour on the DA waves has not yet been studied. Hence, the main motivation of the present work is to study the suprathermality and quantum effects on the propagation of DA waves in dusty plasma. The Sagdeev pseudopotential approach [73] is used for studying arbitrary amplitude solitons. The existence domain of DA solitary waves due to quantum effects and κ-distribution of ions is discussed.

The outline of the paper is as follows. After the introduction in §1, the basic equations of this model are presented in §2 and also the linear dispersion relation is derived. In §3, applying Sagdeev pseudopotential approach, the large amplitude structures are discussed. The results are then summarized in §4.

2. Equations of the model

We consider here the propagation of nonlinear DA waves in dusty plasma with cold dust particles, κ-distributed ions and degenerate electrons. Thus, one-dimensional fluid equation of motion of dust particles is governed by the following normalized equations:

$$\frac{\partial n_{\mathrm{d}}}{\partial t} + \frac{\partial (n_{\mathrm{d}} u_{\mathrm{d}})}{\partial x} = 0 \tag{1}$$

$$\frac{\partial u_{\rm d}}{\partial t} + u_{\rm d}\frac{\partial u_{\rm d}}{\partial x} = \frac{\partial \phi}{\partial x}. \tag{2}$$

The electrostatic Poisson equation is

$$\frac{\partial^2 \phi}{\partial x^2} = \frac{n_{\rm i0}}{Z_{\rm d} n_{\rm d0}}\left[Z_{\rm d} n_{\rm d} + n_{\rm e} - n_{\rm i}\right], \tag{3}$$

where $f = n_{\rm e0}/n_{\rm i0}$. The number density of degenerate electrons, can be obtained through integration of the Fermi–Dirac distribution [74], as we have

$$n_{\rm e} = \frac{8\sqrt{2}m^{3/2}}{(2\pi\hbar)^3}\int \frac{\varepsilon^{1/2}{\rm d}\varepsilon}{{\rm e}^{(\varepsilon-U)/k_{\rm B}T_{\rm e}} + 1}, \tag{4}$$

where $U = \mu + e\phi$; ϕ and μ are the potential which traps the electrons and the chemical potential, respectively. Then, as in refs [75,76], for trapped electrons, we can obtain

$$n_{\rm e} \approx \left(1 + \frac{e\phi}{\varepsilon_{\rm F}}\right)^{3/2} + \frac{\pi^2 k_{\rm B}^2 T_{\rm e}^2/8\varepsilon_{\rm F}^2}{\sqrt{1 + e\phi/\varepsilon_{\rm F}}} \tag{5}$$

and in the fully degenerate case (i.e., $T_{\rm e} \cong 0$), the normalized number density of electrons is obtained as

$$n_{\rm e} = f\left(1 + \frac{\phi}{\varepsilon_{{\rm F}-i}}\right)^{3/2}, \tag{6}$$

where $\varepsilon_{{\rm F}-i} = \varepsilon_{\rm F}/k_{\rm B}T_i$ and Fermi energy is $\varepsilon_{\rm F} = \hbar^2(3\pi^2 n_{\rm e0})^{2/3}/2m_{\rm e}$. To model an ion distribution with superthermal particles, we employ a κ ion distribution function, as given in refs [70,71]. Therefore, the normalized ion number density is accordingly expressed as

$$n_{\rm i} = \left(1 + \frac{\phi}{\kappa - 3/2}\right)^{-\kappa+1/2}. \tag{7}$$

It is noted that the expression given above is only valid for $\kappa > 3/2$, and for the limit $\kappa \to \infty$, it reduces to the usual Boltzmann form. The following normalization $x \to x/\lambda_{\rm Dd}$, $t \to \omega_{\rm pd}t$, $n_j \to n_j/n_{i0}$, $u_{\rm e} \to u_{\rm e}/C_{\rm d}$, $\phi \to e\phi/k_{\rm B}T_{\rm i}$ is applied in eqs (1)–(7), where the dust plasma frequency is $\omega_{\rm pd} = \sqrt{n_{\rm d0}Z_{\rm d}^2 e^2/m_{\rm d}\varepsilon_0}$, the dust fluid speed is $C_{\rm d} = \sqrt{Z_{\rm d}k_{\rm B}T_{\rm i}/m_{\rm d}}$ and Debye length is $\lambda_{\rm Dd} = \sqrt{k_{\rm B}T_{\rm i}/\varepsilon_0 Z_{\rm d} n_{\rm d0} e^2}$. The charge equilibrium condition of the system is $n_{\rm e0} + Z_{\rm d}n_{\rm d0} = n_{\rm i0}$.

