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Linear and Nonlinear Dust Acoustic Waves in Quantum Dusty Electron-Positron-Ion Plasma

Elham Emadi and Hossein Zahed

Department of physics, Sahand University of Technology, Tabriz, Iran
Corresponding Author Email: zahed@sut.ac.ir

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ABSTRACT— **The behavior of linear and nonlinear dust acoustic waves (DAWs) in an unmagnetized plasma including inertialess electrons and positrons, ions, and mobile positive/negative dust grains are studied. Reductive perturbation method is employed for small and finite amplitude DAWs. To investigate the solitary waves, the Korteweg–de Vries (KdV) equation is derived and the solution is presented. By numerical analysis, it is found that the soliton structure of the dust acoustic wave depends upon plasma parameters like electron to ion Fermi temperature ratio, σ, dust to ion temperature ratio δ and quantum diffraction parameter H.**

KEYWORDS: Quantum dusty plasma, Dust acoustic waves, Reductive perturbation method, soliton structure.

I. INTRODUCTION

Plasmas are generally associated with a hot gas of charged particles which behave classically. However, when the temperature is lowered and/or the density is increased sufficiently, the plasma particles (most importantly, electrons) become quantum degenerate, that is, the extension of their wave functions becomes comparable to the distance between neighboring particles. This is the case in many astrophysical plasma, such as those occurring in the interior of giant planets or dwarf and neutron stars, but also in various modern laboratory setups where charged particles are compressed by very intense ion or laser beams to multi megabar pressures. Finally, the exotic state of the Universe immediately after the Big Bang is believed to have been a quantum plasma consisting of electrons, quarks, photons, and gluons [1, 2]. The known mathematical methods such as Schrodinger–Poisson and Wigner-Poisson were widely used for description of hydrodynamic and statistical behaviors of plasma particles in quantum ranges. It is obvious that these methods are similar to the fluid and kinetic models of classical plasma physics. Quantum hydrodynamics (fluid) is generalizations of classical plasma fluid model, within transport equations is used in conservation laws for particles, momentum and energy. Quantum hydrodynamic model (*QHD*) is a reduced model that allows direct investigation of collective dynamics without challenging of complexities in Schrodinger–Poisson and Wigner-Poisson models. Using the standard definition of averaging macroscopic quantities, both Schrodinger–Poisson and Wigner-Poisson models can be lead to the *QHD* equations and also these methods create the same results [3]. Dust impurities exist in the quantum plasma, forming a quantum dusty plasma, for instance, microelectronic devices and metallic nanostrctures are usually contaminated by the presence of highly charged dust impurities. These also appear in astrophysics (e.g. supernova environments) and are likely to be found in ultra intense laser-solid material plasma (clusters) interaction experiments [4]. There has been a number of works focusing on the linear or nonlinear properties of low-frequency DA waves in magnetized or unmagnetized plasmas. Shukla and Ali derived a linear dispersion relation for quantum dust acoustic waves by using *QHD* model, and then obtained solitary wave solutions through the derivation of KdV equation in ultra-cold Fermi dusty plasmas [5, 6]. Misra *et al.* [7] studied the same system quantum dusty plasma considered in [5], to see the influence of quantum-mechanical effects on the modulation instability and envelope solitons by deriving the nonlinear Schrodinger NLS equation employing the well known reductive perturbation technique. They found that quantum mechanical effects affect both the dispersion and nonlinearity. Many researchers observed dust acoustic solitary waves with negatively charged dust grains. But positively charged dust grains are also observed in space due to Photo emission in the presence of flux of ultra-violate photons, thermionic emission induced by radiative heating, and secondary emission of electrons from the surface of dust grains [8]. Most of the theoretical studies are based on deriving Korteweg-deVries (KdV) and Kadomstev-Petviashvili (KP) equations by using reductive perturbation technique [9-11].these techniques are valid for small amplitude solitary waves. In this paper the quantum hydrodynamic model is employed to study the linear and nonlinear structure of dust acoustic solitons in quantum dusty plasmas consisting of inertialess electrons and positrons, ions, and negatively/positively charged dust particles. The manuscript is organized as follows: In Section II the basic equations for DIA solitons in a four component quantum plasma are presented. In Section III the linear behavior of DIA solitons are investigated. In Section IV, a Kdv equation is derived for nonlinear structure. The results are summarized in Section V.

