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Compressive and rarefactive dust-ion acoustic solitary waves in four components quantum plasma with dust-charge variation

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ABSTRACT

Based on quantum hydrodynamics theory (QHD), the propagation of nonlinear quantum dust-ion acoustic (QDIA) solitary waves in a collisionless, unmagnetized four component quantum plasma consisting of electrons, positrons, ions and stationary negatively charged dust grains with dust charge variation is investigated using reductive perturbation method. The charging current to the dust grains carried by the plasma particle, has been calculated with the orbit-limited motion approach. The quantum current of electrons and positrons is obtained by using Fermi-distribution functions. The basic features of QDIA solitary waves are studied by deriving the Korteweg-de Vries (KdV) Equation. It is found that both rarefactive and compressive type of solitons can exist in the model plasma. Further, the nonlinear and dispersive coefficients in KdV equation are modified by consideration dust charge variation effect and Fermi-Dirac distribution function. The present investigations should be useful for researches on astrophysical plasmas as well as for ultra small micro- and nano- electronic devices.
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چکیده

انتشار امواج غیر خطی سولیتاری غبار یون- صوت کوانتومی در یک پلاسمای کوانتومی غیر مغناطیده چهار مؤلفه‌ای شامل الکترون‌ها، پوزیترون‌ها، یون‌ها و ذرات غبار پایا با بار متغیر و منفی، بر اساس نظریه‌ی کوانتوم هیدرودینامیک و با استفاده از روش اختلال کاهشی تحقیق و بررسی شده است. جریان بار دار شدن ذرات غبار توسط ذرات پلاسما، از رهیافت حرکت مداری مقید حاصل شده و در محاسبه‌ی جریان کوانتومی الکترون‌ها و پوزیترون‌ها از تابع توزیع فرمی دیراک استفاده شده است. در این مطالعه مشخصه‌ی اصلی امواج سولیتاری غبار یون- صوت کوانتومی توسط معادله‌ی کورت وگ دوریس بررسی شده و وجود هر دو نوع ساختار رقیق و متراکم سالیتون ها در این مدل پلاسما نشان داده شده است. علاوه براین، نتایج نشان می‌دهد که ضرایب غیر خطی و پراش در معادله کورت وگ دوریس با در نظر گرفتن اثر تغییر بار ذرات غبار و تابع توزیع فرمی، اصلاح می‌شوند. مطالعه‌ی حاضر می‌تواند در درک بهتر رفتار پلاسماهای کوانتومی و وسایل الکترونیکی ابعاد نانو و میکرون مفید باشد.

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1 Introduction

In recent years, a huge number of works have been devoted to the investigation of the collective behavior of quantum plasmas [1]. It has been known that extremely dense and ultracold plasmas behave like an ideal gas, due to the exclusion principle. However, also dilute charged particle systems can exhibit quantum features, provided that the dimensions of the system are small enough. Small enough here means dimensions comparable to the de-Broglie wavelength, $\lambda_B = h/\sqrt{2\pi m k_B T}$, where h is the Planck's constant, T is the thermodynamic temperature, m is the mass of charge particle, and k_{B} is the Boltzmann's constant. For classical regimes, the de Broglie wavelength is so small that particles can be considered as point like; therefore there is no overlapping of the wave functions and no quantum interference. Therefore, one can expect to the quantum mechanical effects start playing a significant role when de-Broglie wavelength is similar to or larger than the average interparticle distance, $n^{-1/3}$, i.e., when $n\lambda_{\mathrm{B}}^3 \geq 1$, [2].

The three well known mathematical formulations to investigate new aspects of dense quantum plasmas by describe the dynamics of quantum plasmas are the Schrodinger-Poisson model, the Wigner-Poisson model and the quantum hydrodynamic (QHD) model. The quantum hydrodynamic model (QHD) as well as the Wigner-Poisson system can be used for investigating the new aspects of dense quantum plasma [3-6]. But it is more efficient to use the QHD model, because of its ease use of the boundary conditions and macroscopic variables. Mathematically, the (QHD) model generalizes the fluid model with the inclusion of quantum statistical pressure and quantum diffraction (also known as Bohm potential) term. These models have been discussed in detail in Refs. [7,8].

The vital role of quantum effects has been recognized in different environments such as: microelectronic devices [9], intense laser-solid density plasma experiments [10], dense astrophysical environments [11], high-gain free electron laser [12,13], thin metal films [14], quantum dots, nanowires [15], carbon nanotubes [16], quantum diodes [17], ultracold plasmas [18] and microplasmas [19].

The most of laboratory and astrophysical quantum plasmas consist of electrons, positrons, and ions (e-p-i). Thus, many researchers investigated the role of quantum corrections on linear and nonlinear electrostatic waves in dense e-p-i plasmas. For instance, Ali et al [20] investigated the linear and nonlinear properties of the ion acoustic wave in an unmagnetized electron-positron-ion quantum plasma and found that the nonlinear waves in this plasma model behaved so differently than that of ordinary e-i plasma. Han et al. [21] studied the nonlinear propagation of ion-acoustic solitary and shock waves in a dissipative, nonplanar quantum plasma comprised of electrons, positrons, and ions. They showed that, both type of rarefactive and compressive of the nonlinear waves can propagate in this plasma system.

In contrast to the ordinary plasmas, the most of the laboratory and astrophysical plasmas usually contain charged (negative or positive) impurities or dust particles in addition to the usual components such as electrons, positrons and ions; for instance, in different environments of low temperature laboratory, microelectronic devices and metallic nanostructures, tokamak edges, plasma coating, cometary tails, interplanetary spaces and in the planetary ring systems.

