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THE FORMATION OF ION-ACOUSTIC SOLITARY WAVES IN A PLASMA HAVING NONEXTENSIVE ELECTRONS AND POSITRONS

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In this plasma model, consisting of ions, electrons, and positrons have been theoretically investigated when both the electrons and positrons are obeying q-nonextensive velocity distribution. The reductive perturbation method is used to obtain Korteweg de Vries (KdV) equation describing the basic set of normalized fluid equations. The existence of ion-acoustic solitary waves depending on nonextensive parameter, electron to positron temperature ratio, ion to electron temperature ratio and streaming velocity are investigated numerically. It has been found that solely fast ion-acoustic modes can produce the coexistence of small amplitude rarefactive solitons.

Keywords: *q-nonextensive distribution; Reductive perturbation method; KdV equation*

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1. INTRODUCTION

The investigation of ion-acoustic solitary waves in a plasmas with nonextensive electrons [1] and positrons are tremendously descrived by Korteweg-de Vries equation. Almost all the systems behaved in statistical mechanics with Boltzmann-Gibbs(BG) statics have been generally extensive [2]. In extensivity, there are two obvious exceptions which are small system or clusters of particles and long range interparticle forces. Small system is consisting of a finite number particles and in this system thermodynamic limit is not used and for long range interparticles, nonextensivity holds for Coulomb electric or Newtonian gravitational forces. However, in recent years, numerous researcher have been showing their interest regarding the study of particle distribution in plasma using the Boltzmann Gibbs (BG) statistics. Renyi [3] was first recognized in generalization of the Boltzmann-Gibbs(BG) statistics and subsequently developed by Tsallis [4]. By citing this approach many researchers have worked nonextensive distribution for the number density of the particles in plasma [5–21]. Latter, this Boltzmann-Gibbs(BG) statistics is known as an additional parameter q and it is used to a number of nonextensive systems. The q-nonextensive distribution function shows distinct behaviors and it is based on the values of q, which determines the quantity of the nonextensivity of the system being recharged. If $q < 1$ which is known as superextensivity and it indicates the plasma with higher number of superthermal particles compared to that of Maxwellian case. If $q > 1$ which is known as subextensivity, the distribution function shows the plasma with large number of low-speed particles compared to that of Maxwellian case. It may be useful for $q < -1$ where q-distribution is unnormalizable. Again, if $q = 1$ then the distribution function is reduced to common Maxwellian-Boltzmann velocity distribution [22].Numerous astrophysical plasma events include the formation of positrons in the plasma. In astrophysical objects electron-positron-ion plasma can be found such as in polar region of neutron stars, active galactic nuclei, the semiconductor plasmas, quasars and pulsar magnetosphere, the centre of Milky way galaxy, the early universe, intense laser fields *etc*. Moskalenko & Strong [23] studied in cosmic-ray nuclei interact with atoms in interstellar medium. Influence of Temperature and Positron Density on Large Amplitude Ion-acoustic Waves in an Electron–Positron–Ion Plasma was examined by Nejoh [24]. In a nonextensive electron-positron-ion plasma, Ghosh *et al.* [25] have investigated the dynamic structures of nonlinear ion acoustic waves. Ion acoustic solitary waves in plasmas including relativistic thermal ions, positrons, and nonextensively distributed electrons have been investigated by Hafez *et al.* [26]. Danehkar [27] has investigated electrostatic solitary waves in a plasma of electron-positron pairs with suprathermal electrons.

In this research, the propagation behavior of nonlinear ion-acoustic solitary waves in a three-component plasma made up of inertial ions, nonextensive electrons and positrons is investigated theoretically. In this paper, the nonlinear ion-acoustic waves are investigated using the reductive perturbation approach. The format of the paper is as follows: the Introduction is given in Section (1); the Basic Governing Equations in Section (2); Derivation of the Korteweg-de Vries equation and Its Solution in Section (3); and Results and Discussions in Section (4), and at the end References are included.