II. BASIC EQUATIONS

We consider an unmagnetized plasma composed of inertialess quantum electrons and positrons, ions, and positively/negatively dust grains and then assume that the plasma particles in a zero-temperature Fermi gas obey the pressure law $p_j = \frac{m_j V_{Fj}^2}{3n_{j0}} n_j^3$ where $V_{Fj} = \sqrt{\frac{2k_B T_{Fj}}{m_j}}$ is Fermi speed and n_{j0} is the equilibrium number density of the *j*th species (*j=e, i, p, d*). Plasma components neutrality condition is $\beta - p = -e + I$ where $\beta = \pm 1$ (+۱ for negative and -۱ for positive dusts), $p = \frac{n_{p0}}{Z_{d0} n_{d0}}$, $e = \frac{n_{e0}}{Z_{d0} n_{d0}}$, $I = \frac{n_{i0}}{Z_{d0} n_{d0}}$. The dynamic of DAWs is governed by following normalized QHD model:

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

$$\frac{\partial^2 \varphi}{\partial x^2} = -\mu(\beta - I) n_e + \beta n_d - I n_i - (1-\mu)(\beta - I) n_p \tag{2}$$

$$\frac{\partial u_d}{\partial t} + u_d \frac{\partial u_d}{\partial x} = \beta \frac{\partial \phi}{\partial x} - \delta n_d \frac{\partial n_d}{\partial x} \tag{3}$$

$$-\frac{\partial \varphi}{\partial x} - n_i \frac{\partial n_i}{\partial x} = 0 \tag{4}$$

$$\frac{\partial \phi}{\partial x} - \sigma n_e \frac{\partial n_e}{\partial x} + \frac{H^2}{2} \frac{\partial}{\partial x}\left(\frac{1}{\sqrt{n_e}} \frac{\partial^2}{\partial x^2} \sqrt{n_e} \right) = 0 \tag{5}$$

$$\frac{\partial \phi}{\partial x} + \gamma n_p \frac{\partial n_p}{\partial x} - \frac{H^2}{2} \frac{\partial}{\partial x}\left(\frac{1}{\sqrt{n_p}} \frac{\partial^2}{\partial x^2} \sqrt{n_p} \right) = 0 \tag{6}$$

The normalization has been made by the following non-dimensional variables: $t \to t\omega_{pd}$, $x \to x/\lambda_D$, $u_j \to u_j / C_d$, $n_j \to n_j / n_{j0}$, $\varphi \to e\varphi / 2k_B T_{Fi}$, where $\omega_{pd} = \sqrt{4\pi Z_{d0}^2 e^2 n_{d0} / m_d}$ is the dust plasma frequency, $\lambda_D = \sqrt{2k_B T_{Fi} / 4\pi Z_{d0} e^2 n_{d0}}$ and $C_d = \sqrt{2 Z_{d0} k_B T_{Fi} / m_d}$ is Debye length and dust acoustic speed. Further, $\mu = 1 - p/(\beta - i)$, $\gamma = T_{Fp} / T_{Fi}$, $\sigma = T_{Fe} / T_{Fi}$, $\delta = T_{Fd} / (Z_{d0} T_{Fi})$ and $H = \sqrt{\hbar^2 Z_{d0} \omega_{pd}^2 / m_e m_d C_d^4}$ are dimensionless quantum parameters [11].

III. LINEAR DAWS–DISPERSION RELATION

To study the properties of linear DAWs, Fourier transforming the first order perturbed quantities of the Eqs. 1-6, we obtain the dispersion relation for DAWs in form of

$$\omega^2 = k^2\delta + \frac{k^2\left(\gamma + \frac{H^2}{4}k^2\right)}{\left(\gamma + \frac{H^2}{4}k^2\right)\left[k^2 + I\right] + k^2\left[-\mu(\beta - I) + (1-\mu)(\beta - I)\right]} \tag{7}$$

Note that, we assume the Fermi temperatures of electrons and positrons to be equal ($\sigma = \gamma$). In Fig. 1 the dispersion relation of DAWs is plotted for plasma consisting of positive or negative dust particles. It is shown that spite of similar behaviors, in the small wavelength regime, the phase velocity in plasma with positive dust grains is greater than negative one. But in very small and large wavelength regime, both dispersion relation curves are coincident and phase velocity are equal.