The presence of this charged dust particles changes the equilibrium condition and introduces different types of new wave modes such as dust-ion acoustic (DIA) waves. Therefore, it is important to study linear and nonlinear waves in various configuration of laboratory and spaces dusty plasma. It is well known that Shukla and Silin [22] were the first ones to investigate DIA waves theoretically in an unmagnetized collisionless dusty plasma and then DIA waves have been observed in laboratory [23,24]. Recently, many researchers have discussed several aspects of linear and nonlinear wave propagation in dusty plasmas [25-31]. Dust ion acoustic solitary wave, a kind of nonlinear waves associated with the DIA waves, have also received a great deal of attention in study the basic properties of localized electrostatic perturbations in space and laboratory dusty plasmas. Several authors have investigated theoretically in this subject. Rouhani et al. [32] investigated the nonlinear propagation of compressive and rarefactive QDIA solitary waves in four components quantum plasma. They studied the effect of quantum diffraction parameter (H) and dust density (n_d) on the structure of QDIA solitary waves. Emadi and Zahed 2016 [33] studied the behavior of linear and nonlinear dust ion acoustic (DIA) solitary waves in an unmagnetized quantum dusty plasma, including inertialess electrons and positrons, ions, and mobile negative dust grains. They employed Reductive perturbation and Sagdeev pseudopotential methods for small and large amplitude DIA solitary waves, respectively. They observed that the variation on the values of the plasma parameters such as different values of Mach number M, ion to electron Fermi temperature ratio σ, and quantum diffraction parameter H can lead to the creation of compressive solitary waves.

As usual, the dust charge is a function of the plasma parameters, but as a consequence of that, the typical dust charging time scale may be longer than the DIA time scale, and we anticipate that the dust charge fluctuations have no essential effect on the DIA mode, and the dust charge can therefore be assumed to be constant. All of the works that mentioned in above satisfy this situation and in other words, dust charge assumed to be constant. However, in a realistic situation in space and laboratory devices the charge on a dust grain is not constant but varies with space and time [34]. Ghosh et al. [35-37] have studied nonlinear propagation of the DIA waves, particularly solitary [35] in a dusty plasma by taking into account the dust charge variation. Alinejad 2010 [38] investigated the one dimensional dynamics of nonlinear electrostatic dust ion-coustic (DIA) waves in an unmagnetized dusty plasma consisting of ion fluid, non-thermal electrons and fluctuating immobile dust particles has been made by the reductive perturbation technique. He found that the dust charge fluctuation is a source of dissipation, and is responsible for the formation of the dust ion-acoustic shock waves. To the best of our knowledge, no investigation for nonlinear DIA solitary waves in four component quantum plasma with consideration of dust charge variation has been made.

On the other hand, the nonlinear wave propagation of any plasma system depends on the velocity distribution of the corresponding plasma species. The Maxwellian velocity distribution is considered as the usual distribution in a collisionless plasma [39-44]. But it is often noticed that the velocity distribution of plasma particles in space and laboratory are not exactly Maxwellian and may be deviated from that [45,46]. In quantum plasmas, the Fermi-Dirac statistical distribution is usually employed rather than the widely used Boltzman-Maxwell distribution in classical plasmas. Therefore, one would expect a great deal of interest effects to follow from the inclusion of the grain charge evolution and Fermi-distribution function for quantum particles. Following our trend on applications of the quantum plasma, in this paper, using the QHD model, we investigate the DIA solitary waves in an un-magnetized collision-less four component quantum plasma consisting of inertia-less quantum electrons and positrons with Fermi-distribution function, classical cold ions and stationary negative-dust-charge variation. The rate of dust grain charge variation is determined by the current associated with the electrons, positrons and ions in the plasma.

Our manuscript is organized as follows: The basic set of equations for QDIA waves are presented in Sec 2. In Sec 3, KdV equation is derived and the reductive perturbation method is used in its stationary solution. The structures of compressive and rarefactive solitary waves are investigated in Sec 4 and the Result and brief discussion is finally presented in Sec 5.

2 Basic equations

Following the quantum hydrodynamic model, we consider the homogeneous, collision-less, un magnetized and dissipative dust-electron-positron-ion quantum plasma consisting of inertia-less electrons and positrons. The stationary negative-dust-charge is not constant and varies with time. Since the electrons and positrons are fermions, their equation of state is described from the Fermi-gas model at approximately zero temperature as $P_j = 2k_B T_{Fj} n_j^3 / 3n_{j0}^2$, where $T_{Fj} = \hbar^2 (3\pi^2 n_j)^{2/3} / (2m_j k_B)$ is the Fermi temperature, kB is the Boltzmann constant, and n_{j0} is the equilibrium number density of the jth species (j=e, p). The quasi-neutrality condition in the equilibrium state can be written as $e_i + d_i = 1 + p_i$, where $e_i = n_{e0}/n_{i0}$, $p_i = n_{p0}/n_{i0}$, and $d_i = n_{d0}Q_{d0}/en_{i0}$. By using the QHD model, the set of normalized basic equation for DIA in the quantum plasma model are given as follow:

$$\partial_t n_i + \partial_x (n_i u_i) = 0 \ , \tag{1}$$

$$\partial_t u_i + u_i \partial_x u_i = -\partial_x \varphi \ , \tag{2}$$

$$\partial_x \varphi - n_e \partial_x n_e + \kappa \frac{H^2}{2} \partial_x \left[\frac{\partial_x^2 \sqrt{n_e}}{\sqrt{n_e}} \right] = 0 \ , \tag{3}$$

$$-\partial_x \varphi - \sigma n_p \partial_x n_p + \kappa \frac{H^2}{2} \partial_x \left[\frac{\partial_x^2 \sqrt{n_p}}{\sqrt{n_p}} \right] = 0 \ , \tag{4}$$

$$\partial_x^2 \varphi = (1-d_i)\alpha_d n_e + (1-d_i)(1-\alpha_d) n_p - n_i + d_i \frac{Q_d}{Q_{d0}} \ , \tag{5}$$

where $\alpha_d = e_i/(1-d) = 1 + (p_i/(1-d))$, $\sigma = T_{Fp}/T_{Fe}$, $m_e = m_p = m, \kappa = n_{i0}/n_{e0}$, The non-dimensional quantum diffraction parameter H is defined as $H = \hbar\omega_{pe}/k_B T_{Fe}$, that $\omega_{pe} = (4\pi n_{e0} e^2/m_e)^{1/2}$. The number density, n_j (j=e, i, p, d), of the jth species are normalized by their equilibrium density n_{j0}, the fluid ion velocity u by the quantum ion-acoustic speed $c_i = (k_B T_{Fe}/m_i)^{1/2}$, the electrostatic wave potential φ is normalized by $k_B T_{Fe}/e$, the space and time coordinates x and t are normalized, respectively, by the quantum Debye length $\lambda_D = (k_B T_{Fe}/4\pi e^2 n_{i0})^{1/2}$, and the ion plasma period $\omega_{pi}^{-1} = (4\pi e^2 n_{i0}/m_i)^{-1/2}$.