In the linear limit, the dispersion relation of dust-acoustic waves is obtained as

$$\omega^2 = \frac{k^2}{k^2 + k_{\rm c}^2}, \tag{8}$$

where $k_{\rm c}^2 = [3f/2\varepsilon_{{\rm F}-i} + (2\kappa - 1)/(2\kappa - 3)]/(1 - f)$. For Maxwellian ions and nondegenerate electrons, eq. (8) reproduces eq. (7) of ref. [8]. In the classical limit, eq. (8) reduces to eq. (29) of Saini and Kourakis [77], where they have studied modulation of DA waves in a dusty plasma comprising κ-distributed ions and Maxwellian electrons. Also in this limit, our results are similar to those found by Bryant [78]. When ions tend

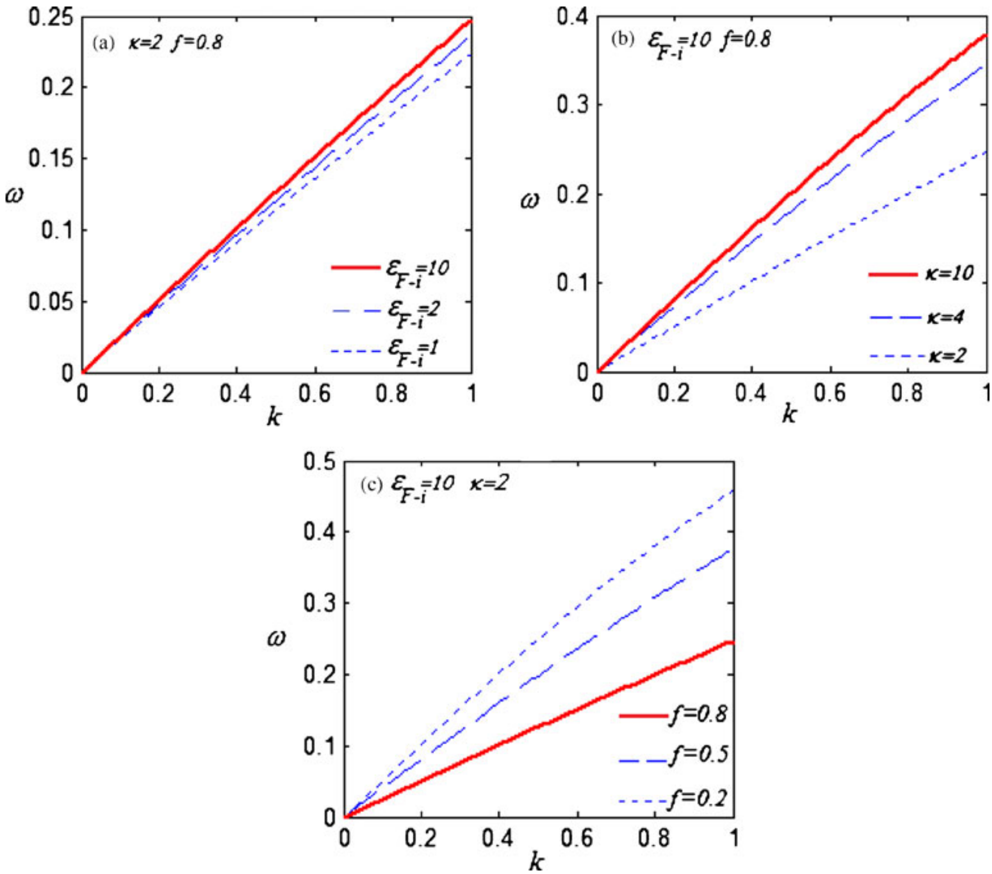

Figure 1. The behaviour of ω^2 vs. κ. (**a**) For various values of $\varepsilon_{\mathrm{F}-i}$, with $\kappa = 2$ and $f = 0.8$ (**b**) for various values of κ with $\varepsilon_{\mathrm{F}-i} = 10$ and $f = 0.8$ and (**c**) for various values of f with $\varepsilon_{\mathrm{F}-i} = 10$ and $\kappa = 2$.

towards the Maxwellian distribution ($\kappa \to \infty$), eq. (8) recovers eq. (9) of Ayub *et al* [58], which is obtained for DA waves in a self-gravitating dusty plasma comprising cold fluid dust grains, Maxwellian ions and degenerate electrons (ignoring the Jeans frequency and differences due to their notation and normalization).