2. BASIC GOVERNING EQUATIONS

In this paper we consider one-dimensional collisionless three component plasma consisting of ions, electrons and positrons. We assume that ions are extensive but electrons and positrons both are nonextensive that means both are obeying

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q-nonextensive distribution. The nonlinear dynamics of the ion-acoustic waves is governed by the following normalized continuity and motion equations for ions, electrons, positrons and the poisson equations are

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

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

$$\frac{\partial p_i}{\partial t} + v_i \frac{\partial p_i}{\partial x} + 3p_i \frac{\partial v_i}{\partial x} = 0 \tag{3}$$

$$n_e = \alpha \left[1 + (q-1)\phi\right]^{\frac{q+1}{2(q-1)}} \tag{4}$$

$$n_p = \beta \left[1 - \sigma_p (q-1)\phi\right]^{\frac{q+1}{2(q-1)}} \tag{5}$$

$$\frac{\partial^2 \phi}{\partial x^2} = \alpha - \beta - n_i + (\alpha + \beta\sigma_p) s_1 \phi + (\alpha - \beta\sigma_p^2) s_2 \phi^2 + (\alpha + \beta\sigma_p^3) s_3 \phi^3 + \dots \tag{6}$$

where

$$\left.\begin{aligned} s_1 &= \frac{(1+q)}{2},\ s_2 = \frac{(1+q)(3-q)}{8}, \\ s_3 &= \frac{(1+q)(3-q)(5-3q)}{48} \end{aligned}\right\} \tag{7}$$

where parameter q is the real number greater than -1 and it stands for the strength of nonextensive ion; α is the electron to ion density ratio; β is the positron to ion density ratio; n_e, n_p and n_i are the electron, positron and ion number density; v_i is the fluid velocity; p_i is the ion pressure and ϕ is the electric potential. We, normalize n_i, n_e and n_p by their unperturbed densities n_{i0}, n_{e0} and n_{p0} respectively; v_i by the ion-acoustic speed $C_{si} = \sqrt{K_B T_e / m_i}$; and ϕ by $K_B T_e / e$. The space and time variables are in units of the ion Debye lengh $\lambda_{Di} = \sqrt{K_B T_e / 4\pi n_i e^2}$, and the ion plasma period $\omega_{pi}^{-1} = \sqrt{m_i / 4\pi n_i e^2}$, respectively. Here, K_b is the Boltzmann constant; $\sigma = T_i / T_e$ is the ion to electron temperature ratio; $\sigma_p = T_e / T_p$ is the electron to positron temperature ratio.

3. DERIVATION OF THE KORTEWEG-DE VRIES EQUATION AND ITS SOLUTION

To derive the KdV equation from the set of equations (1)-(6) we use the stretch variables:

$$\eta = \epsilon^{1/2}(x - Nt), \quad \tau = \epsilon^{3/2} t \tag{8}$$

where N represents the wave's phase velocity and the following flow variable expansions are expressed in terms of the smallness parameter ϵ

$$\left.\begin{aligned} n_i &= 1 + \epsilon n_{i1} + \epsilon^2 n_{i2} + \epsilon^3 n_{i3} + \dots \\ n_e &= 1 + \epsilon n_{e1} + \epsilon^2 n_{e2} + \epsilon^3 n_{e3} + \dots \\ n_p &= 1 + \epsilon n_{p1} + \epsilon^2 n_{p2} + \epsilon^3 n_{p3} + \dots \\ v_i &= v_{i0} + \epsilon v_{i1} + \epsilon^2 v_{i2} + \epsilon^3 v_{i3} + \dots \\ p_i &= 1 + \epsilon p_{i1} + \epsilon^2 p_{i2} + \epsilon^3 p_{i3} + \dots \\ \phi &= \epsilon \phi_1 + \epsilon^2 \phi_2 + \epsilon^3 \phi_3 + \epsilon^4 \phi_4 + \dots \end{aligned}\right\} \tag{9}$$

Following the standard perturbation method with the use of transformation (8), expansions (9) in the normalized set of equations (1)-(6) and the boundary conditions $n_{i1} = 0,\ v_{i1} = 0,\ \phi_1 = 0$ at $|\eta| \longrightarrow \infty$, we obtain the lowest order perturbation in ϵ as

$$\left.\begin{aligned} n_{i1} &= \frac{\phi_1}{(N - v_{i0})^2 - 3\sigma}, \quad n_{e1} = \alpha s_1 \phi_1, \\ v_{i1} &= \frac{(N - v_{i0})\phi_1}{(N - v_{i0})^2 - 3\sigma}, \quad n_{p1} = -\beta\sigma_p s_1 \phi_1, \\ p_{i1} &= \frac{3\phi_1}{(N - v_{i0})^2 - 3\sigma} \end{aligned}\right\} \tag{10}$$