Since the dust grains are charged by the currents of the other particles in plasma model, the charge of dust grain (Qd) is not constant. The charge of dust grains depends on the number density and thermal speed of charged particles. The dust grains can acquire the negative charge when the number density of the electrons is larger than that of the positrons [47]. By considering a simple situation in which the charging current is due to the collections of electrons and ions hitting the grain surface, the variable dust charge Q_d is obtained by

$$dQ_d / dt = \sum_j I_j \ , \tag{6}$$

Where j represents the plasma species (i.e., j=e, p and i) and I_j is the current associated with the species j. According to the well-known orbit limited motion approach [34],

$$I_j(\vec{r}, t, q_d) = q_j \int v \sigma_j (q_d, v) f_j(\vec{r}, v, t) d^3 p \ , \tag{7}$$

Where f_j and q_j are, respectively, the velocity distribution and charge of the plasma species j and σ_j is the cross section for charging collisions between the dust and the plasma particle species j. Distribution function for classical particles (i.e., ions) is Maxwell-Boltzmann distribution and for quantum particles (i.e., electrons and positrons) is Fermi-Dirac distribution as defined as:

$$\begin{aligned} f_j(\varepsilon) &\propto \frac{1}{e^{\beta(\varepsilon-\mu_j)}} \qquad j = i, \\ f_j(\varepsilon) &\propto \frac{1}{e^{\beta(\varepsilon-\mu_j)}+1} \quad j = e, p \end{aligned} \ , \tag{8}$$

Therefore, one can obtain the following expressions for the plasma species currents for dust grains

$$I_e = -er_d^2 n_e V_{Te} \left((\mu_e + \varphi_d)^2 + \frac{\pi^2}{3} \right) , \tag{9}$$

$$I_p = er_d^2 n_p V_{Tp} \left(\mu_p^2 - 2\mu_p \varphi_d + \frac{\pi^2}{3} \right) , \tag{10}$$

$$I_i = 4\pi r_d^2 n_i e V_{Ti} \left(1 - \varphi_d \left(\frac{T_e}{T_i} \right) \right) , \tag{11}$$

where r_d is the radius of the dust grain, $T_e = T_p = T$ is the thermal temperature of electrons and positrons. μ_e *and* μ_p are, respectively, chemical potential of electrons and positrons that are normalized by $k_B T$ and $\varphi_d = \frac{Q_d}{r_d}$ is the electrostatic potential of dust particles and is normalized by $k_B T / e$.

Note that, to obtain I_e and I_p in relations (9) and (10), we have assumed that the chemical potential of electrons and positrons are large and the integral in relation (7) has been solved in this limit.

Summation of equilibrium currents; say, $I_{j0} = I_j(Q_d = Q_{d0})$, are zero

$$I_{e0} + I_{p0} + I_{i0} = 0 \ , \tag{12}$$

by letting $Q_d=Q_{d0}+q_d$, and $I_j=I_{j0}+I_{j1}$ and substituting (9-12) into (6), one can obtain

$$\frac{dq_d}{dt} = I_{e1} + I_{p1} + I_{i1} \ , \tag{13}$$

where, I_{j1} are the perturbed currents that normalized by I_{i0} as follows:

$$\begin{aligned}
&I_{j1} = I_j - I_{j0} \\
&I_{e1} = I_{e0}\left[\delta n_e + n_e(Aq_d^2 + Bq_d)\right] \\
&I_{p1} = I_{p0}\left[\delta n_p - n_p C q_d\right] \\
&I_{i1} = \left[\delta n_i - n_i D q_d\right] \\
&with\ \delta n_j = n_j - 1
\end{aligned} \tag{14}$$

The coefficients A, B, C and D are the functions of plasma parameters as follow:

$$A = \frac{\varphi_{d0}^2}{(\mu_e + \varphi_d)^2 + \dfrac{\pi^2}{3}} \ , \tag{15}$$

$$B = \frac{2\left(\varphi_{d0}^2 + \mu_e \varphi_{d0}\right)}{(\mu_e + \varphi_{d0}) + \dfrac{\pi^2}{3}} \ , \tag{16}$$

$$C = \frac{2\mu_p \varphi_{d0}}{\mu_p^2 - 2\mu_p \varphi_{d0} + \dfrac{\pi^2}{3}} \ , \tag{17}$$

$$D = \frac{\varphi_{d0}}{1 - \varphi_{d0}\dfrac{T_e}{T_i}} \ . \tag{18}$$

3 Derivation of the KdV equation

Now, using the reductive perturbation methods [49] and additional rescaling [48] $\xi = \varepsilon^{1/2}(x - v_0 t)$, $\tau = \varepsilon^{3/2} t$, where ε is a small parameter proportional to the amplitude of the perturbation and v_0 is the phase velocity normalized to the fixed acoustic speed c_i, we can study the dynamics of the propagation of small but finite amplitude quantum dust- ion acoustic solitary waves in plasma model. Therefore, we expand the perturbed variables around the equilibrium value as