Dispersion relation is plotted in figure 1, for different values of $\varepsilon_{\mathrm{F}-i}$, κ and f, in three parts (a), (b) and (c), respectively. It is found that the frequency of the wave increases with $\varepsilon_{\mathrm{F}-i}$ and κ, but decreases when f increases.

3. Soliton solution

In order to study solitons moving in a stationary frame, we work in the comoving frame, in which the plasma species flow through the stationary wave structure with an undisturbed normalized speed M at $x \to \pm\infty$. Thus, we introduce new transformation $\xi = x - Mt$.

Then, we can obtain [79,80] the normalized dust density from eqs (1) and (2)

$$n_{\mathrm{d}} = \frac{n_{\mathrm{d0}}/n_{\mathrm{i0}}}{\sqrt{1+2\phi/M^2}}. \tag{9}$$

To obtain eq. (9) from boundary conditions, it follows that $n_{\mathrm{d}} \to 1$ for $\phi \to 0$. Thus, the condition for dust density to be real is $2\phi/M^2 + 1 > 0$, which leads to an upper limit for M.

Substituting eqs (6), (7) and (9) into eq. (3), and after integration, we can obtain the energy equation

$$\frac{1}{2}\left(\frac{\partial\phi}{\partial\xi}\right)^2 + \psi(\phi, M) = 0, \tag{10}$$

where the Sagdeev potential $\psi(\phi)$ is defined as

$$\psi(\phi, M) = \frac{2\varepsilon_{\mathrm{F}-i}}{5}\frac{f}{1-f}\left[1-\left(1+\frac{\phi}{\varepsilon_{\mathrm{F}-i}}\right)^{5/2}\right] + M^2\left[1-\left(1+\frac{2\phi}{M^2}\right)^{1/2}\right] + \frac{1}{1-f}\left[1-\left(1+\frac{\phi}{\kappa-3/2}\right)^{-\kappa+3/2}\right]. \tag{11}$$

To obtain eq. (10), we have used the appropriate boundary conditions, namely $\{\phi, \partial\phi/\partial\xi\} \to 0$ as $\xi \to \pm\infty$. In the limit of Maxwellian behaviour, i.e., $\kappa \to \infty$, eq. (11) is reduced to that obtained by Ayub *et al* [58], Maxwellian ions and degenerate electrons (ignoring differences due to their notation and normalization).

Neglecting quantum effects, then the remaining terms in eq. (11) are similar to the results obtained by Baluku and Helberg for DA waves with κ-distributed ions [71]. Also in an electron-depleted dusty plasma (i.e., $f \to 0$) and for weak potentials, eq. (11) is the same as eq. (9) of ref. [72], which is obtained for DA waves with κ-distributed ions.

The existence condition of localized solution of eq. (10) requires that

(i) $\psi(\phi = 0) = \psi(\phi_{\max}) = (\partial\psi/\partial\xi)\big|_{\phi=0} = 0$,
(ii) $(\partial^2\psi/\partial\xi^2)\big|_{\phi=0} < 0$,
(iii) $\psi(\phi) < 0$, when $0 < \phi < \phi_{\max}$ for positive solitary waves and $\psi(\phi) < 0$, when $\phi_{\min} < \phi < 0$ for negative solitary waves, where $\phi_{\max}(\phi_{\min})$ is the maximum (minimum) value of ϕ for which, $\psi(\phi, M) = 0$.