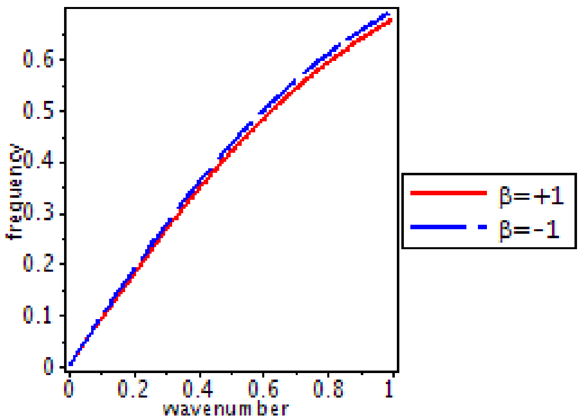


Fig. 1 Dispersion relation of linear DAWs for negative ($\beta = +1$) and positive ($\beta = -1$) dust grains for small amount of k, with fixed values $u_0 = 1$, $\sigma = \gamma = 20$, $\delta = 0.005$, $\mu_+ = 1.63$, $\mu_- = 0.13$, $I = 1.18$, $H = 0.61$.

Figure 2 shows the plot of frequency versus σ, δ, *H*, and *I*. It indicates that increasing of electron to ion Fermi temperature ratio σ and quantum diffraction parameter *H*, can be lead to the increasing in frequency for plasma with negative dust grains and vice versa for positive one.