$$\begin{aligned}
&n_j = 1 + \varepsilon n_{j1} + \varepsilon^2 n_{j2} + ..., \\
&u_i = 0 + \varepsilon u_{i1} + \varepsilon^2 u_{i2} + ..., \\
&\varphi = 0 + \varepsilon \varphi_1 + \varepsilon^2 \varphi_2 + ..., \\
&q_d = \varepsilon q_{d1} + \varepsilon^2 q_{d2} + ...,
\end{aligned} \tag{19}$$

with these new independent coordinates, and by substituting the expansions (19) into the one dimensional Eqs. (1)-(5) and (13), one can find a set of equations in the form of the lowest-order power series on ε,

$$\begin{aligned}
&u_{i1} = \frac{\varphi_1}{v_0}, \\
&n_{i1} = (1 - d_i)\left[\alpha_d - \frac{(1-\alpha_d)}{\sigma}\right]\varphi_1, \\
&n_{p1} = \frac{-\varphi_1}{\sigma}, \\
&n_{e1} = \varphi_1. \\
&q_{d1} = \frac{I_{e0} n_{e1} + I_{p0} n_{p1} + n_{i1}}{\eta}
\end{aligned} \tag{20}$$

where

$$\begin{aligned}
&\eta = -BI_{e0} + CI_{p0} + D, \\
&v_0 = \pm\left[\frac{1 - d_i/\eta}{(1-d_i)\left\{\alpha_d - \dfrac{(1-\alpha_d)}{\sigma}\right\} + d_i\left(\dfrac{I_{e0} - I_{p0}/\sigma}{\eta}\right)}\right]^{1/2}.
\end{aligned} \tag{21}$$

The positive or negative sign of v_0 corresponds to the right or left propagation of the QDIA wave, respectively.

To next higher order in ε, one can obtain the following set of equations:

$$-v_0 \partial_\xi n_{i2} + \partial_\xi u_{i2} = -\partial_\tau n_{i1} - \partial_\xi\left(n_{i1} u_{i1}\right), \tag{22}$$

$$\partial_\xi \varphi_2 - v_0 \partial_\xi u_{i2} = -u_{i1}\partial_\xi u_{i1} - \partial_\tau u_{i1} \tag{23}$$

$$-\partial_\xi \varphi_2 + \partial_\xi n_{e2} = -n_{e1}\partial_\xi n_{e1} + \kappa \frac{H^2}{4}\partial_\xi^3 n_{e1} \tag{24}$$

$$\partial_\xi \varphi_2 + \sigma \partial_\xi n_{p2} = -\sigma n_{p1}\partial_\xi n_{p1} + \kappa \frac{H^2}{4}\partial_\xi^3 n_{p1} \tag{25}$$

$$\partial_\xi^2 \varphi_1 = (1-d_i)\alpha_d n_{e2} + (1-d_i)(1-\alpha_d) n_{p2} - n_{i2} + d_i q_{d2} \tag{26}$$

$$\begin{aligned}
&I_{e0}\left[n_{e2} + Aq_{d1}^2 + Bn_{e1}q_{d1} + Bq_{d2}\right] + \\
&I_{p0}\left[n_{p2} - Cn_{p1}q_{d1} - Cq_{d2}\right] + \left[n_{i2} - Dn_{i1}q_{d1} - Dq_{d2}\right] = 0
\end{aligned} \tag{27}$$

Eliminating the second order perturbed quantities by using the first order relations; finally one can derive the KdV equation as

$$\partial_\tau \varphi_1 + P\varphi_1 \partial_\xi \varphi_1 + R\partial_\xi^3 \varphi_1 = 0 \quad , \tag{28}$$

where the coefficients of the nonlinear (P) and dispersive (R) terms are as follows:

$$P = \frac{1}{N}\left[\begin{array}{l} \frac{3}{v_0^{\,4}} + (1-d_i)(\alpha_d + \frac{(1-\alpha_d)}{\sigma^2}) + \\ \frac{d_i}{\eta}(I_{e0} + \frac{I_{p0}}{\sigma^2} - 2C\frac{I_{p0}}{\sigma v_0^{\,2}} - \frac{3}{v_0^{\,4}}) + \\ \frac{2d_i}{\eta^2}(-B\delta) + C(-\frac{I_{p0}I_{e0}}{\sigma} + \frac{I_{p0}^{\,2}}{\sigma^2}) + \frac{D}{v_0^{\,2}}\delta - \frac{2d_i}{\eta^3}A\delta^2 \end{array}\right]$$

$$R = \frac{1}{N}\left[1 - \frac{H^2}{4}\left[\left(1 - \frac{(1-\alpha_d)}{\alpha_d \sigma^2}\right) - \frac{\kappa d_i}{\eta}\left(I_{e0} - \frac{I_{p0}}{\sigma^2}\right)\right]\right] \tag{29}$$

with $N = \frac{2}{v_0^{\,3}}(1 - d_i/\eta)$, and $\delta = \left(I_{e0} - \frac{I_{p0}}{\sigma} + \frac{1}{v_0^{\,2}}\right)$.

The structure of the nonlinear propagation of the QDIA solitary waves in a dusty plasma model is described by the KdV equation. We find that in relation (29), the effect of dust charge variation and Fermi-Dirac statistics are applied through currents in coefficients P and R of KdV equation. Also, the quantum diffraction effects are responsible for the term proportional to H^2.

Using the transformation $\rho = \xi - u_0\tau$, where u_0 is the constant speed normalized by c_i, one can obtain the analytical solution of KdV equation in (28). Accordingly, the KdV equation can be written as

$$-u_0\frac{d\phi}{d\rho} + P\phi\frac{d\phi}{d\rho} + R\frac{d^3\phi}{d\rho^3} = 0 \quad , \tag{30}$$

where $\phi = \varphi_1$.

