East European Journal of Physics. 2. 113-118 (2025)
DOI:10.26565/2312-4334-2025-2-11 ISSN 2312-4334

ION-ACOUSTIC SOLITARY WAVES IN AN UNMAGNETISED DUSTY PLASMA HAVING INERTIALESS ELECTRONS WITH QUANTUM EFFECTS

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Received February 2, 2025; revised February 17, 2025; accepted March 20, 2025

This investigation illustrates the presence and characteristics of compressive and rarefactive solitons in an unmagnetized plasma that includes positive ions, negatively charged dust, inertialess electrons with quantum effect and nonextensively distributed electrons and positrons. For this unmagnetized dusty plasma with positive ions, negatively charged dust, inertialess electrons with quantum effect and nonextensively distributed electrons and positrons, the Korteweg-de Vries (KdV) equation is derived and thus existence and behaviour of compressive and rarefactive soliton is examined. The fluid equations of motion governing the one-dimensional plasma serve as the foundation for the analysis. Using different relational forms of the strength parameter (ε) to stretch the space and time variables results in different nonlinearities. When discussing the effects on soliton amplitude, nonlinearity, and dispersion, various plasma parameters have been considered.
Keywords: *Soliton; q-nonextensive distribution; Reductive perturbation method; KdV equation*
PACS: 52.35.Sb, 52.35.Fp, 52.35.Qz, 52.27.Ep

1. INTRODUCTION

Since electron-positron-ion plasma has so many uses and can be used to observe a variety of astrophysical environments, including the Milky Way galaxy's centre [1], and the production of hard thermal photons with relativistic heavy ion collisions in quark-gluon plasmas [2], it is one of the most crucial areas for researchers to study. Novel statistical techniques like q-nonextensive statistics or Tsallis statistics are gaining popularity. Tsallis statistics yields a power law distribution for all values of q, while the Maxwellian distribution is only obtained for $q = 1$ [3]. Saini and Shalini have investigated the ion acoustic solitons in a nonextensive plasma with multi-temperature electrons [4]. Shahmansouri and Alinejad [5] discussed two dust ion-acoustic (DIA) solitary wave modes based on population and electron superthermality. When charged dust grains are present in a plasma, the existing plasma wave spectra undergo modifications [6] and several new modes are introduced, such as the dust-acoustic mode [7–8], the dust ion-acoustic mode [9–10], the dust lattice mode [11], etc. Das [12] investigated the combination of the immobile dust charge and relativistic electrons and ion streaming speeds to produce dust-ion acoustic compressive and rarefactive relativistic solitons in a multispecies plasma model for immobile dusty plasma. In astrophysical environments, compact astrophysical objects and the interiors of planets both contain quantum plasmas [13]. In laboratories, quantum plasmas are observed in semiconductors and micromechanical systems [14], in next-generation intense laser–solid density plasma interaction experiments, and in quantum x-ray free-electron lasers [15]. The first study of the quantum counterpart of ion-acoustic waves was conducted by Haas, Garcia, Goedert and Manfredi [16]. They determine a dimensionless parameter that measures the quantum diffraction effects, beginning with the quantum hydrodynamical model. It is demonstrated that the characteristics of solitary waves are significantly impacted by quantum effects [16,17]. Chabrier, Douchin and Potekhin [18] examined the properties of dense plasmas characteristic of the atmospheres of neutron stars and of the interior of massive white dwarfs. Masood [19] used renormalization scheme of quantum electrodynamics (QED) at high temperatures to calculate the effective parameters of relativistic plasma in the early universe. Hasnan, Biswas, Habib, and Sultana [20] have investigated different dust ion acoustic wave modes theoretically and numerically, taking into account a four-component magnetised collisional k-nonthermal plasma that comprises non-inertial k-distributed super thermal electrons, inertial ion fluid, and stationary dust grains of opposite charges. Compressive and rarefactive solitons are demonstrated to exist in a plasma model that includes unmagnetized weak-relativistic positive ions, negative ions, electrons, electron beam and positron beam by Barman and Talukdar [21]. However, in this paper we try to investigate properties of compressive and rarefactive solitons in a non-relativistic plasma model. The reflection of a dust acoustic solitary wave from a potential barrier in a dusty plasma medium was observed experimentally by Kumar, Bandyopadhyay, Singh, Arora and Sen[22], in which experiments were conducted in a DC glow discharge plasma environment using an inverted Π-shaped dusty plasma experimental (DPEx) device. In the presence of Gaussian-shaped and solitary-pulse-type external forces, the damped forced Korteweg–de Vries equation is obtained using the reductive perturbation technique in a dusty plasma with non-thermally distributed electrons by A.Paul, N. Paul, Mondal and Chatterjee [23]. Using the quantum hydrodynamic model, the dynamics of ion-acoustic solitary waves (IASWs) in an unmagnetized, highly relativistic quantum plasma with positive and negative ions and electrons is investigated by Madhukalya, Das, Hosseini, Hincal, Osman and Wazwaz [24].