It is evident that eq. (11) satisfies the first condition. The second condition (called the soliton solution), leads to the constraint

$$\left.\frac{\partial^2\psi}{\partial\xi^2}\right|_{\phi=0} = -\frac{3}{2\varepsilon_{\mathrm{F}-i}}\frac{f}{1-f} - \frac{\kappa-1/2}{\kappa-3/2}\frac{1}{1-f} + \frac{1}{M^2} < 0. \tag{12}$$

We can calculate the critical value of M from eq. (12) as follows:

$$M^2 > \frac{1}{\frac{3}{2\varepsilon_{\mathrm{F}-i}}\frac{f}{1-f} + \frac{2\kappa-1}{2\kappa-3}\frac{1}{1-f}} = M^2_{\mathrm{crit}}, \tag{13}$$

where M_{crit} can be defined as the minimum value of M above which, the compressive as well as rarefactive solitary waves can exist. Equation (13) indicates the lower limit of the soliton existence domain in the space of (f, M). Thus it leads to a lower limit for M, which is represented by $M_{\rm crit}$, and it follows that $M_{\rm crit} < M$. Here, $M_{\rm crit}$ is the DA wave speed, in this system. Also, constraint (13) exerts a condition on f as given by

$$f_{\rm crit} \equiv \frac{2\varepsilon_{{\rm F}-i}[(\kappa - 3/2) - M^2(\kappa - 1/2)]}{(\kappa - 3/2)[3M^2 + 2\varepsilon_{{\rm F}-i}]} < f. \tag{14}$$

Thus, the existence condition of solitons is $f > f_{\rm crit}$ or $M > M_{\rm crit}$. It seems that there are three other constraints on f (or M), which arise from conditions of reality of number density of plasma species. The condition for dust density to be real is $\phi > \phi_{\rm ud} = -M^2/2$, which leads to the restriction of $\psi(\phi_{\rm ud}) > 0$, a condition that is essential for obtaining the upper limit to the Mach number for the existence of positive dust-acoustic solitons. Then, one can obtain upper limit in the plane of (M, f)

$$\begin{aligned}\psi(\phi_{\rm d}) &= M^2 + \frac{f}{1-f}\frac{2\varepsilon_{{\rm F}-i}}{5}\left[1 - \left(1 - \frac{M^2}{2\varepsilon_{{\rm F}-i}}\right)^{5/2}\right] \\ &\quad + \frac{1}{1-f}\left[1 - \left(1 - \frac{M^2}{2\kappa - 3}\right)^{-\kappa+3/2}\right] > 0,\end{aligned} \tag{15}$$

where this constraint is in accordance with a curve in the plane of (M, f), as it needs to have

$$f < f_{\rm ud} = \frac{M^2 + 1 - \left[1 - M^2/(2\kappa - 3)\right]^{-\kappa+3/2}}{2\varepsilon_{{\rm F}-i}[1 - M^2/2\varepsilon_{{\rm F}-i}]^{5/2}/5 + M^2 - 2\varepsilon_{{\rm F}-i}/5}. \tag{16}$$

The reality condition of the electron density requires that $-\varepsilon_{{\rm F}-i} = \phi_{\rm ue} < \phi$. Thus, we should have $\psi(\phi_{\rm ue}) > 0$. But, it is found that $\psi(\phi_{\rm ue})$ is complex, and thus ψ does not satisfy the requirement for limiting the potential.

Finally, perhaps eq. (7) can exert another limitation on ϕ, which would in principle be provided by the ions at the critical potential $\phi_{\rm ui} = -(\kappa - 3/2)$, beyond which the ion density is complex. In this case, it requires that $\psi(\phi_{\rm ui}) > 0$. Equation (11) shows that for $\phi \rightarrow \kappa - 3/2$, we have $\psi[(\kappa - 3/2), M] \rightarrow -\infty$, thus, ψ does not satisfy the requirement for limiting the potential, viz., $\psi[(\kappa - 3/2), M] > 0$ (see ref. [71] and references therein).

3.1 *Nondegenerate κ-distributed electrons*

In this section, we consider nondegenerate κ-distributed electrons, for comparison with degenerate electrons. Baluku and Helberg have studied dust-acoustic solitons in plasmas with κ-distributed electrons and ions, and we use their resultants [71]. They obtained the following soliton condition:

$$M_{\rm scrit}^2 = \frac{1}{\frac{f\sigma}{1-f}\frac{2\kappa_{\rm e}-1}{2\kappa_{\rm e}-3} + \frac{1}{1-f}\frac{2\kappa_{\rm i}-1}{2\kappa_{\rm i}-3}}, \tag{17}$$

where $\sigma = T_{\rm i}/T_{\rm e}$. Constraint (17) exerts a condition on f which is given by

$$f_{\rm scrit} \equiv \frac{1 - M^2(2\kappa_{\rm i} - 1)/(2\kappa_{\rm i} - 3)}{M^2\sigma(2\kappa_{\rm e} - 1)/(2\kappa_{\rm e} - 3) + 1} < f, \tag{18}$$