Integrating equation (30) and inserting the boundary conditions, namely: $\phi \to 0$, $\frac{d\phi}{d\rho} \to 0$, and $\frac{d^2\phi}{d\rho^2} \to 0$ as $\rho \to \pm\infty$, the stationary solitary wave solution of the KdV equation is obtained,

$$\phi = \phi_m \sec h^2(\frac{\rho}{w}) . \tag{31}$$

Where, $w = \sqrt{\frac{4R}{u_0}}$ and $\phi_m = \frac{3u_0}{P}$ are width and maximum amplitude of the solitary wave, respectively. Accordingly, the soliton amplitude depends on the nonlinear coefficient (P) and the soliton width depends on dispersive coefficient (R). Note that, in the solitary waves as equation (31), the quantity $\frac{4R}{u_0}$ has to be positive.

Dependence of the width of the solitary waves on μ_e and d_i are shown in Figs. 1 and 2, respectively.

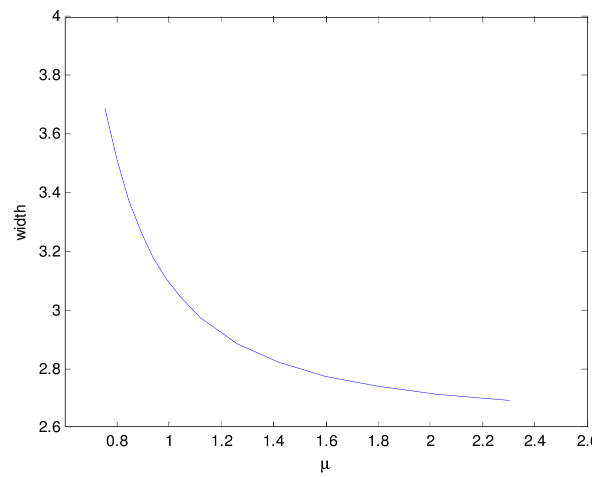

Fig.1 The dependence of soliton width on normalized chemical potential of electrons with: P=1.35, d=0.85, u0=0.1

According to Fig. 1, the width of solitary wave decreases as μ_i increases and from Fig. 2, it is observed that, the width of the solitary wave increases as d_i increases.

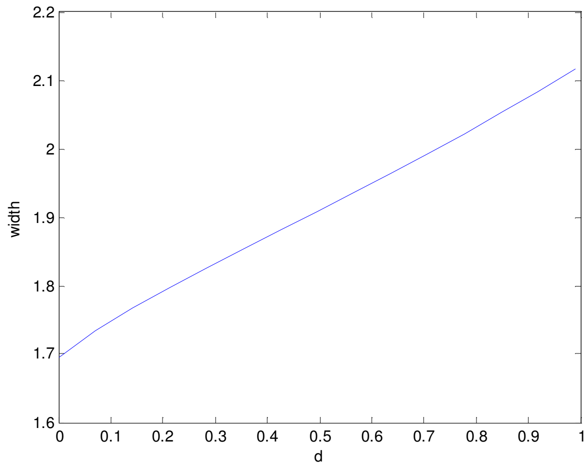

Fig.2 The dependence of soliton width on d_i with: e=2, μ_e=1.27, u_0=0.1

The effect of μ_e on profile of QDIA solitary waves in model plasma is shown in Fig. 3.

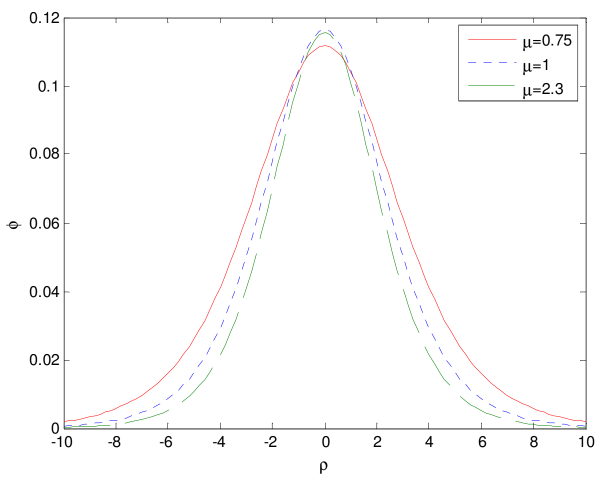

Fig. 3 stationary solitary wave for different values of μ_e with: P=1.35, d=0.85, u_0=0.1

4 Compressive and rarefactive solitons

Solitary wave is established by balancing the effects of dispersive and nonlinear effects. The characteristic of such soliton structures depends on the relative values between these two effects. Thus, the coefficients R and P have a significant role in the solitary wave structure. From the expressions in Eq. (29), it is found that the coefficients R and P are affected by the dusty density (d_i) and quantum diffraction (H). The coefficient P depends on d_i but is independent of H, whereas, the coefficient R depends interestingly on d_i and H. By calculating, one can shows that the value of R vanishes at specific values of H (H_c), where

$$R=\frac{1}{N}\left[1-\frac{H^2}{4}\left[\left(1-\frac{(1-\alpha_d)}{\alpha_d\sigma^2}\right)-\frac{\kappa d_i}{\eta}\left(I_{e0}-\frac{I_{p0}}{\sigma^2}\right)\right]\right]=0$$
$$\Rightarrow 1-\frac{H^2}{4}\left[\left(1-\frac{(1-\alpha_d)}{\alpha_d\sigma^2}\right)-\frac{\kappa d_i}{\eta}\left(I_{e0}-\frac{I_{p0}}{\sigma^2}\right)\right]=0$$
$$\Rightarrow H_c=2\left[\left(1-\frac{(1-\alpha_d)}{\alpha_d\sigma^2}\right)-\frac{\kappa d_i}{\eta}\left(I_{e0}-\frac{I_{p0}}{\sigma^2}\right)\right]^{-\frac{1}{2}}. \tag{32}$$

For these critical values of H, the KdV soliton disappears. The plot of the variation of H_c with d_i is shown in Fig. 4. It is observed that H_c decreases as d_i increases. In acceptable situation such as R>0 (below) with u_0>0 only compressive solitary wave structure is formed and it is clear that no solitonic structure is possible for R < 0 (above) with velocity u_0>0. The other acceptable situation is for R<0 and u_0<0, where the rarefactive soliton is formed.

