Article

Effects of Non-Thermal Electrons and Non-Extensive Positrons on Solitary Waves in an Unmagnetized Dusty Plasma

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Effects of Non-Thermal Electrons and Non-Extensive Positrons on Solitary Waves in an Unmagnetized Dusty Plasma

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Abstract

In this study, we have investigated the existence and properties of solitons in an unmagnetized plasma composed of positive ions, negative ions, negatively charged dust grains, non-thermal electrons and non-extensive positrons. We have conducted our study on this complex plasma model because it moves away from simplistic and idealized plasma models. Also, study of solitons has not been conducted previously on this complex plasma model. Through the Sagdeev potential method we have derived the energy integral and investigated the variation of the Sagdeev potential for different values of the parameters that are involved in our plasma model. We have found that the non-thermal parameter (β) and the non-extensive parameter(q) significantly influence the features of the solitons. The features of the solitons are also found to be influenced by the Mach number (M), the negative ion to positive ion mass ratio (Ω), the positron to positive ion density ratio (δp), the electron to positron temperature ratio (σp), the dust charge density ratio (δd) and the negative ion to positive ion density ratio(δ_). The results from our study can be useful in investigating plasma in astrophysical environments, such as cometary tails and interstellar clouds.

Keywords: dusty plasma; Sagdeev potential; non-thermality; non-extensive; solitary waves

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1. Introduction

Unmagnetized plasma is crucial in studying astrophysical phenomena, such as solar winds, cometary tails and interstellar clouds. Several research has been conducted on unmagnetized plasma in recent years [1–15]. Presence of dust grains can effect the soliton amplitude and Mach number for both compressive and rarefactive solitons [16]. The positive and negative solitons can significantly depend on the mass number density, ion number density, and dust polarity in the adiabatic and isothermal system [17]. In some plasma system presence of positively charged dust grains results in existence of compressive solitons; however, the presence of negatively charged dust grains results in compressive solitons only up to a certain concentration of dust, and above the critical concentration of negative charge, the dusty plasma supports rarefactive solitons [18]. The presence of negatively charged dust particulates can result in existence of two critical concentrations of ion–electron density ratio [19]. The presence of dust charge of immobile dust plays crucial role to form compressive and rarefactive solitons in plasma where the massive dust particles in the stationary background of the plasma, and the lighter ions and relativistic electrons get appreciable initial drifts which makes great change in the growth of solitons [20]. The Dust-ion-acoustic (DIA) solitary waves are highly sensitive to the ion streaming speed and their amplitude decreases with an increase of the ion streaming speed [21]. It has also been found that the ionization instability leads to the exponential growth of the DIA solitary wave amplitude with time, whereas ion–dust and ion–neutral collisions reduce the growth rate [22]. In the presence of low dust charges and lower ion streaming, compressive and rarefactive solitons of either concave or convex characters can reflect. The higher streaming of mobile dusts causes the amplitudes of rarefactive solitons characteristically change from higher to lower showing convex character [23]. Dust grain density enhances the amplitude of solitary waves but weakens their reflection. In which the amplitudes of both the incident and reflected solitons remain higher for fluctuating charge on the dust grains in comparison with the case of fixed charge [24]. Compressive and rarefactive ion-acoustic solitary wave's characteristics significantly depend on the density and mass ratios of the positive to negative ions, the nonthermal electron parameter, and the geometry factor [25]. Large amplitude solitary structures significantly depends on various plasma parameters such as ion drift velocity, non-thermal parameter, electron to positron temperature ratio, positron density, and Mach number [26]. The presence of non-thermal electrons significantly modifies the parametric region where electron acoustic solitons can exist [27]. The nonthermal parameter significantly modify the conditions of the modulational instability of ion-acoustic waves in an electron–positron–ion plasma with nonthermal electrons [28]. The solitary excitations also strongly depend on the mass and density ratios of the positive and negative ions as well as the nonthermal electron parameter [29].   When the non-thermality of hot electrons rises, the speed of electron beam decreases, the density ratio of the beam to the cold electron increases, and the existence domain for electron acoustics solitons gets bigger [30]. The presence of nonthermal electrons also significantly affect the existence of the supersolitons [31]. The presence of non-thermal electrons and protons in oxygen plasma of the ionosphere plays destructive role in the formation of electrostatic structures by nonlinear ion acoustic waves (IAWs) [32]. Different values of the non-extensive parameter q shows significant effect on chaotic motions of ion acoustic waves [33]. The combined effects of electron non-extensivity, positron non-extensivity, and ions significantly modify the behaviour of the electrostatic solitary structures that exists with positive and negative potential in some plasma model [34].Ion-acoustic solitary wave can also depend on non-extensive parameter, electron to positron temperature ratio, ion to electron temperature ratio and streaming velocity. Fast ion-acoustic modes solely can produce the coexistence of small amplitude rarefactive solitons [35]. The effects of relativistic ions and q-nonextensive distribution of electrons and positrons are also crucial on the characteristics of the ion acoustic periodic (cnoidal) wave, such as the amplitude, wavelength, and frequency [36]. The non-extensive parameter, positron-to-electron density ratio, ion-to-electron temperature ratio, electron-to-positron temperature ratio and relativistic factor can significantly influence the phase shifts of solitary waves [37]. No study on solitons has yet been conducted for an unmagnetized plasma model composed of positive and negative ions, negatively charged dust grains, non-thermal electrons, and non-extensive positrons. This lack of research motivates the current study.