Again, using (8) and (9) in equation(6), we obtain the coefficient of ϵ^0 and ϵ^1 as

$$\alpha - \beta = 1 \tag{11}$$

$$n_{i1} - (\alpha + \beta\sigma_p) s_1 \phi_1 = 0 \tag{12}$$

Using the expression of n_{i1} from (10), the expression for phase velocity N is obtained as

$$N = v_{i0} \pm \sqrt{\frac{1 + 3\sigma(\alpha + \beta\sigma_p)s_1}{(\alpha + \beta\sigma_p)s_1}} \tag{13}$$

Again, equating the coefficients of second higher order terms of ϵ from (1)-(6) we get,

$$\frac{\partial n_{i1}}{\partial \tau} - (N - v_{i0})\frac{\partial n_{i2}}{\partial \eta} + \frac{\partial v_{i2}}{\partial \eta} + \frac{\partial (n_{i1}v_{i1})}{\partial \eta} = 0 \tag{14}$$

$$\frac{\partial v_{i1}}{\partial \tau} - (N - v_{i0})\frac{\partial v_{i2}}{\partial \eta} - (N - v_{i0})n_{i1}\frac{\partial v_{i1}}{\partial \eta} + v_{i1}\frac{\partial v_{i1}}{\partial \eta} + \sigma\frac{\partial p_{i2}}{\partial \eta} + \frac{\partial \phi_2}{\partial \eta} + n_{i1}\frac{\partial \phi_1}{\partial \eta} = 0 \tag{15}$$

$$\frac{\partial p_{i1}}{\partial \tau} - (N - v_{i0})\frac{\partial p_{i2}}{\partial \eta} + 3\frac{\partial v_{i2}}{\partial \eta} + 3p_{i1}\frac{\partial v_{i1}}{\partial \eta} + v_{i1}\frac{\partial p_{i1}}{\partial \eta} = 0 \tag{16}$$

Now, putting the values of n_{i1}, v_{i1} and p_{i1} in (14), (15) and (16) and eliminating $\frac{\partial v_{i2}}{\partial \eta}$ and $\frac{\partial p_{i2}}{\partial \eta}$, we obtain the following equations

$$\frac{\partial n_{i2}}{\partial \eta} = \frac{2(N - v_{i0})}{[(N - v_{i0})^2 - 3\sigma]^2}\frac{\partial \phi_1}{\partial \tau} + \frac{1}{(N - v_{i0})^2 - 3\sigma}\frac{\partial \phi_2}{\partial \eta} + \frac{3(N - v_{i0})^2}{[(N - v_{i0})^2 - 3\sigma]^3}\phi_1\frac{\partial \phi_1}{\partial \eta} \tag{17}$$

$$\frac{\partial n_{e2}}{\partial \eta} = 2\alpha s_2\phi_1\frac{\partial \phi_1}{\partial \eta} + \alpha s_1\frac{\partial \phi_2}{\partial \eta} \tag{18}$$

$$\frac{\partial n_{p2}}{\partial \eta} = 2\beta s_2\sigma_p^2\phi_1\frac{\partial \phi_1}{\partial \eta} - \beta s_1\sigma_p\frac{\partial \phi_2}{\partial \eta} \tag{19}$$

$$\frac{\partial^2 \phi_1}{\partial \eta^2} = -n_{i2} + \alpha s_1\phi_2 + \alpha s_2\phi_1^2 + \beta s_1\sigma_p\phi_2 - \beta s_2\sigma_p^2\phi_1^2 \tag{20}$$

$$\Longrightarrow \frac{\partial^3 \phi_1}{\partial \eta^3} = -\frac{\partial n_{i2}}{\partial \eta} + \alpha s_1\frac{\partial \phi_2}{\partial \eta} + 2\alpha s_2\phi_1\frac{\partial \phi_1}{\partial \eta} + \beta s_1\sigma_p\frac{\partial \phi_2}{\partial \eta} - 2\beta s_2\sigma_p^2\phi_1\frac{\partial \phi_1}{\partial \eta} \tag{21}$$