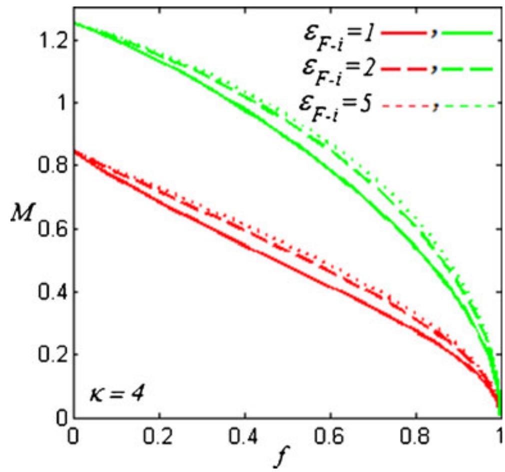

Figure 2. The existence domain of solitary waves in (f, M) plane for various values of ε_{F-i} with $\kappa = 4$.

where it needs $f_{\mathrm{scrit}} < f$. Equations (13) and (17), for $f = 0$ (i.e., in the absence of electrons), reduce to the unit form. Then, Baluku and Helberg have considered small-amplitude dust-acoustic solitons, and have obtained the existence domain of solitons and also studied formation of double layers. But, here we considered arbitrary amplitude soliton and followed the same mathematical treatment of their work. We found the condition for dust density to be real, exerts an upper limit on M (or f), and it can be obtained as the following constraint:

$$f < f_{\mathrm{sud}} = \frac{M^2 + 1 - [1 - M^2/(2\kappa_{\mathrm{i}} - 3)]^{-\kappa_{\mathrm{i}}+3/2}}{[1 + M^2\sigma/(2\kappa_{\mathrm{e}} - 3)]^{-\kappa_{\mathrm{e}}+3/2}/\sigma + M^2 - 1/\sigma}. \tag{19}$$

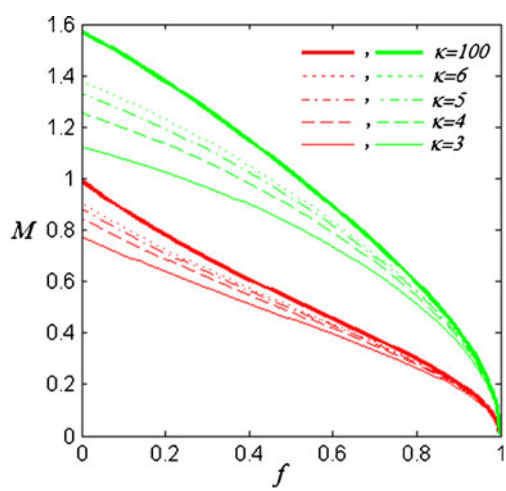

Figure 3. The existence domain of solitary waves in (f, M) plane for different values of κ with $\varepsilon_{F-i} = 1$.

We can plot two curves representing the range of soliton existence for degenerate electrons (lower bound is given by eq. (14), and upper bound is given by eq. (16)) or for nondegenerate electrons (lower bound is given by eq. (18), and upper bound is given by eq. (19)).

Figure 2 indicates the influence of quantum effects (via different values of ε_{F-i}) on the existence domain of solitons, with $\kappa = 4$. This figure shows that solitons propagate with higher values of Mach number for larger values of ε_{F-i}. Figure 3 shows the range of allowed Mach numbers as a function of the number density ratio, for different values of κ, with $\varepsilon_{F-i} = 1$. This figure indicates the interval of M, where solitons may exist. It is evident that both bounds (according to eqs (14) and (16)) decrease with f. Also we can see that for larger values of f (high electron density) dependency of M on κ becomes weaker (than other values of f). Furthermore, we found that the existence domain of solitons shifts towards larger values of M, for higher values of κ. It is obvious that the suprathermality effect results in the propagation of solitons with lower values of Mach numbers.