In this paper, we have represented the introduction in section 1. The fluid equations (that govern our plasma model) and the standard energy integral equation is represented in section 2. Effects of several parameters on the characteristics of solitons are discussed in section 3. Finally, we have concluded our research in section 4.

2. Equations Governing Dynamics of Plasma

We consider an unmagnetized plasma model composed of positive and negative ions, negatively charged dust grains, non-thermal electrons and non-extensive positrons. The equations governing dynamics of plasma are as follows:

For positive ions,

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

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

For negative ions,

$$\frac{\partial n_{i-}}{\partial t} + \frac{\partial}{\partial x}(n_{i-}u_{i-}) = 0 \tag{3}$$

$$\frac{\partial u_{i-}}{\partial t} + u_{i-}\frac{\partial u_{i-}}{\partial x} - \frac{1}{\Omega}\frac{\partial \phi}{\partial x} = 0 \tag{4}$$

For negatively charged dust grains,

$$\frac{\partial n_{d-}}{\partial t} + \frac{\partial}{\partial x}(n_{d-}u_{d-}) = 0 \tag{5}$$

$$\frac{\partial u_{d-}}{\partial t} + u_{d-}\frac{\partial u_{d-}}{\partial x} = \mu_{d-}\frac{\partial \phi}{\partial x} \tag{6}$$

Here, $\Omega = \frac{m_{i-}}{m_{i+}}$ is the negative ion to positive ion mass ratio, $\mu_{d-} = \frac{Z_{d-}m_{i+}}{m_{d-}}$ is the charge-to- mass ratio of the dust relative to the positive ions, where Z_{d-} is negative dust charge number, and m_{i+}, m_{i-} and m_{d-} are the mass of positive ion, mass of negative ion and mass of negatively charged dust grain respectively. We shall consider $\mu_{d-} \ll 1$, since the negatively charged dust grains are massive as compared to ions.

The non-thermal electron's number density can be obtained over velocity space with dimensionless potential ϕ as [38],

$$n_e = (1 - \beta\phi + \beta\phi^2)e^{\phi} \tag{7}$$

Here, $\beta = \frac{4\vartheta}{1+3\vartheta}$ represents the non-thermality, where ϑ determines the nonthermal electrons in the nonthermal plasma model. The parameter ϑ determines the population of dynamic nonthermal electrons in the nonthermal plasma model.