Using the relation (12) and entering the values of $\frac{\partial n_{i2}}{\partial \eta}$, $\frac{\partial n_{e2}}{\partial \eta}$ and $\frac{\partial n_{p2}}{\partial \eta}$ in (21), we ultimately obtain the Korteweg-de Vries(KdV) equation as

$$\frac{\partial \phi_1}{\partial \tau} + A\phi_1\frac{\partial \phi_1}{\partial \eta} + B\frac{\partial^3 \phi_1}{\partial \eta^3} = 0 \tag{22}$$

where the nonlinear coefficient A and the dispersion coefficient B are given by

$$A = \frac{3(N - v_{i0})^2 - 2s_2(\alpha - \beta\sigma_p^2)\left[(N - v_{i0})^2 - 3\sigma\right]^3}{2(N - v_{i0})\left[(N - v_{i0})^2 - 3\sigma\right]} \quad \text{and} \quad B = \frac{\left[(N - v_{i0})^2 - 3\sigma\right]^2}{2(N - v_{i0})}$$

From the expressions of A and B, we have $2(N - v_{i0})\left[(N - v_{i0})^2 - 3\sigma\right] \neq 0$

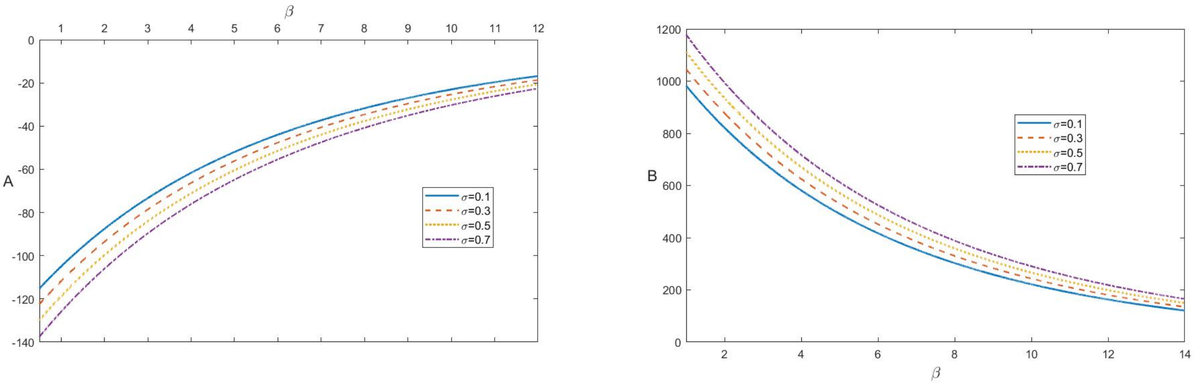
In order to determine the stationary solitary wave solutions of the KdV equation (22), we introduce the variable $\chi = \eta - C_1\tau$, where C_1 represents the wave's velocity in the linear χ-space. With this, the solitary wave solution can be obtained by integrating the KdV equation (22) as

$$\phi_1 = \phi_0 \operatorname{sech}^2\left(\frac{\chi}{\Delta}\right) \tag{23}$$

Here, $\phi_0 = 3C_1/A$ is the wave amplitude of the soliton and it is proportional to the soliton speed C_1; $\Delta = 2\sqrt{B/C_1}$ is the width, and is inversely proportional to the soliton speed C_1.

4. RESULTS AND DISCUSSIONS

In this present plasma system, ion-acoustic solitary waves in plasma comprising q-nonextensive electrons and positrons through the KdV equation are discussed. In our investigations, only fast ion-acoustic mode is found to exist. We have examined numerically, the influences of plasma parameters such as nonextensive parameter (q), the positron to ion density ratio (β), electron to ion density ratio (α), electron to ion temperature ratio (σ), positron to ion temperature ratio (σ_p) and ion streaming velocities (v_{i0}) on the variations of nonlinear term A and dispersion term B given in (22). In our