Cite as: S.N. Barman, K. Talukdar, East Eur. J. Phys. 2, 113 (2025), https://doi.org/10.26565/2312-4334-2025-2-11

The treatment takes into consideration that electrons are inertialess, which explains the inertial properties of both positive and negative ions. They have derived Korteweg–de Vries equation using the reductive perturbation method to examine the nonlinear nature of quantum IASWs. The objective of our research is to investigate the presence of solitary plasma waves and their behaviour in a multicomponent plasma model and observe the effects of various parameters on the amplitude, nonlinearity and dispersion of solitons.

In this study, we theoretically investigate the characteristics of nonlinear ion-acoustic solitary waves in a multicomponent plasma composed of positive ions, negatively charged dust, inertialess electrons with quantum effect and nonextensively distributed electrons and positrons. This study examines nonlinear ion-acoustic waves using the reductive perturbation approach. The format of the paper is as follows: The introduction is given in Section (1), followed by the Equations Governing Dynamics of Plasma in Section (2), the KdV equation and its solution in Section (3), Results and Discussions in Section (4) and Conclusions in Section (5).

2. EQUATIONS GOVERNING DYNAMICS OF PLASMA

The fluid equations of motion, governing the collision less dusty plasma in one dimension are:

For positive ion,

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

$$\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial x} + \frac{\partial \phi}{\partial x} = 0 \tag{2}$$

For negatively charged dust,

$$\frac{\partial n_d}{\partial t} + \frac{\partial (n_d v_d)}{\partial x} = 0 \tag{3}$$

$$\frac{\partial v_d}{\partial t} + v_d \frac{\partial v_d}{\partial x} - \frac{\partial \phi}{\partial x} = 0. \tag{4}$$

For inertialess electrons with quantum effect,

$$0 = \frac{\partial \phi}{\partial x} - B n_{eq} \frac{\partial n_{eq}}{\partial x} + \frac{1}{2} H_e^2 \frac{\partial}{\partial x}\left(\frac{1}{n_{eq}^{\frac{1}{2}}} \frac{\partial^2 (n_{eq}^{\frac{1}{2}})}{\partial x^2}\right), \tag{5}$$

where, $B = \frac{V_{Fe}^2 \alpha m_e}{c_s^2 r^2 m_i} = \frac{V_{Fe}^2 Q_d}{c_d^2 r^2}$, $H_e^2 = \frac{h \omega_{Pd}}{Z_d k T_i Q_d}$,
where $Q_d = \frac{m_e}{m_d}$.

$$n_e = \delta_e \left[1 + (q - 1)\phi\right]^{\frac{q+1}{2(q-1)}}, \tag{6}$$

$$n_p = \delta_p \left[1 - \sigma_F (q - 1)\phi\right]^{\frac{q+1}{2(q-1)}}, \tag{7}$$

where $\delta_e = \frac{1}{1-p}$, $\delta_p = \frac{p}{1-p}$.
Here, H_e is the quantum diffraction term (which is proportional to the ratio of plasma energy to fermi energy), V_{Fe} is the fermi speed, p is the unperturbed positron-to-electron density ratio, σ_F is the electron-to-positron temperature ratio, and parameter q is the real number greater than -1 and represents the strength of the nonextensive ion.