The Non-extensive positron number density can be given by [38],

$$n_p = (1 - \sigma_p(q-1)\phi)^{\frac{q+1}{2(q-1)}} \tag{8}$$

where, $\sigma_p = \frac{T_e}{T_p}$ is the electron to positron temperature ratio and q represents the non-extensive strength. Extensivity, sub extensivity and super extensivity are represented by q =1, q >1 and q < 1 respectively.

The normalised form of the Poisson equation can be obtained as,

$$\frac{\partial^2 \phi}{\partial x^2} = \delta_e n_e + \delta_- n_{i-} + \delta_d n_{d-} - n_{i+} - \delta_p n_p \tag{9}$$

The charge neutrality condition at equilibrium is $\delta_e + \delta_- + \delta_d = 1 + \delta_p$, where $\delta_- = \frac{n_{i-_0}}{n_{i+_0}}$ is the equilibrium negative ion to positive ion density ratio, $\delta_p = \frac{n_{p_0}}{n_{i+_0}}$ is the equilibrium positron to positive ion density ratio, $\delta_e = \frac{n_{e_0}}{n_{i+_0}}$ is the equilibrium electron to positive ion density ratio and $\delta_d = \frac{Z_{d-}n_{d-_0}}{n_{i+_0}}$ is the equilibrium dust charge density ratio.

The number density of positive ions, negative ions, negatively charged dust grains, non-thermal electrons and non-extensive positrons are represented by n_{i+}, n_{i-}, n_{d-}, n_e and n_p respectively. The number densities are normalized by the equilibrium density of positive ion n_{i+_0}. The fluid velocity of positive ions, negative ions and negatively charged dust grains is represented by u_{i+}, u_{i-} and u_{d-} respectively, which are normalized by the ion acoustic speed $c_s = \sqrt{\frac{k_B T_e}{m_{i+}}}$, and the electrostatic potential ϕ is normalized by $\frac{k_B T_e}{e}$, where T_e, k_B, m_{i+} and e represents electron temperature, Boltzmann's constant, positive ion mass and electronic charge respectively. The time and space variables are normalized by the inverse of the ion plasma frequency $\omega_{pi}{}^{-1} = \sqrt{\frac{m_{i+}}{4\pi e^2 n_{i+_0}}}$ and Debye length $\lambda_D = \sqrt{\frac{k_B T_e}{4\pi e^2 n_{i+_0}}}$ respectively.

We consider a variable $\xi = x - Mt$ (where, M represents the Mach number), that influences all the dependent variables in the nonlinear equations to employ the Sagdeev Potential (Pseudopotential) method.

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Applying the boundary conditions $\xi \to \pm\infty$, $n_{i+} \to 1$, $n_{i-} \to 1$, $n_{d-} \to 1$ $u_{i+} \to 0$, $u_{i-} \to 0$, $u_{d-} \to 0$, $\phi \to 0$, we obtain the overall solution for n_{i+}, n_{i-} and n_{d-} as the following respectively,

$$n_{i+} = \left(1 - \frac{2\phi}{M^2}\right)^{-\frac{1}{2}} \tag{10}$$

$$n_{i-} = \left(1 + \frac{2\phi}{\Omega M^2}\right)^{-\frac{1}{2}} \tag{11}$$

$$n_{d-} = \left(1 + \frac{2\mu_{d-}\phi}{M^2}\right)^{-\frac{1}{2}} \tag{12}$$

Applying the fundamental densities from the equations (7), (8), (10), (11) and (12) into the equation (9) and then multiplying $\frac{d\Phi}{d\xi}$, we get the standard energy integral equation as,

$$\frac{1}{2}\left(\frac{d\Phi}{d\xi}\right)^2 + V(\phi) = 0 \tag{13}$$

Here, $V(\phi)$ denotes the Sagdeev Potential in the energy integral equation (13). The $V(\phi)$ is given by,