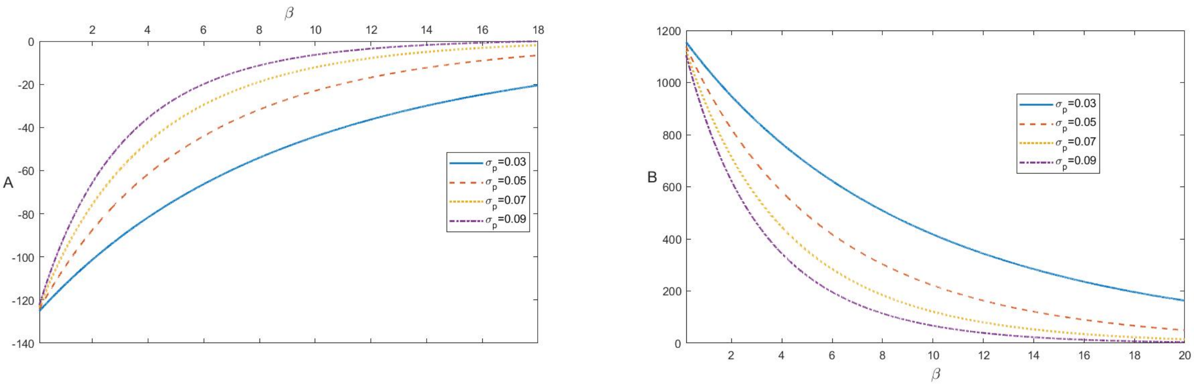


(a) **(b)**

Figure 1. The variation of (a) A and (b) B versus β for different values of σ.

investigation, for all the cases, we consider $-1 < q < 0$ and $v_{i0} < 5$; otherwise no solitons found to exist in this model of plasma.

Fig. [1a-1b] shows the numerical analysis of the variation of the nonlinear term A and the dispersion term B versus β for various values of $\sigma = 0.1, 0.3, 0.5, 0.7$, for fixed $\sigma_p = 0.05,\ v_{i0} = 2.5,\ q = -0.9,\ C_1 = 0.5$ and $\alpha = 1.1$. In Fig. [1a], we observe that A is negative and grows as σ increases, while in Fig. [1b] B is positive, indicating that it increases as σ increases.



(a) **(b)**

Figure 2. The variation of (a) A and (b) B versus β for different values of σ_p.

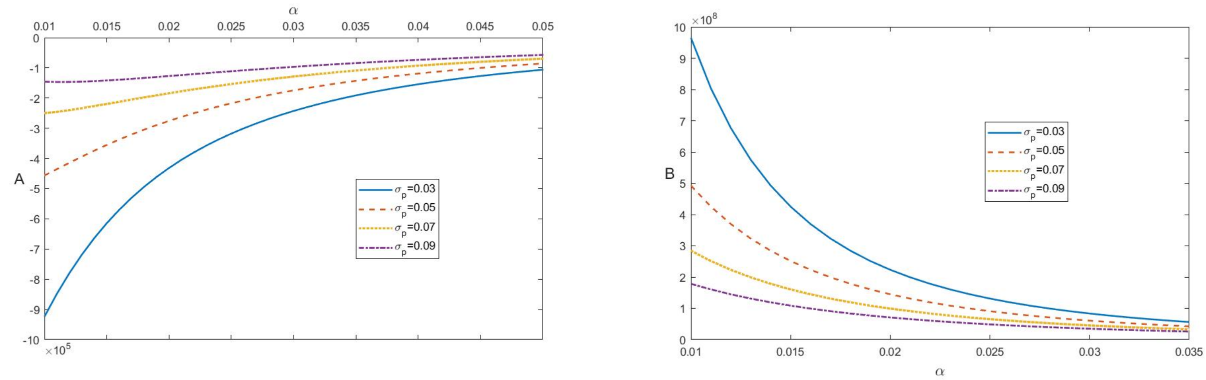
Fig. [2a-2b] revels that the nonlinear term A and the dispersion term B are varying with β for various values of $\sigma_p = 0.03, 0.05, 0.07, 0.09$ for fixed $\sigma = 0.1,\ v_{i0} = 2.5,\ q = -0.9,\ C_1 = 0.5$ and $\alpha = 1.1$. For all values of σ_p, the nonlinear term A is negative (Fig.[2a]), and dispersion term B is positive (Fig.[2b]).