The extensivity limits q < 1, q > 1, and q →1 represents the cases of superthermality, subthermality, and Maxwell-Boltzmann distribution function, respectively. It is possible to expand the normalised nonextensive electron and positron densities of Eqs. (6) and (7), respectively, as

$$n_e = \frac{1}{1-p}\left[1 + \frac{q+1}{2}\phi + \frac{(q+1)(3-q)}{8}\phi^2 + \cdots\right]$$

$$n_p = \frac{p}{1-p}\left[1 - \frac{q+1}{2}\sigma_F \phi + \frac{(q+1)(3-q)}{8}\sigma_F^2 \phi^2 - \cdots\right]$$

The continuity and momentum equations of the plasma's acoustic mode are the fundamental governing equations. The following Poisson equation for the charge imbalances should be added to these equations.

$$\frac{\partial^2 \phi}{\partial x^2} = n_{eq} + n_e - n_i - n_p + Z_d n_d \tag{8}$$

Here, suffixes *i, p, e, eq* and *d* stand for positive ion, nonextensive positron, nonextensive electron, quantum electron and dust respectively.

3. KdV EQUATION AND ITS SOLUTION

We use the stretched variables,

$$\xi = \varepsilon^{\frac{1}{2}}(x - Vt) \text{ and } \tau = \varepsilon^{\frac{3}{2}} t, \tag{9}$$

(where V is the phase velocity) along with the expansions of the flow variables in terms of the smallness parameter ε as $n_i = n_{i0} + \varepsilon n_{i1} + \varepsilon^2 n_{i2} + \varepsilon^3 n_{i3} + \ldots$, $n_p = 1 + \varepsilon n_{p1} + \varepsilon^2 n_{p2} + \varepsilon^3 n_{p3} + \ldots$, $n_e = 1 + \varepsilon n_{e1} + \varepsilon^2 n_{e2} + \varepsilon^3 n_{e3} + \ldots$, $n_{eq} = n_{eq0} + \varepsilon n_{eq1} + \varepsilon^2 n_{eq2} + \varepsilon^3 n_{eq3} + \ldots$, $n_d = n_{d0} + \varepsilon n_{d1} + \varepsilon^2 n_{d2} + \varepsilon^3 n_{d3} + \ldots$, $v_i = v_{i0} + \varepsilon v_{i1} + \varepsilon^2 v_{i2} + \varepsilon^3 v_{i3} + \ldots$, $v_d = v_{d0} + \varepsilon v_{d1} + \varepsilon^2 v_{d2} + \varepsilon^3 v_{d3} + \ldots$, $\phi = \varepsilon\phi_1 + \varepsilon^2\phi_2 + \varepsilon^3\phi_3 + \ldots$, to derive the KdV equation from the set of equations (1) to (8).

Using the transformation (9) and the expansions of $n_i, n_p, n_e, n_d, n_{eq}, v_i$ and v_d in equations (1) to (8) and equating the coefficient of the first lowest-order of ε we get,

$$n_{d1} = -\frac{n_{d0}}{(v_{d0} - V)^2}\phi_1,\ v_{d1} = \frac{1}{v_{d0} - V}\phi_1,\ n_{eq1} = -\frac{1}{Bn_{eq0}}\phi_1,\ n_{e1} = \mu_e\frac{(1+q)}{2}\phi_1,$$
$$n_{i1} = \frac{n_{i0}}{(V - v_{i0})^2}\phi_1,\ v_{i1} = \frac{1}{V - v_{i0}}\phi_1,\ n_{p1} = -\mu_p\sigma_F\frac{(1+q)}{2}\phi_1,$$

where v_{i0} and v_{d0} are initial streaming velocities of positive ions and dust grains respectively.