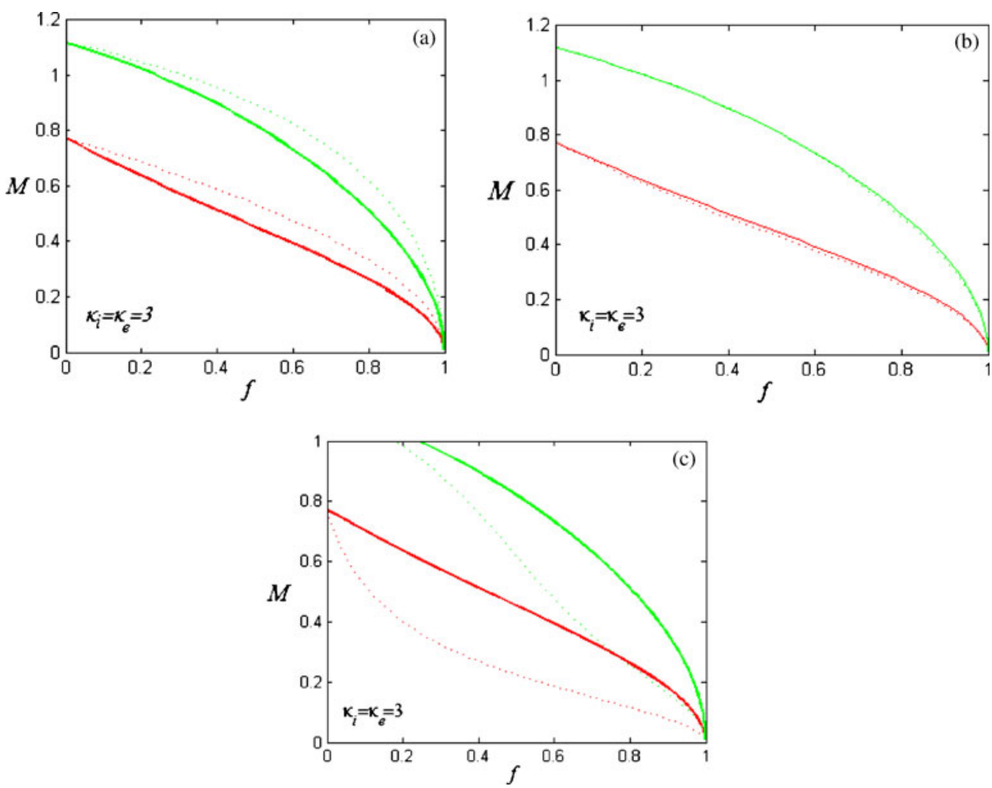

Figure 4. Comparison of the existence domain of soliton when electrons are degenerate (solid lines) with nondegenerate κ-distributed electrons (dotted lines). (**a**) $\sigma = 0.1$, (**b**) $\sigma = 1$ and (**c**) $\sigma = 10$, where $\kappa = \kappa_i = \kappa_e = 3$, $\varepsilon_{F-i} = 1$.

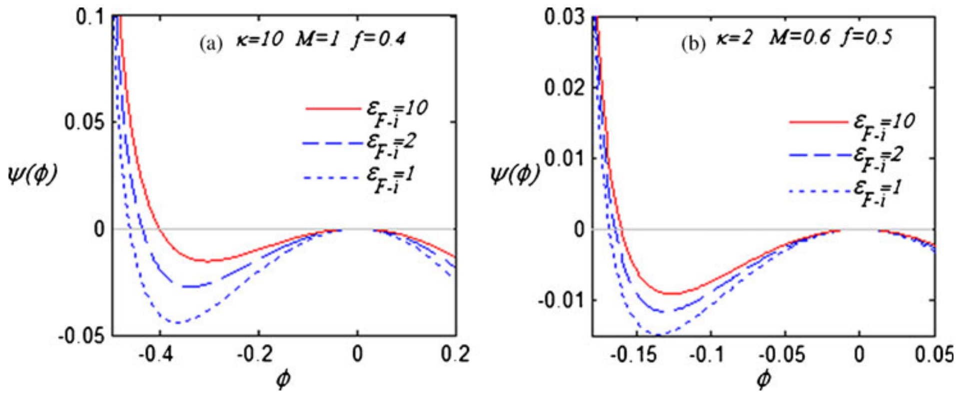

Figure 5. Variation of ψ with ϕ for different values of $\varepsilon_{\mathrm{F}-i}$, with (**a**) $\kappa = 10$ and (**b**) $\kappa = 2$; where $M = 1.25$, $f = 0.25$.