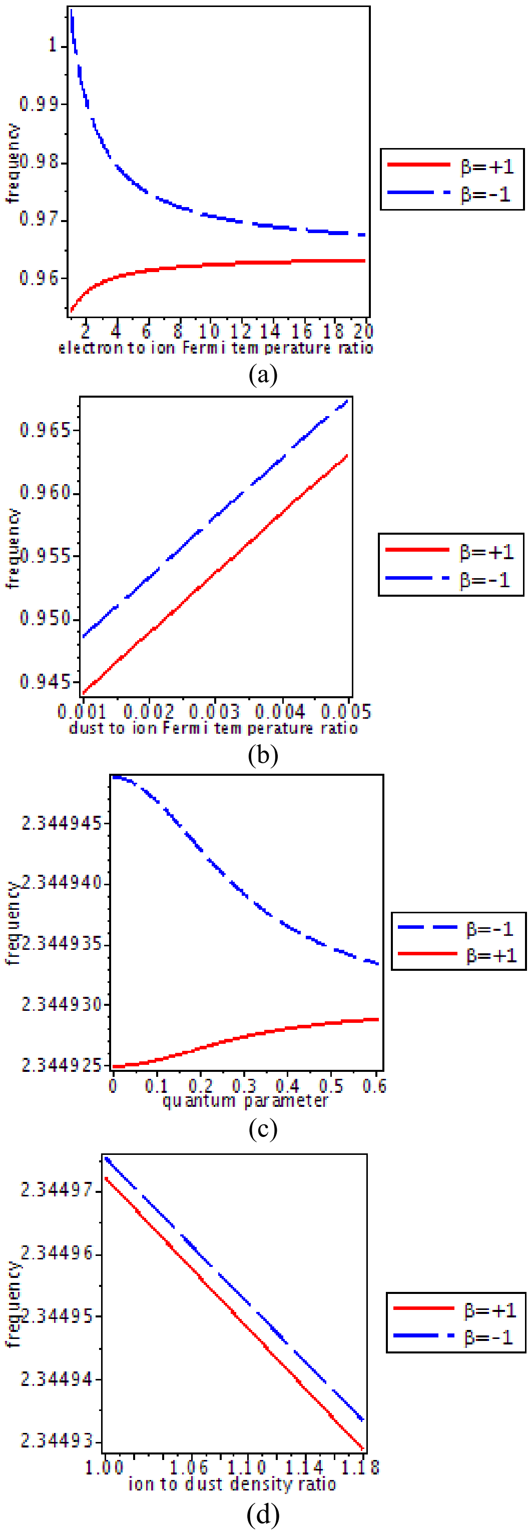


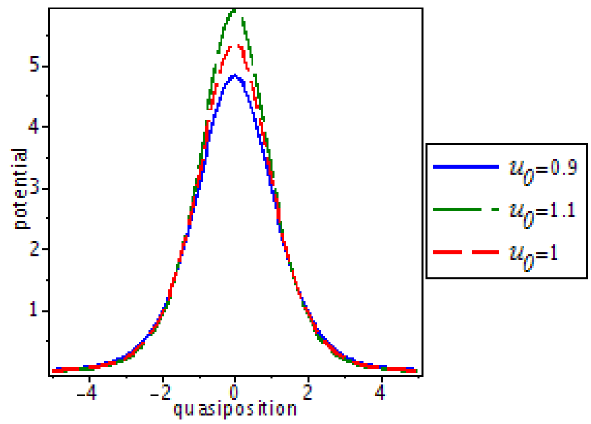
Fig. 2. Frequency of linear DAW versus σ(a), δ(b), *H*(c) and *I*(d) for negative (solid line) and positive (dashed line) dust grains.

Increasing of dust to ion temperature ratio δ can be leads to the faster increasing of frequency, while increasing of ion to dust initially density ratio I, can be leads to the faster decreasing of frequency for plasma with negative dust grains.

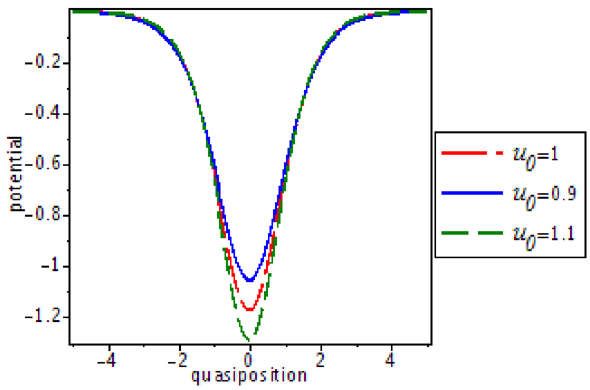
IV. The Nonlinear DAWs- Limit and Small Amplitude

We employ the reductive perturbation method to Eqs. 1-6 to obtain the nonlinear Korteweg devries (KdV) equation for one-dimensional DAWs. For This purpose, plasma parameters can be expanded in powers of ε as [12]

$$
\begin{aligned}
n_j &= 1+\varepsilon n_{j1}+\varepsilon^2 n_{j2}+\ldots \\
u_j &= \varepsilon u_{j1}+\varepsilon^2 u_{j2}+\ldots \qquad (8)\\
\phi &= \varepsilon\phi_1+\varepsilon^2\phi_2
\end{aligned}
$$



(a)



(b)

Fig. 3. Electrostatic potential in terms of η for positive (a) and negative (b) charge of dust grains for different value of u_0 with fixed values $u_0=1$, $\sigma=\gamma=20$, $\delta=0.005$, $\mu_+=1.63$, $\mu_-=0.13$, $I=1.18$, $H=0.61$.

We also introduce the following independent variables scaled as $\xi=\varepsilon^{1/2}(x-\lambda)$ and $\tau=\varepsilon^{3/2}t$. Substituting Eq. 8 into Eqs. 1-6 and collecting the various order terms of ε, we obtain a KdV equations