Using the expansions of n_{i1}, n_{p1}, n_{e1} , n_{eq1} and n_{d1} in $n_{e1} + n_{eq1} + Z_d n_{d1} - n_{p1} - n_{i1} = 0$, the expression of phase velocity V is found as,

$$-\frac{n_{i0}}{(V - v_{i0})^2} + \mu_e\frac{(1+q)}{2} + \mu_p\sigma_F\frac{(1+q)}{2} - \frac{1}{Bn_{eq0}} - \frac{Z_d n_{d0}}{(v_{d0} - V)^2} = 0$$

Eliminating v_{i2} and v_{d2} from the equations obtained by equating the coefficient of second higher order terms of ε we get the KdV equation as,

$$\frac{\partial\phi_1}{\partial\tau} + P\,\phi_1\frac{\partial\phi_1}{\partial\xi} + Q\frac{\partial^3\phi_1}{\partial\xi^3} = 0, \tag{10}$$

where,

$$P = \frac{\left[\frac{2n_{i0}}{(V - v_{i0})^4} - \frac{(q+1)(3-q)(\mu_e - \mu_p\sigma_F{}^2)}{4} + \frac{n_{i0}}{(V - v_{i0})^4} - \frac{3Z_d n_{d0}}{(v_{d0} - V)^4} + \frac{B}{B^3 n_{eq0}{}^3}\right]}{\left[\frac{2n_{i0}v}{(V - v_{i0})^3} - \frac{2Vn_{d0}Z_d}{(v_{d0} - V)^3}\right]}$$

$$Q = \frac{\left[1 - \frac{H_e{}^2}{4B^2 n_{eq0}{}^3}\right]}{\left[\frac{2n_{i0}V}{(V - v_{i0})^3} - \frac{2Vn_{d0}Z_d}{(v_{d0} - V)^3}\right]}$$

We introduce the variable $\eta = \xi - U\tau$, where U is the velocity of the wave in the linear η space, to find a stationary solution of the KdV equation (10). Equation (10) can be integrated using the boundary conditions $\phi_1 = \frac{\partial\phi_1}{\partial\eta} = \frac{\partial^2\phi_1}{\partial\eta^2} = 0$ as $|\eta| \to \infty$, to give

$$\phi_1 = \phi_0\,\mathrm{sech}^2(\eta/\Delta) \tag{11}$$

where $\phi_0 = (3U/P)$ is the amplitude and $\Delta = (4Q/U)^{1/2}$ is the width of the soliton respectively.

4. RESULTS AND DISCUSSIONS

We have obtained KdV equation from the set of governing equations [1-7] and the Poisson equation [8]. Since the existence and characteristics of solitary waves are explained by the KdV equation, we have computationally investigated the existence and characteristics of our multicomponent plasma model for a variety of parameters. In this manuscript we have considered some standard ranges for plasma parameters. The value of B= 18000000, which is because of high fermi speed (V_{Fe}). Analysing the variation of soliton amplitude with respect to q (Figure 1), we observe the presence of compressive solitons for some fixed parameters H_e=5, B=18000000, U=0.6, n_{eq0}=1, n_{i0}=0.8, v_{i0}=1.3, δ_e=0.38, δ_p=0.21, σ_F=0.088, Z_d=3, n_{d0}=0.7, V_{d0}=1.0. As q increases from 0 to 0.8, the solitary wave amplitude increases gradually. On describing the variation of soliton amplitude with respect to q while keeping the remaining parameters fixed and changing the value δ_e, we can observe the presence of comparatively higher amplitude KdV compressive solitons for higher values of δ_e. Also, analysing the variation of soliton amplitude with respect to V_{i0} (Figure 2), we observe that as V_{i0} increases the amplitude of rarefactive soliton decreases gradually. Keeping the remaining parameters fixed as H_e=5, B=18000000,U=0.01, n_{eq0}=0.8, n_{i0}=1.3, δ_e=0.26, n_{i0}=1.3, q=0.216, δ_e=0.26, μ_p=0.26, σ_F=0.01, Z_d=2, n_{d0}=1, V_{d0}=0.8 and analysing the variation of rarefactive soliton amplitude for comparative higher values of q , we observe that as q increases from 0.026 to 0.216 , the amplitude of rarefactive soliton decreases.