$$\begin{aligned} V(\phi) = &-\frac{\delta_d M^2}{\mu_{d-}}\left(\sqrt{1 + \frac{2\mu_{d-}\phi}{M^2}} - 1\right) - \Omega\ \delta_- M^2\left(\sqrt{1 + \frac{2\phi}{M^2\Omega}} - 1\right) - M^2\left(\sqrt{1 - \frac{2\phi}{M^2}} - 1\right) \\ &- \delta_e\left(\left(1 + 3\beta - 3\beta\Phi + \beta\phi^2\right)e^{\phi} - (1 + 3\beta)\right) \\ &- \frac{2\delta_p}{\sigma_p(3q-1)}\left(\left(1 - (q-1)\sigma_p\phi\right)^{\frac{3q-1}{2(q-1)}} - 1\right) \end{aligned} \tag{14}$$

It is clear that for $\phi = 0$, the fixed point at the origin is unstable since $V(\phi) = 0$, $\frac{dV(\phi)}{d\Phi} = 0$ and $\frac{d^2V(\phi)}{d\phi^2} < 0$. Also, $V(\phi) < 0$ must be satisfied between $\phi = 0$ and $\phi = \phi_m$, where ϕ_m represents the maximum (or minimum) value of ϕ for which $V(\phi_m) = 0$.

The condition, $\frac{d^2V(\phi)}{d\phi^2} < 0$ at $\phi = 0$ gives the lower limit of Mach number (M_{min}) as,

$$M_{min} = \sqrt{\frac{2\left(\delta_- + \Omega + \delta_d\mu_{d-}\Omega\right)}{2\delta_e\Omega(1-\beta) + \Omega\delta_p\sigma_p(q+1)}}$$

From equation (10) we observe that for n_{i+} to be real we must have $M^2 \geq 2\phi$. Thus, the extreme value of ϕ is,

$$\phi_m = \phi_0 = \frac{M^2}{2} \tag{15}$$

Substituting the extreme value of ϕ from equation (15) in (14) we get the M upper limit as $V(\phi) \geq 0$, which gives,

$$\begin{aligned} &-\delta_e\left[\left(1 + 3\beta - \frac{3}{2}\beta M^2 + \frac{1}{4}\beta M^4\right)e^{\frac{M^2}{2}} - (1 + 3\beta)\right] - \Omega\delta_- M^2\left[\sqrt{1 + \frac{1}{\Omega}} - 1\right] + M^2 \\ &- \frac{2\delta_p}{\sigma_p(3q-1)}\left[\left(1 - (q-1)\sigma_p\frac{M^2}{2}\right)^{\frac{3q-1}{2(q-1)}} - 1\right] - \frac{\delta_d M^2}{\mu_{d-}}\left[\sqrt{1 + \mu_{d-}} - 1\right] \geq 0 \end{aligned}$$

3. Results and Discussion

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The existence, structure, and characteristics of large-amplitude nonlinear waves, particularly solitary waves can be analysed by using the Sagdeev potential method. In this section of the paper, we investigate the variation of the Sagdeev potential for different values of the plasma parameters.

Figure 1 shows the variation of the Sagdeev Potential for different values of q and fixed δ_e=0.7,β=0.15, Ω =1, δ_=0.18,M=1.4, μ_d=0.0000778,δ_d=0.67,δ_p=0.55, σ_p=0.3. We can observe that, as the non-extensive parameter (q) increases, depth of the Sagdeev potential well increases. A higher value of q indicates a distribution that is more concentrated at lower energies and the positrons respond more strongly to the wave's electric field. This strengthens the nonlinearity of the plasma, allowing it to support taller and more robust solitary pulses, which corresponds to a deeper Sagdeev potential well. Figure 2 shows the variation of the Sagdeev Potential for different values of M and fixed δ_e =0.7, β=0.15, Ω =1, δ_=0.18, μ_d=0.0000778, δ_d=0.67, δ_p=0.55, σ_p=0.3,q=0.6. We can observe that, as the Mach number (M) increases, depth of the Sagdeev potential well increases. A higher Mach number corresponds to a faster, more energetic solitary wave. To sustain such a wave, the plasma creates a stronger electrostatic trench (deeper potential well) to keep the particles trapped in the solitary structure.