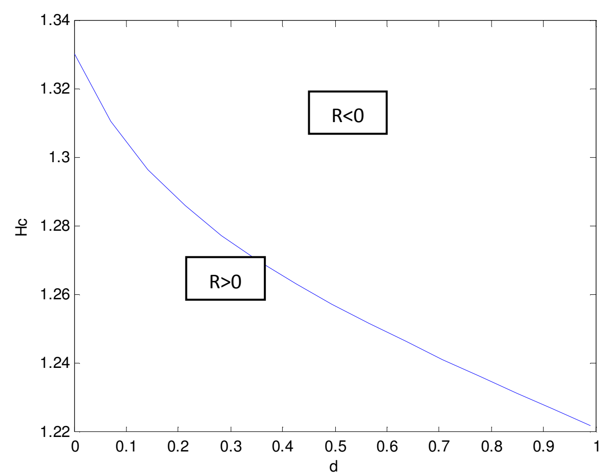

Fig. 4 Critical values of H versus d_i with e=2, μ_e=1.27, u_0=0.1

Figures 5 and 7 respectively show the structures of compressive (H<H_c) and rarefactive (H>H_c) solitary wave in a plasma model with d_i=0.85 and different values of H.

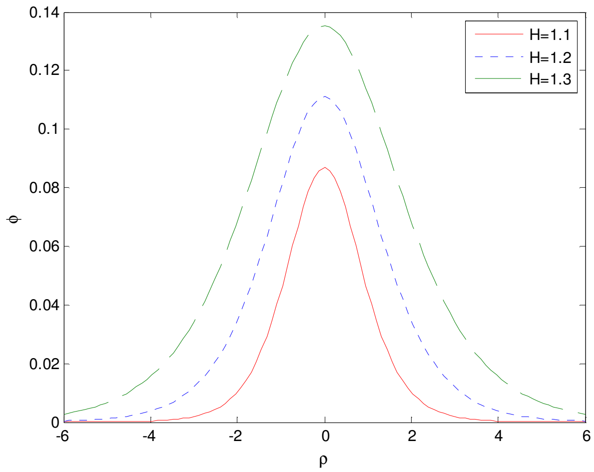

Fig. 5 QDIA compressive solitons for different values of H and with d_i=0.85 ، u_0=0.1.

The effect of quantum diffraction (H) on amplitude and width of the compressive solitary wave is shown in Figs. 6 (a) and 6 (b), respectively. It is found that the amplitude of compressive soliton and its width increase with the increase of H.

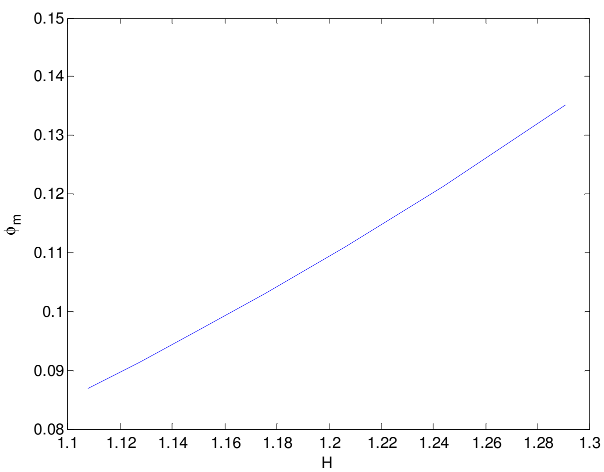

Fig. 6 (a) Dependence of QDIA compressive soliton amplitude on H with d_i=0.85 ، u_0=0.1.

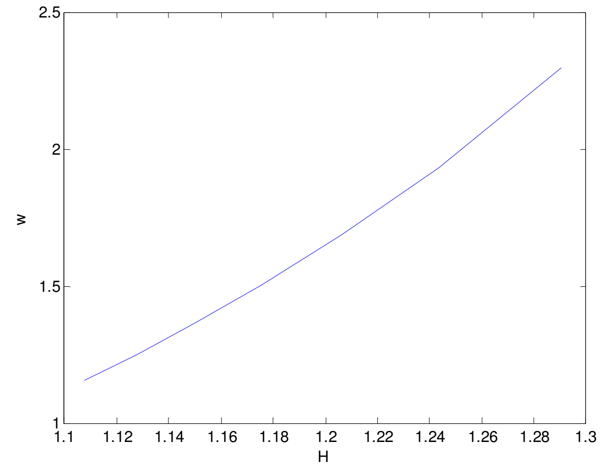

Fig. 6 (b) Dependence of QDIA compressive soliton width on H with d_i=0.85 ، u_0=0.1.

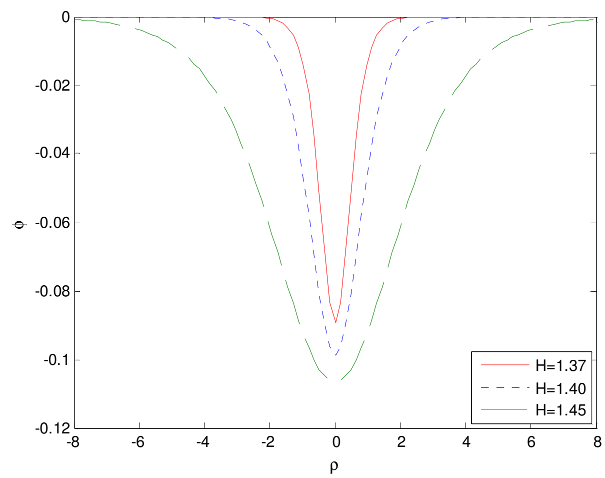

Fig. 7 QDIA rarefactive solitons for different values of H and with d_i=0.85 ، u_0=-0.1.

Also, in Figs. 8 (a) and 8 (b), it is shown that the amplitude and width of rarefactive soliton increase as H increases.