The variation of (a) A and (b) B versus α for various values of $\sigma_p = 0.03, 0.05, 0.07, 0.09$ with $\sigma = 0.1,\ v_{i0} = 2.5,\ q = -0.9,\ C_1 = 0.5$, and $\beta = 0.1$ are plotted in Fig. [3a-3b]. Fig. [3a] shows that A is negative and decreases nonlinearly as σ_p increases, while Fig. [3b] shows a compressive reduction as σ_p increases.

In Fig.[4a-4b] we observe the variation of amplitude (ϕ_0) and width (Δ) versus nonextensive parameter q with different values of $\sigma = 0.1, 0.3, 0.5, 0.7$ and $\sigma_p = 0.05,\ v_{i0} = 2.5,\ q = -0.9,\ C_1 = 0.5$ and $\alpha = 1.1$. In (Fig.4a) we find that amplitude is rarefactive and linearly decreasing as the increasing values of σ, and width (Fig.4b) is increasing linearly as well as σ.

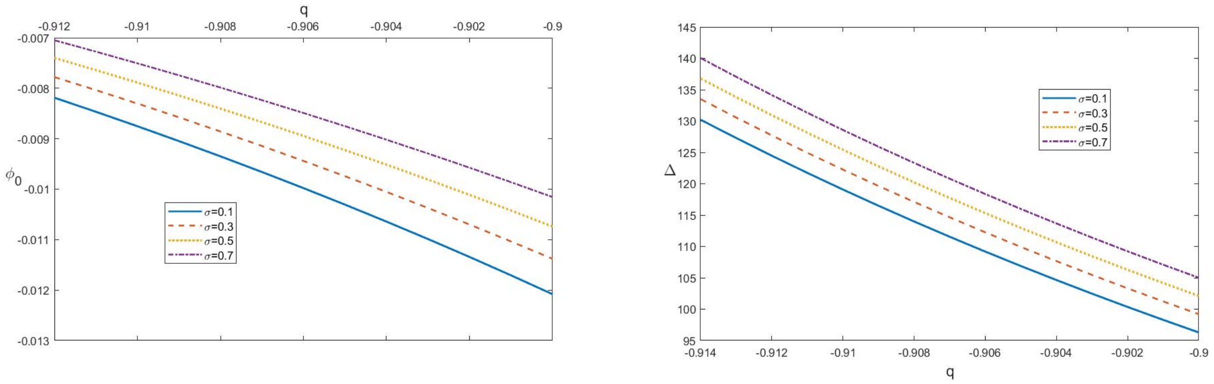
In Fig.[5a-5b] we have seen the variation of amplitude (ϕ_0) and width (Δ) versus nonextensive parameter q with different values of $\sigma_p = 0.03, 0.05, 0.07, 0.09$ with $\sigma_p = 0.05,\ v_{i0} = 2.5,\ q = -0.9,\ C_1 = 0.5$ and $\alpha = 1.1$. In (Fig.5a) we find that amplitude is rarefactive and linearly increasing for the increasing values of σ_p, and width (Fig.5b) is decreasing linearly as well as σ_p. In Fig.[6a-6b] we shown the variation of amplitude (ϕ_0) and width (Δ) versus streaming velocity v_{i0} with different values of $\sigma = 0.1, 0.3, 0.5, 0.7$ and $\sigma_p = 0.05,\ v_{i0} = 2.5,\ q = -0.9,\ C_1 = 0.5,\ \alpha = 1.1$. In (Fig.6a) we observe that the amplitude is rarefactive and linearly decreasing as the increasing values of σ and width (Fig.6b) is increasing linearly as well as σ.

The variation of amplitude (ϕ_0) and width (Δ) versus streaming velocity v_{i0} with varying values of $\sigma_p = 0.03, 0.05, 0.07, 0.09$ for fixed $\sigma = 0.1,\ v_{i0} = 2.5,\ q = -0.9,\ C_1 = 0.5$ and $\alpha = 1.1$ are shown in Fig. [7a-7b].



(a) **(b)**

Figure 3. The variation of (a) A and (b) B versus α for different values of σ_p.