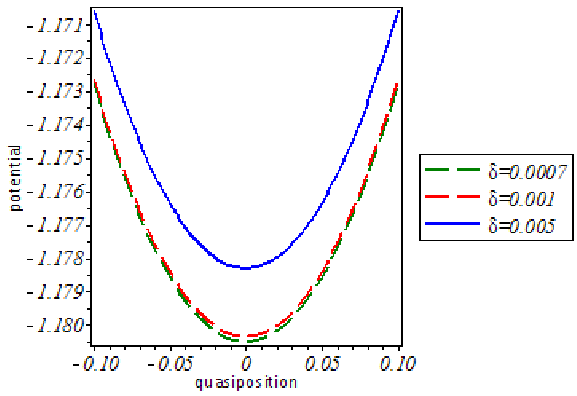
$$A_1\frac{\partial\varphi_1}{\partial\tau}+A_2\varphi_1\frac{\partial\varphi_1}{\partial\xi}+A_3\frac{\partial^3\varphi_1}{\partial\xi^3}=0 \qquad (9)$$

with the coefficients

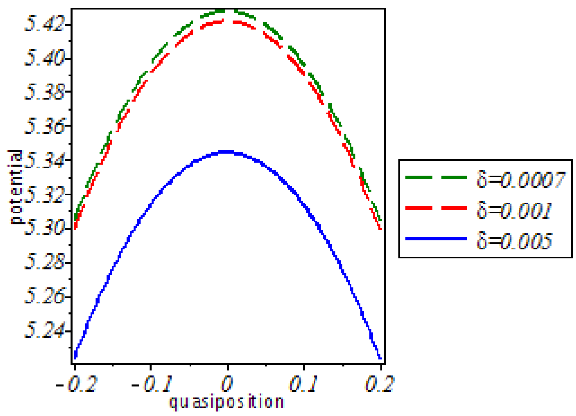
$$A_1=\frac{-2\beta^2\lambda}{\left(\lambda^2-\delta\right)^2}$$

$$A_2=\left[\frac{\mu(\beta-I)}{\sigma^2}+I+\frac{(1-\mu)(\beta-I)}{\gamma^2}+\frac{\left(3\lambda^2\beta^3+\delta\beta^3\right)}{\left(\lambda^2-\delta\right)^3}\right]$$

$$A_3=\left[\frac{-\mu(\beta-I)H^2}{4\sigma^2}+\frac{(1-\mu)(\beta-I)H^2}{4\gamma^2}-1\right]$$



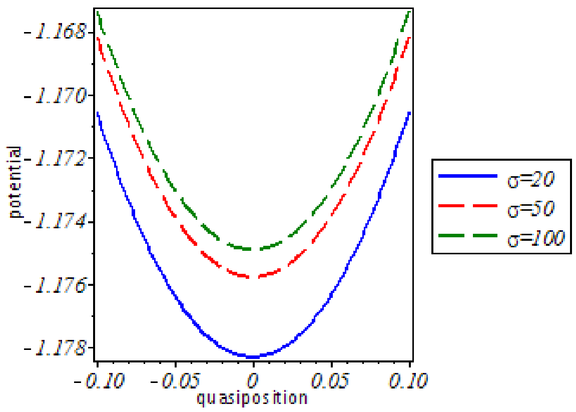
(a)



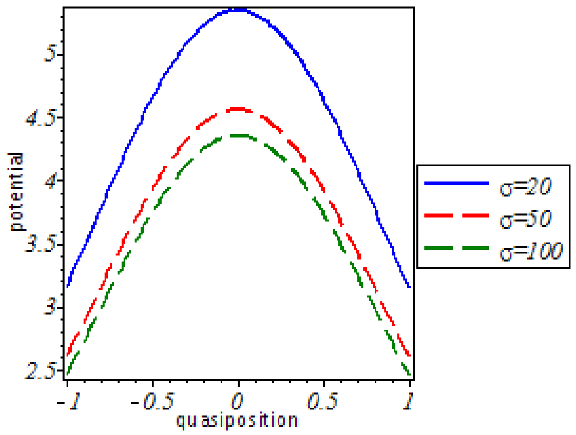
(b)

Fig. 4. Plot of electrostatic potential in terms of η for positive (a) and negative (b) charge of dust grains for different value of δ.