Analysing the variation of soliton amplitude with respect to σ_F (Figure 3) we observe the presence of compressive solitons for some fixed parameters H_e=4, B=18000000, U=0.1, n_{eq0}=0.8, n_{i0}=1, v_{i0}=1, δ_e=0.16, δ_p=0.8, q=0.021, Z_d=1, n_{d0}=0.8. As σ_F increases from 0 to 0.5 the solitary wave amplitude decreases gradually. On describing the variation of soliton amplitude with respect to σ_F while keeping the remaining parameters fixed and changing Vd_0, we can observe the presence of comparatively higher amplitude KdV compressive solitons for higher value of V_{d0}. Also, analysing the variation of soliton amplitude with respect to V_{d0} (Figure 4), we observe that as V_{d0} increases the rarefactive soliton amplitude decreases gradually. Keeping the remaining parameters fixed as H_e=4, B=18000000, U=0.01, n_{eq0}=1, n_{i0}=1, V_{i0}=0.8, δ_e=0.26, δ_p=1, Z_d=8, n_{d0}=0.1, σ_F=0.028 and analysing the variation of rarefactive soliton amplitude for different values of q, we observe that as q increases from 0.156 to 0.456, the amplitude of rarefactive soliton decreases.

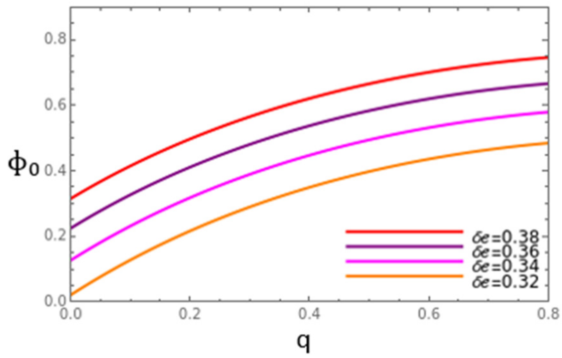

Figure 1. Variation of amplitude with respect to q for different δ_e and fixed H_e=5, B=18000000, U=0.6, n_{eq0}=1, n_{i0}=0.8, v_{i0}=1.3, δ_p=0.21, σ_F=0.088, Z_d=3, n_{d0}=0.7, V_{d0}=1.0

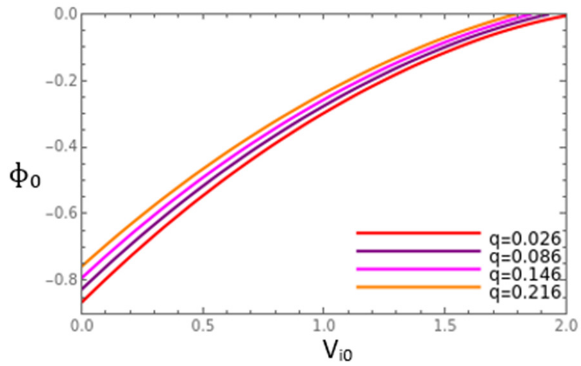

Figure 2. Variation of amplitude with respect to V_{i0} for different q and fixed H_e=5, B=18000000, U=0.01, n_{eq0}=0.8, n_{i0}=1.3, δ_e=0.26, δ_p=0.26, σ_F=0.01, Z_d=2, n_{d0}=1, V_{d0}=0.8