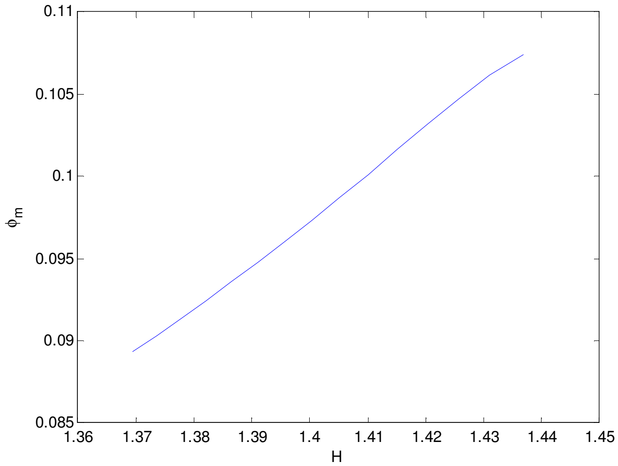

Fig. 8 (a) Dependence of QDIA rarefactive soliton amplitude on H with d_i=0.85 ‹u_0=-0.1.

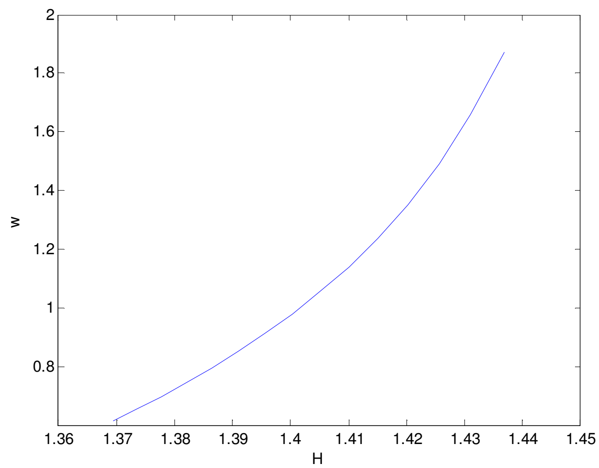

Fig. 8 (b) Dependence of QDIA rarefactive soliton width on H with d_i=0.85 ‹u_0=-0.1.

This study has been done with considering dust charge variation. But, if the dust charge is considered fixed, the structure of compressive and rarefactive solitary waves is obtained from KdV equation as follows [32]:

$$\phi = \phi_m \sec h^2 (\frac{\rho}{w}). \tag{33}$$

Where, $\phi_m = \frac{3u_0}{P}$ and $w = \sqrt{\frac{4R}{u_0}}$ and the nonlinear and dispersive coefficients are defined as

$$P = \frac{3}{2v_0} + \frac{v_0^3}{2}(1-d_i)\left[\alpha_d + (1-\alpha_d)/\sigma^2\right], \tag{34}$$

$$R = \frac{v_0^3}{2}\left[1 - \frac{H^2}{4}\left[1 - \frac{(1-\alpha_d)}{\alpha_d \sigma^2}\right]\right], \tag{35}$$

$$v_0 = \pm \frac{1}{\sqrt{(1-d_i)\left[\alpha_d - \frac{(1-\alpha_d)}{\sigma}\right]}}. \tag{36}$$

For critical values of H (H_c), the dispersive coefficient (R) vanishes. One can show that this critical values of H is obtained as follows,

$$R = \frac{v_0^3}{2}\left[1 - \frac{H^2}{4}\left[1 - \frac{(1-\alpha_d)}{\alpha_d \sigma^2}\right]\right] = 0$$
$$\Rightarrow \left[1 - \frac{H^2}{4}\left[1 - \frac{(1-\alpha_d)}{\alpha_d \sigma^2}\right]\right] = 0 \tag{37}$$
$$\Rightarrow H_c = 2\left(\frac{\alpha_d \sigma^2}{\alpha_d(\sigma^2+1)-1}\right)^{\frac{1}{2}}.$$

Figures 9 and 11 respectively show the structures of compressive ($H<H_c$) and rarefactive ($H>H_c$) solitary wave without considering the dust charge variation in a same plasma model with d_i=0.85 and different values of H.

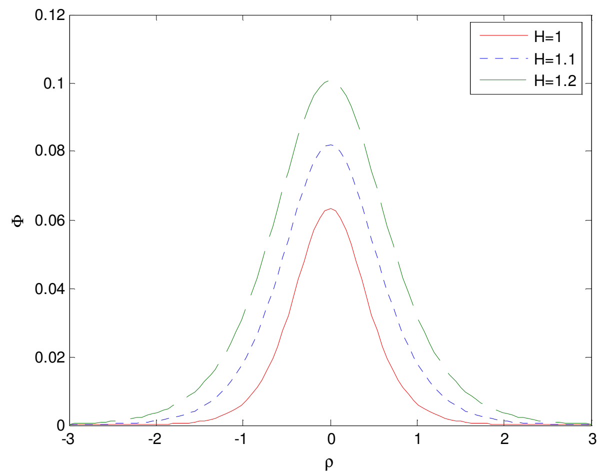

Fig. 9 QDIA compressive solitons without dust charge variation for different values of H and with d_i=0.85 ‹u_0=0.1.

The dependence of amplitude and width of the compressive and rarefactive solitary waves on H are shown in Figs. 10 and 12, respectively. It is found that in the both compressive and rarefactive structures, its width and amplitude increases with the increase of H.

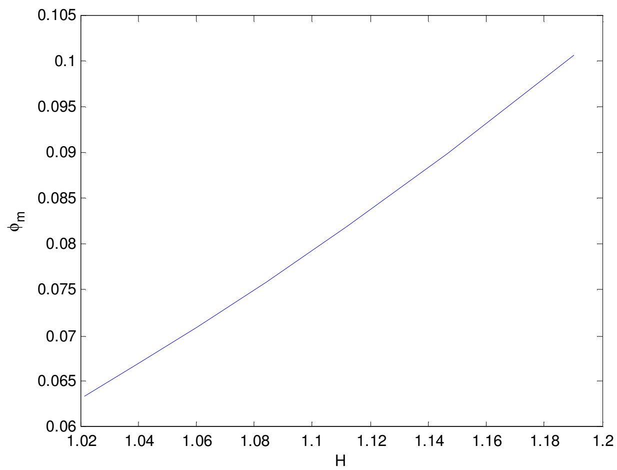

Fig. 10 (a) Dependence of QDIA compressive soliton amplitude on H without dust charge variation and with d_i=0.85 ،u_0=0.1.