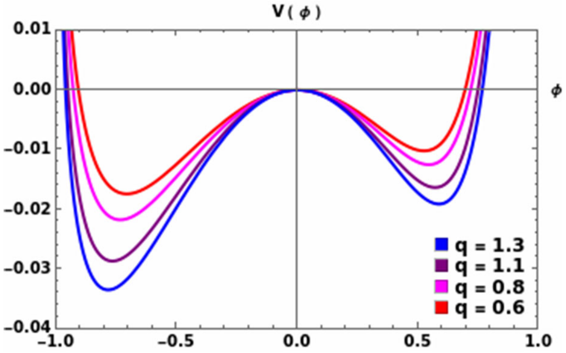

Figure 1. Variation of Sagdeev Potential V(ϕ) with respect to ϕ for different values of q.

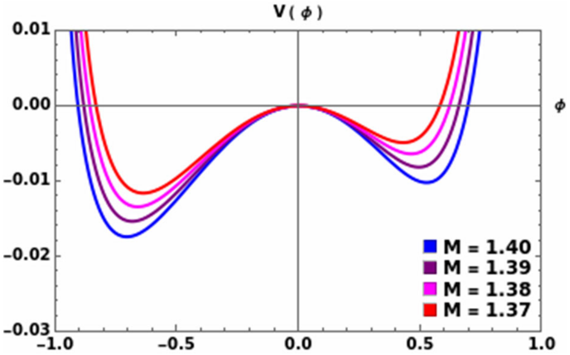

Figure 2. Variation of Sagdeev Potential V(ϕ) with respect to ϕ for different values of M.

Figure 3 shows the variation of the Sagdeev Potential for different values of β and fixed δ_e =0.7, Ω =1, δ_=0.18,M=1.4, μ_d=0.0000778, δ_d=0.67, δ_p=0.55, σ_p=0.3,q=0.6. We can observe that, as the non-thermal parameter (β) increases, depth of the Sagdeev potential well decreases. Therefore, the non-thermal parameter significantly modifies the balance between nonlinear steepening and wave dispersion. The extra energy from non-thermal electrons acts to suppress the growth of large-amplitude solitary waves. Figure 4 shows the variation of the Sagdeev Potential for different values of σ_p and fixed δ_e =0.7, β=0.15, Ω =1, δ_=0.18,M=1.4, μ_d=0.0000778, δ_d=0.67, δ_p=0.55, q=0.6. We can observe that, as the electron to positron temperature ratio (σ_p) increases, depth of the Sagdeev potential well increases. Therefore, as σ_p increases positrons becomes colder relative to electrons, and the nonlinearity of the plasma system increases while the dispersion decreases. This shifts the balance towards more robust nonlinear structures, allowing the potential well to extend to greater depths.

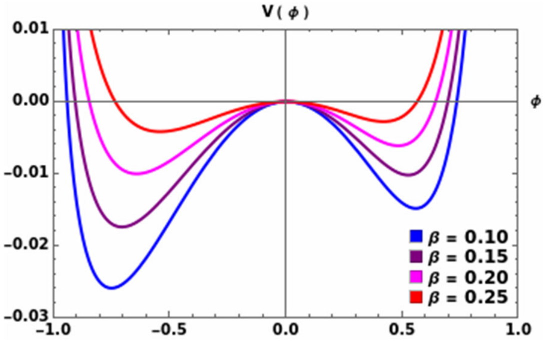

Figure 3. Variation of Sagdeev Potential V(ϕ) with respect to ϕ for different values of β.