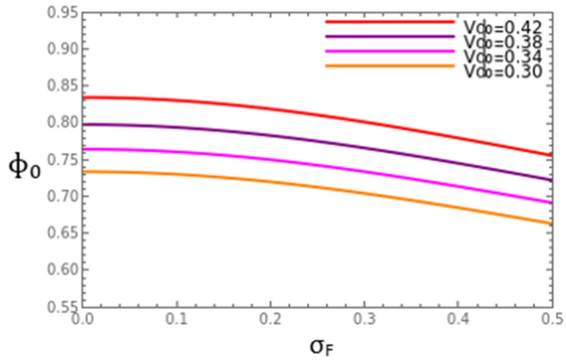

Figure 3. Variation of amplitude with respect to σ_F for different V_{d0} and fixed H_e=4, B=18000000, U=0.1, n_{eq0}=0.8, n_{i0}=1, v_{i0}=1, δ_e=0.16, δ_p=0.8, q=0.021, Z_d=1, n_{d0}=0.8

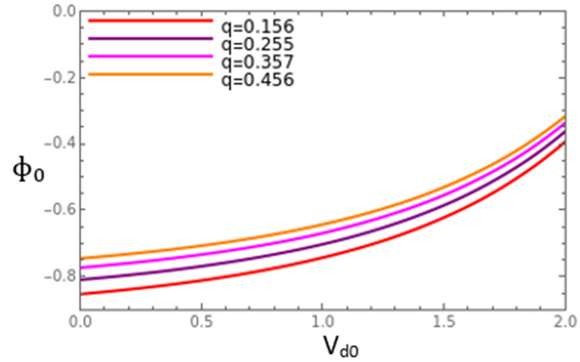

Figure 4. Variation of amplitude with respect to V_{d0} for different q and fixed H_e=4, B=18000000, U=0.01, n_{eq0}=1, n_{i0}=1, V_{i0}=0.8, δ_e=0.26, δ_p=1, Z_d=8, n_{d0}=0.1, σ_F=0.028

Analysing the deviation of nonlinear term (P) with respect to q (Figure 5) we observe that nonlinearity decreases as q increases. Checking the effect of nonlinear term with respect to q for fixed H_e=5, B=18000000, U=1.3, n_{eq0}=1.3, n_{i0}=1.8, δ_e=0.32, V_{d0}=1, δ_p=0.21, Z_d=3, n_{d0}=1, σ_F=0.01 and changing values of V_{i0}, we observe that for V_{i0} from 1.27 to 1.42 the nonlinearity appears comparatively higher. Also, observing the deviation of nonlinear term with respect to V_{i0} (Figure 6), we see that as V_{i0} increases from 0 to 2 the nonlinearity decreases gradually for H_e=5, B=18000000, U=1, n_{eq0}=1, n_{i0}=2.1, δ_e=0.16, V_{d0}=0.8, δ_p=0.26, q=0.021, n_{d0}=1, σ_F=0.013. Checking the variation of Nonlinear term with respect to V_{i0} we observe that the nonlinearity is comparatively lower for greater values of Z_d.

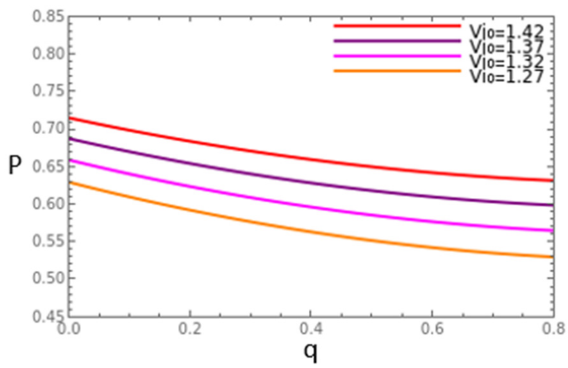

Figure 5. Variation of nonlinearity with respect to q for different v_{i0} and fixed H_e=5, B=18000000, U=1.3, n_{eq0}=1.3, n_{i0}=1.8, δ_e=0.32, V_{d0}=1, δ_p=0.21, Z_d=3, n_{d0}=1, σ_F=0.01