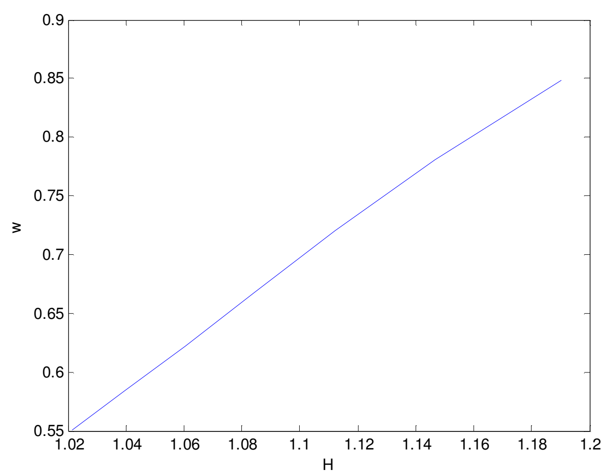

Fig. 10 (b) Dependence of QDIA compressive soliton width on H without dust charge variation and with di=0.85 ،u0=0.1.

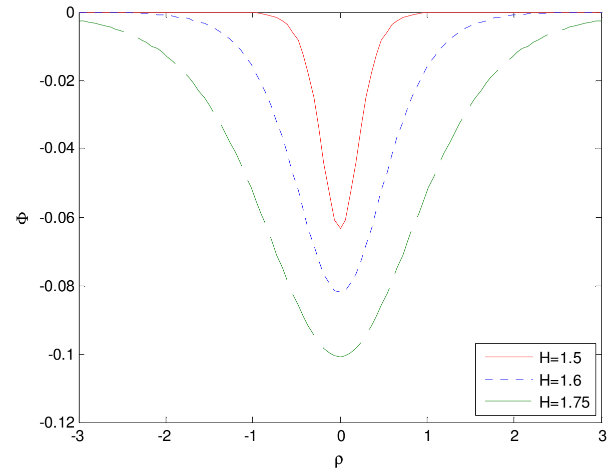

Fig. 11 QDIA rarefactive solitons without dust charge variation for different values of H and with d_i=0.85 ،u_0=-0.1.

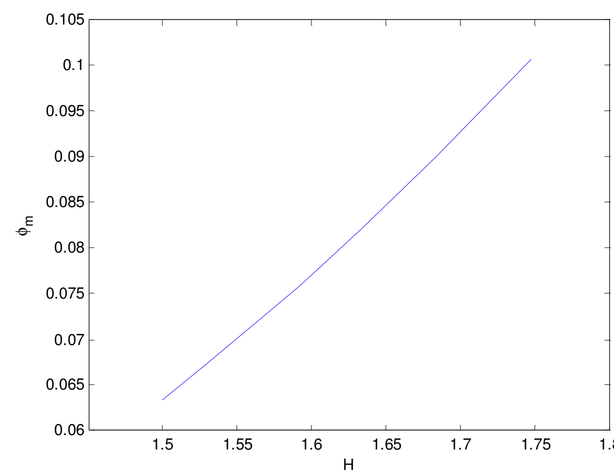

Fig. 12 (a) Dependence of QDIA rarefactive soliton amplitude on H without dust charge variation and with d_i=0.85 ،u_0=-0.1.

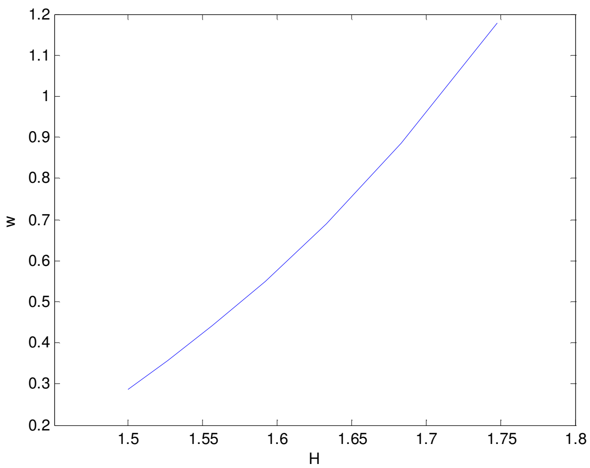

Fig. 12 (b) Dependence of QDIA rarefactive soliton width on H without dust charge variation and with d_i=0.85 ‹u_0=-0.1.

5 Conclusions

In this paper, we have investigated the propagation of nonlinear QDIA compressive and rarefactive solitary waves in quantum dusty plasma containing inertia-less quantum electrons and positrons, classical ions and stationary dust by using fluid theory. The dust charge variation effects and quantum mechanical effects are taken into account. Considering the dust charge variation gives rise to calculating of charging current of the plasma particles. The quantum current of electrons and positrons and the classical current of ions are obtained by using Fermi-distribution functions and Boltzman-Maxwell distribution, respectively. The reductive perturbation method is applied to derive the KdV equation to study small amplitude solitary waves. With attention to the kind of stretched space-time coordinates that has been used in this method, dust charge variation effects appear in the coefficients of the nonlinear (P) and dispersive (R) terms, where these effects don't lead to dissipation. The coefficients P and R are modified through the currents associated with the species of particles in model plasma. Also we have found in analytical and numerical stationary solitary wave solution that these waves depend on the chemical potential as well as the quantum diffraction parameter (H).

We are hopeful that the current findings can be applicable to highly degenerate dense space dusty plasma such as white dwarfs.

Acknowledgments

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