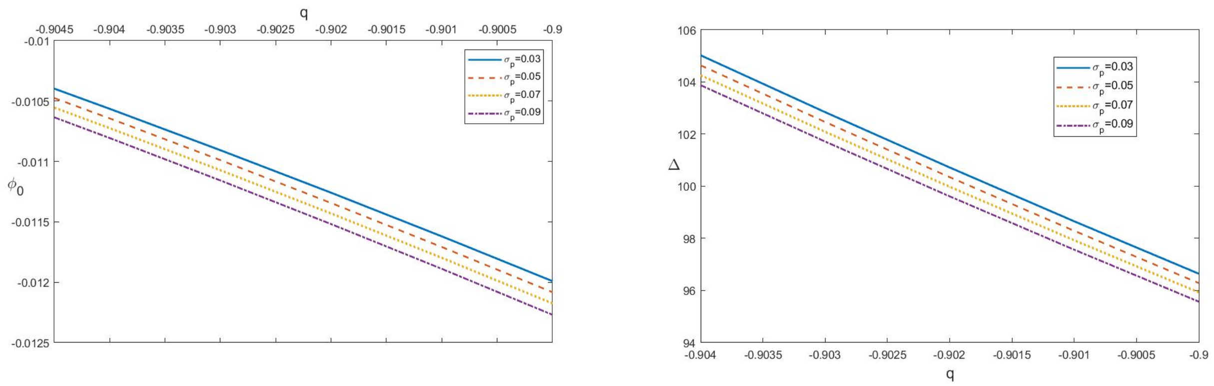


(a) **(b)**

Figure 4. The variation of (a) ϕ_0 and (b) Δ versus q for different values of σ.

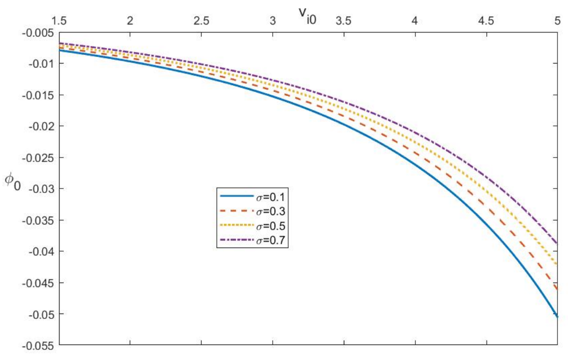
The amplitude is rarefactive and increases linearly as σ_p increases, while the width decreases linearly as σ_p increases.

Again, the variation of solitary wave potential $\phi_1(\chi)$ given in (23) versus χ are plotted in the Fig.[8a-8b] with different values of (a) $\sigma_p = 0.03, 0.05, 0.07, 0.09$ with $\sigma = 0.1,\ v_{i0} = 2.5,\ q = -0.9,\ V = 0.5$ and (b) $\sigma = 0.1, 0.3, 0.5, 0.7$ with $\sigma_p = 0.05,\ v_{i0} = 2.5,\ q = -0.9,\ C_1 = 0.5$ and $\alpha = 1.1$. For both the positron to ion density ratio β and electron to ion density ratio α, we have observed that the ion-acoustic soliton propagates rarefactively and that the amplitude of the solitary pulse increases (Fig.8a). We have also observed that as σ grows, the width of the solitary pulse increases slightly and the amplitude decreases.

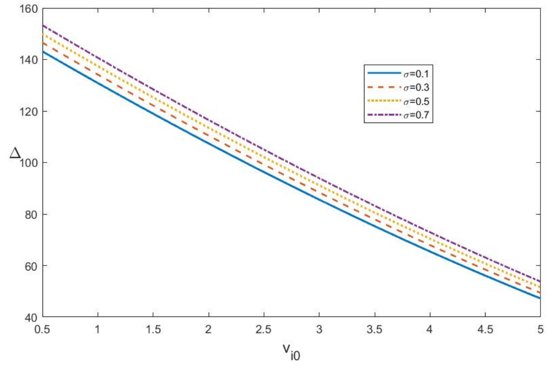


(a) **(b)**

Figure 5. The variation of (a) ϕ_0 and (b) Δ versus q for different values of σ_p.