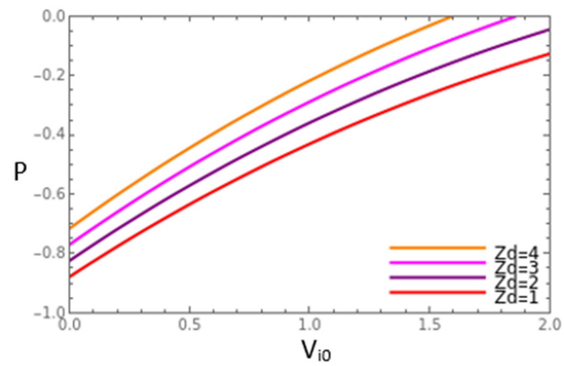

Figure 6. Variation of nonlinearity with respect to V_{i0} for different Z_d and fixed H_e=5, B=18000000, U=1, n_{eq0}=1, n_{i0}=2.1, δ_e=0.16, V_{d0}=0.8, δ_p=0.26, q=0.021, n_{d0}=1, σ_F=0.013

As the dispersion term (Q) describes the broadening of solitary wave profile so analysing dispersion with respect to V_{i0} (Figure 7) we observe that Q decreases as V_{i0} increases for B=18000000, n_{eq0}=0.52, n_{i0}=2.1, Z_d=3, n_{d0}=1, H_e=4.

Keeping the remaining parameters fixed, as we observe the variation of Q with respect to V_{i0} we observe that dispersion gets comparatively higher as V_{d0} increases. Also, observing the variation of dispersion with respect to V_{d0} (Figure 8), we observe that dispersion increases as V_{d0} increases. For fixed B=18000000, n_{eq0}=0.52, n_{i0}=2.6, n_{d0}=1.3, H_e=3, V_{i0}=0.32 and different Z_d in the comparison of dispersion with respect to V_{d0}, we observe that dispersion increases as Z_d increases.

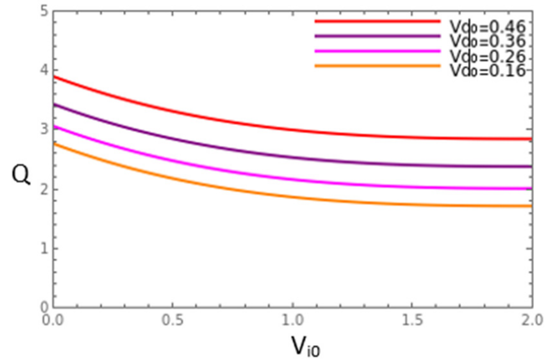

Figure 7. Variation of dispersion with respect to V_{i0} for different v_{d0} and fixed B=18000000, n_{eq0}=0.52, n_{i0}=2.1, Z_d=3, n_{d0}=1, H_e=4

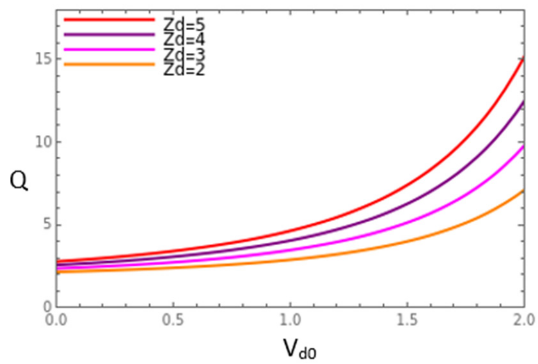

Figure 8. Variation of dispersion with respect to V_{d0} for different Z_d and fixed B=18000000, n_{eq0}=0.52, n_{i0}=2.6, n_{d0}=1.3, H_e=3, V_{i0}=0.32

Further, we have observed variation of solitary wave potential φ_1 versus η for four different values of V_{i0} as shown in Figure 9 and for four different values of q as shown in Figure 10. We have found that the wave potential of compressive solitons (Figure 9) is higher for higher values of V_{i0} and that of rarefactive solitons (Figure 10) is lower for higher values of q .