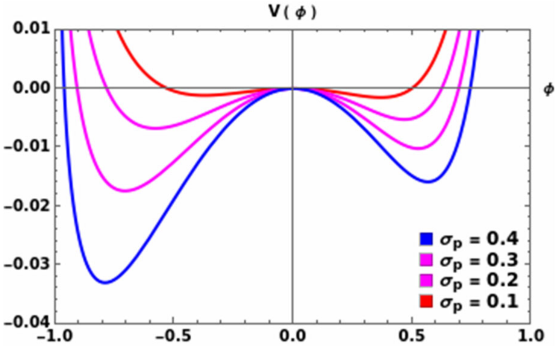

Figure 4. Variation of Sagdeev Potential V(ϕ) with respect to ϕ for different values of σ_p.

Figure 5 shows the variation of the Sagdeev Potential for different values of δ_p and fixed β=0.1, Ω =1, $\delta\_$=0.18,M=1.4, μ_d=0.0000778, δ_d=0.67, σ_p=0.3,q=0.6. We can observe that, as the positron to positive ion density ratio (δ_p) increases depth of the Sagdeev potential well increases. Therefore, when positrons follow a non-extensive (q-distributed) distribution, the system becomes more sensitive to density changes. The non-extensivity parameter (q) amplifies the effects of adding positrons, further deepening the potential well. Figure 6 shows the variation of the Sagdeev Potential for different values of $\delta\_$ and fixed β=0.1, Ω =1, M=1.4, μ_d=0.0000778, δ_d=0.67, δ_p=0.55, σ_p=0.3,q=0.6. We can observe that, as the negative ion to positive ion density ratio ($\delta\_$) increases, depth of the Sagdeev potential well decreases. Therefore, as the density of negative ions increases, they compete with electrons to balance the charge of the positive ions. Electrons are highly mobile and shield potentials effectively as compared to negative ions that are heavy and sluggish. The shift in the population from the electrons to the negative ions modifies the Debye shielding length. This modification restricts the maximum electrostatic pulse height that the plasma can support before the wave breaks, leading to a shallower potential well.

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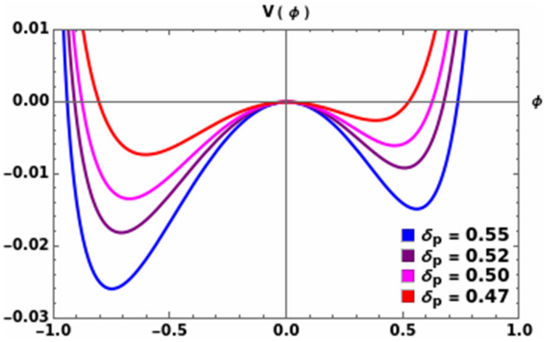

Figure 5. Variation of Sagdeev Potential V(ϕ) with respect to ϕ for different values of δ_p.

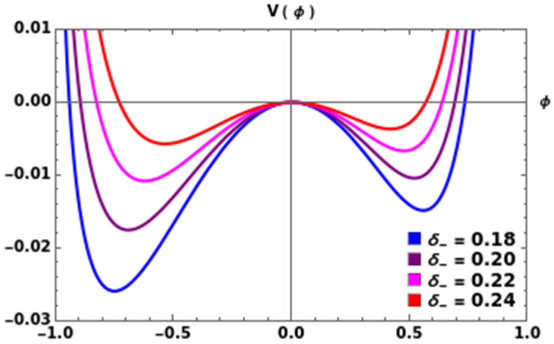

Figure 6. Variation of Sagdeev Potential V(ϕ) with respect to ϕ for different values of δ_.