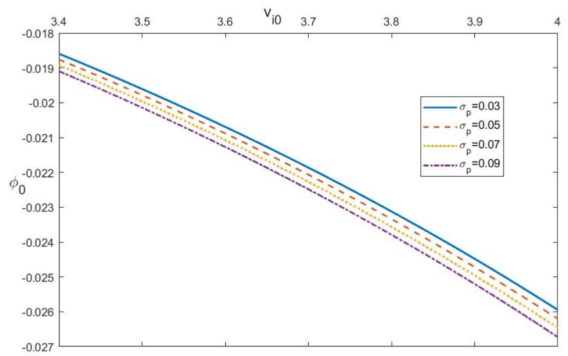


(a)

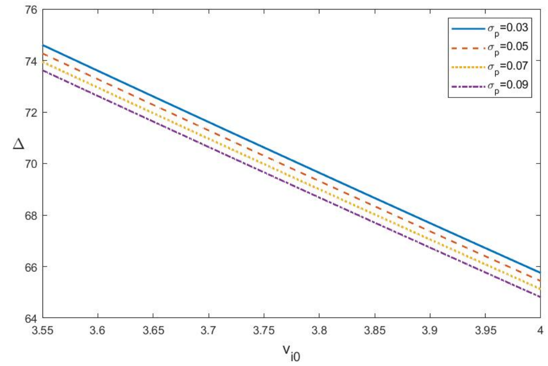


(b)

Figure 6. The variation of (a) ϕ_0 and (b) Δ versus v_{i0} for different values of σ.

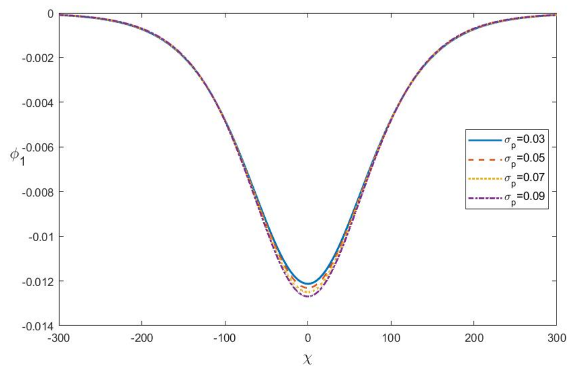


(a)

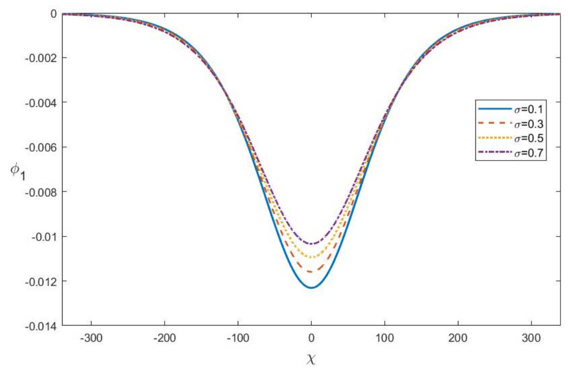


(b)

Figure 7. The variation of (a) ϕ_0 and (b) Δ versus v_{i0} for different values of σ_p.



(a)



(b)

Figure 8. The variation of electric potential (ϕ_1) versus χ for different values of (a) σ_p with $\alpha = 1.1$ and (b) σ with $\beta = 0.1$.

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УТВОРЕННЯ ІОННО-АКУСТИЧНИХ ОДИНОЧНИХ ХВИЛЬ У ПЛАЗМІ З НЕЕКСТЕНСИВНИМИ ЕЛЕКТРОНАМИ І ПОЗИТРОНАМИ

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У цій моделі плазми теоретично досліджено іони, електрони та позитрони, коли і електрони, і позитрони підкоряються q-неекстенсивному розподілу швидкостей. Метод відновного збурення використовується для отримання рівняння Кортевега де Фріза (KdV), що описує базовий набір нормалізованих рівнянь рідини. Чисельно досліджено існування іонно-акустичних одиночних хвиль залежно від неекстенсивного параметра, відношення температур електрона до позитрона, відношення температур іона до електрона та швидкості потоку. Було виявлено, що лише швидкі іонно-акустичні моди можуть викликати співіснування розріджених солітонів малої амплітуди.

Ключові слова: *q-неекстенсивний розподіл; редуктивний метод збурень; рівняння KdV*