By imposing boundary conditions $\varphi_1 \to 0$, $\partial\phi_1 / \partial\xi \to 0$, $\partial^2\phi_1 / \partial\xi^2 \to 0$ at $\xi \to \pm\infty$, the possible stationary solution of Eq. 9 is $\varphi_1 = \varphi_0 \sec h^2(\eta / \Delta s)$ where $\phi_0 = 3A_1 u_0 / A_2$ and $\Delta s = \sqrt{4A_3 / A_1 u_0}$. Figures 3-5 show the variation of the electrostatic potential φ_1 as a function of η. It is noted that the nonlinear DAW is associated with a negative (positive) potential, which is due to the presence of negative (positive) charged dust grains in an ultracold Fermi gas.



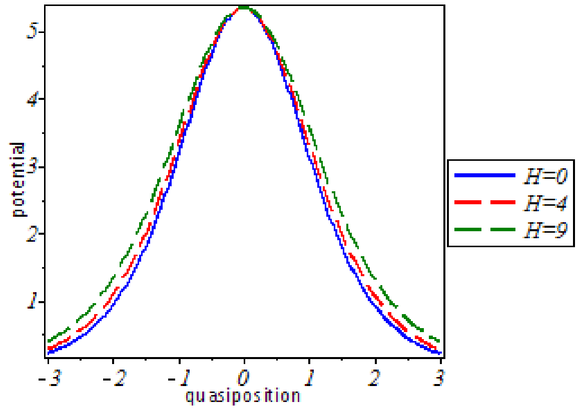
(a)



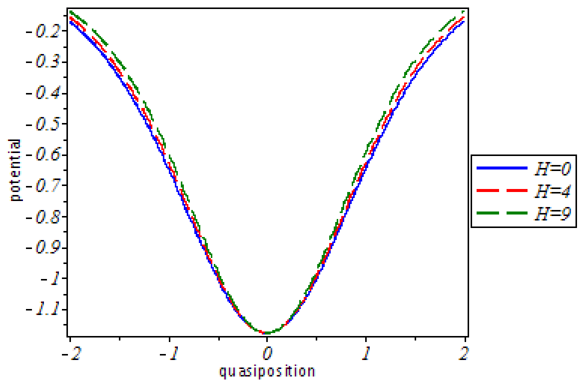
(b)

Fig. 5. Plot of electrostatic potential in terms of η for positive (a) and negative (b) charge of dust grains for different value of σ.

Fig. 4 indicates that increasing in speed u_0 can be leads to the increasing the amplitude of electrostatic potential In both quantum dusty plasma with negative or positive dust grains. Figs. 4 and 5 show that decreasing in δ and σ increase the amplitude of electrostatic potential. In Fig. 6, we could observe that quantum diffraction correction does not affect the amplitude of positive or negative potential, while increasing in *H*, decreases (increase) the width of electrostatic potential in quantum dusty plasma with positive (negative) dust grains.



(a)



(b)

Fig. 6. Plot of electrostatic potential in terms of η for positive (a) and negative (b) charge of dust grains for different value of *H*.

V. Conclusion

In this paper by using the quantum hydrodynamics model (QHD), the properties of linear and nonlinear DAWs are investigated. For nonlinear DAWs with small amplitude, reductive perturbation method is applied. It is shown that for linear DAWs, in the small wavelength regime, the dispersion relation gradient (phase velocity) of plasma including positive dust grains is greater than the plasma with negative one. It is also found that, increasing of σ and H, can be lead to increasing in the frequency of these waves for plasma with negative dust grains and vice versa for plasma with positive one. The KdV equation is derived to investigate DA solitary waves. From numerical analysis, it is found that the quantum diffraction effects, are significant in plasmas with ultrahigh density, which may be found in the atmospheres of neutron stars and the interior of white dwarfs. The soliton is also found to be affected by electron to ion Fermi temperature ratio σ and dust to ion temperature ratio δ. This work is aimed to study some basic features of DAWs in dense quantum plasmas, which are ubiquitous in massive astrophysical objects.

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Hossein Zahed, received his PhD degree in plasma physics from Tabriz University in 2006. He is currently Assistant Professor at Sahand University of Technology, He is a member of Physics, Optics and Photonics Society of Iran.

Elham Emadi received her M.Sc. degree in plasma physics from Sahand University of Technology in 2014. She is currently Ph.D. student at Sahand University of Technology. She is a member of Physics, Optics and Photonics society of Iran.

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