Figure 7 shows the variation of the Sagdeev Potential for different values of δ_d and fixed $\beta=0.1$, $\Omega=1$,$\delta\_=0.18$,$M=1.4$, $\mu_d=0.0000778$, $\delta_p=0.55$,$\sigma_p=0.3$,$q=0.6$. We can observe that, as the dust charge density ratio (δ_d) increases, depth of the Sagdeev potential well decreases. The dust grains reduces the effective electron density and dampen the nonlinear restoring forces required to sustain large-amplitude solitary waves. This causes decrease in the depth of the Sagdeev potential well with an increasing dust charge density ratio. Figure 8 shows the variation of the Sagdeev Potential for different values of Ω and fixed $\delta_e=0.7$,$\beta=0.15$, $\delta\_=0.18$,$M=1.39$,$\mu_d=0.0000778$, $\delta_d=0.67$, $\delta_p=0.55$, $\sigma_p=0.1$,$q=0.6$. We can observe that, as the negative ion to positive ion mass ratio (Ω) increases, depth of the Sagdeev potential well increases. As the negative ions becomes heavier, they becomes harder to move and carries more momentum. Therefore, to successfully govern their motion and maintain a stable soliton structure, the plasma generates a deeper Sagdeev potential well.

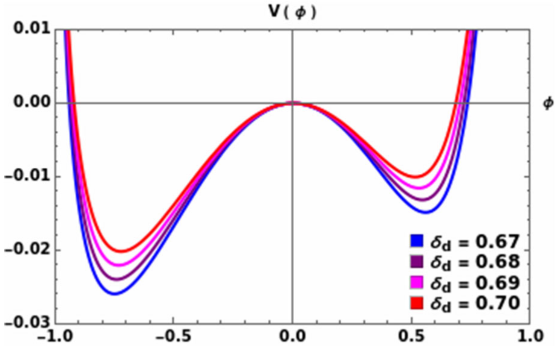

Figure 7. Variation of Sagdeev Potential V(ϕ) with respect to ϕ for different values of δ_d.

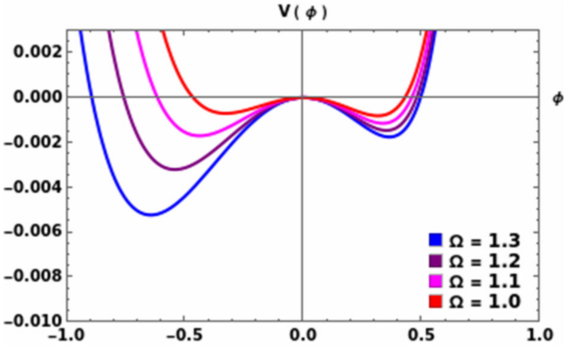

Figure 8. Variation of Sagdeev Potential V(ϕ) with respect to ϕ for different values of Ω.

4. Conclusions

In the study of an unmagnetized plasma composed of positive ions, negative ions, negatively charged dust grains, nonthermal electrons and non-extensive positrons, we have found the existence of both the compressive and rarefactive solitons. Increase in the depth of the Sagdeev potential well represents increase in the energy and amplitude of the solitons. The amplitude of the Rarefactive solitons are found to be comparatively higher than the compressive solitons. The amplitude of both the compressive and rarefactive solitons are found to be decreased for increasing value of the nonthermal parameter(β); however, the amplitude of both the compressive and rarefactive solitons are found to be increased for increasing value of the non-extensive parameter (q). Also, increase in the Mach number (M), the negative ion to positive ion mass ratio (Ω), the positron to positive ion density ratio (δ_p) and the electron to positron temperature ratio (σ_p) increases the amplitude of both the compressive and rarefactive solitons; however, increase in the dust charge density ratio (δ_d) and the negative ion to positive ion density ratio(δ_) decreases the amplitude of both the compressive and rarefactive solitons. Solitons are found to exist for $0.6 \leq q \leq 1.3$ (q < 1 and q > 1 represents super extensivity and sub extensivity respectively).

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Conflicts of Interest Statement: The authors declare no conflict of interests.

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