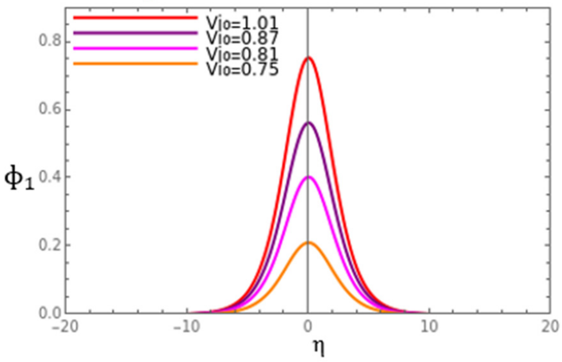

Figure 9. Variation of ϕ_1 with respect to η for different V_{i0} and fixed H_e=5, B=18000000, U=2.4, n_{eq0}=1, n_{i0}=1.7, q=0.015, δ_e=0.26, δ_p=0.32,σ_F=0.01,Z_d=1,n_{d0}=1.6,V_{d0}=1.3

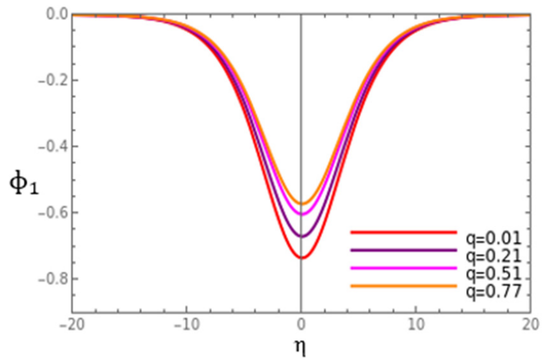

Figure 10. Variation of ϕ_1 with respect to η for different q and fixed H_e=5, B=18000000, U=0.52, n_{eq0}=1, n_{i0}=1.7, δ_e=0.16, δ_p=0.26,σ_F=0.008,Z_d=1,n_{d0}=1.6,V_{i0}=0.5,V_{d0}=1

5. CONCLUSIONS

We have found that both compressive and rarefactive solitons are present in our plasma model that includes positive ions, negatively charged dust, inertialess electrons with quantum effect and nonextensively distributed electrons and positrons. Both the compressive and rarefactive solitons are found to exist in a definite range of parameters such as, $0.21 \le \delta_p \le 1$, $0.16 \le \delta_e \le 0.38$, $1 \le Z_d \le 8$ and for $q < 1$, which represents the case of superthermality. Also, both the compressive and rarefactive solitons are found to exist for unperturbed density of inertialess electrons with quantum effect $n_{eq0} \le 1.3$, quantum diffraction term $H_e \le 5$ (for heavy dust mass $H_e \approx 10$) and B=18000000. Our investigation can be useful for the researcher investigating on plasma in astrophysical environments.

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ІОННО-АКУСТИЧНІ ОДИНОЧНІ ХВИЛІ В НЕМАГНІТИЗОВАНІЙ ПИЛОВІЙ ПЛАЗМІ З БЕЗІНЕРЦІЙНИМИ ЕЛЕКТРОНАМИ З КВАНТОВИМИ ЕФЕКТАМИ

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Це дослідження ілюструє наявність і характеристики стискаючих і розріджених солітонів у ненамагніченій плазмі, яка включає позитивні іони, негативно заряджений пил, безінерційні електрони з квантовим ефектом і нерозподілені електрони та позитрони. Для цієї ненамагніченої пилоподібної плазми з позитивними іонами, негативно зарядженим пилом, безінерційними електронами з квантовим ефектом і нерозповсюдженими електронами та позитронами було виведено рівняння Кортевега-де Фріза (KdV), і таким чином досліджено існування та поведінку стисливого та розрідженого солітону. Основою для аналізу є рівняння руху рідини, що керують одновимірною плазмою. Використання різних реляційних форм параметра сили (ε) для розтягування просторових і часових змінних призводить до різних нелінійностей. При обговоренні впливу на амплітуду, нелінійність і дисперсію солітонів розглядалися різні параметри плазми.
Ключові слова: *солітон; q-неекстенсивний розподіл; редуктивний метод збурень; рівняння KdV*