In figure 4, the effect of degenerate electrons on the existence domain of solitons is compared with nondegenerate electrons, using Baluku and Helberg model [71], for different values of σ ($\sigma = 0.1$ in part (a); $\sigma = 1$ in part (b); $\sigma = 10$ in part (c)). It is evident that the degenerate electrons affect the existence domain of solitons in comparison with nondegenerate κ-distributed electrons.

Variations of the Sagdeev pseudopotential against the normalized potential, for different values of the normalized Fermi energy $\varepsilon_{\mathrm{F}-i}$ is depicted in figure 5, for two values of κ. It is obvious that the Sagdeev potential well becomes deeper and wider as $\varepsilon_{\mathrm{F}-i}$ decreases. For lower κ values, the influence of quantum effects on the Sagdeev pseudopotential profile is smaller (than higher values of κ).

The electrostatic soliton profiles corresponding to the Sagdeev pseudopotentials, which is depicted in figure 5 is shown in figure 6 (with the same parameters). The electrostatic

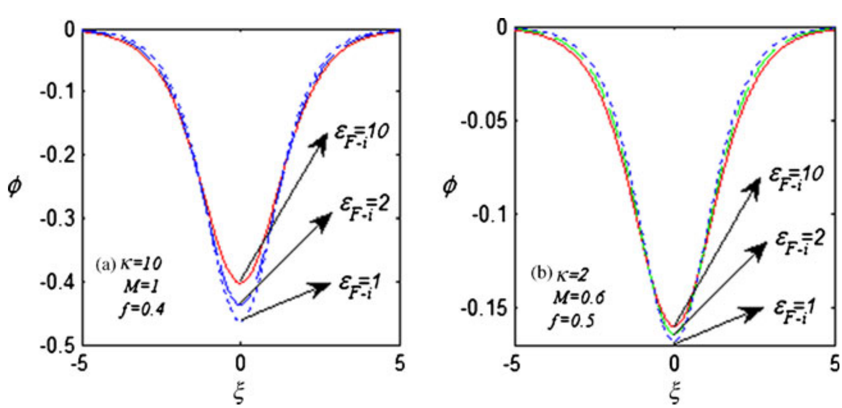

Figure 6. The influence of quantum effects and spectral index on the behaviour of electrostatic potential as a function of ξ, corresponding to $\psi(\phi)$ in figure 5.

potential is obtained via numerical integration. This figure shows that amplitude of soliton decreases with $\varepsilon_{\mathrm{F}-i}$. Also figures 5a and b show that the influence of quantum effects on the soliton profile are stronger for larger values of κ (than smaller values of κ).

4. Conclusions

The large-amplitude dust-acoustic solitary waves have been investigated in dusty plasma, consisting of fluid cold dust, κ-distributed ions and degenerate electrons. We have used a Sagdeev pseudopotential approach in a moving frame, where nonlinear structures are stationary.

The influence of suprathermality and quantum effects on the existence domain of DA solitary waves is investigated and compared with nondegenerate electrons. We found that the existence domain in number density ratio shifts toward lower values of Mach numbers, when f increases. The comparison of the existence domain for higher and lower values of κ shows that suprathermality results in the propagation of solitons with lower Mach numbers. Also figure 2 shows that the quantum effects, through increasing $\varepsilon_{\mathrm{F}-i}$, lead to propagation of solitons with higher values of Mach number.

We found that the Sagdeev potential well becomes deeper and wider as $\varepsilon_{\mathrm{F}-i}$ decreases, as for lower κ-values; the influence of quantum effects on the Sagdeev pseudopotential profile is smaller. The electrostatic soliton profiles corresponding to the Sagdeev pseudopotentials, which is depicted in figure 5 is shown in figure 6, for the same parameters. This figure shows that the amplitude of soliton decreases with $\varepsilon_{\mathrm{F}-i}$. Also, it is obvious that the influence of quantum effects on soliton profile is stronger for larger values of κ (than smaller values of κ) (figures 6a and b).

The results of this paper would be useful in understanding the basic nonlinear feature of DA wave propagation in laboratory and space dusty plasmas, especially those including degenerate electrons and suprathermal ions.

Acknowledgement

The author gratefully acknowledges the expert comments of the referees.

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