Large Amplitude Solitary Waves in a Four-Component Dusty Plasma with Nonthermal Ions

Prasanta Chatterjee and Kaushik Roy

Department of Mathematics, Siksha Bhavana, Visva Bharati, Santiniketan, India

Reprint requests to P. C.; E-mail: prasantachatterjee1@rediffmail.com

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Dust acoustic solitary waves are studied in a four-component dusty plasma. Positively and negatively charged mobile dust and Boltzmann-distributed electrons are considered. The ion distribution is taken as nonthermal. The existence of a soliton solution is determined by the pseudo-potential approach. It is shown that in small amplitude approximation our result obtained from the Sagdeev potential technique reproduce the result obtained by Sayed and Mamun [Phys. Plasmas **14**, 014501 (2007)] provided one cosiders the nonthermal distribution for ions.

Key words: Pseudo-Potential; Solitary Waves; Four-Component Dusty Plasma; Nonthermal Ions.

1. Introduction

Dust and plasmas are omnipresent in the universe. They play significant roles in space plasma, astrophysical plasma, laboratory plasma and environment. The presence of dusty plasmas in cometary tails, asteroid zones, planetary ring, interstellar medium, lower part of earth's ionosphere and magnetosphere [1 – 8] makes this subject increasingly important. Dusty plasmas also play a vital role in low temperature physics, radio frequency plasma discharge [9], coating and etching of thin films [10], plasma crystals [11] etc.

Nonlinear wave phenomena like solitons, shocks and vortices in dusty plasmas have also been studied by several investigators during the last two decades [12 – 22]. Bliokh and Yarashenko [14] first theoretically observed such waves while dealing with waves in Saturn's ring. Later the discovery of dust-acoustic wave (DAW) [15, 16], dust ion-acoustic wave (DIAW) [17, 18] and dust lattice (DL) waves [19, 20] gave a new impetus to the study of waves in dusty plasmas. Due to the dust grain dynamics few new eigenmodes like dust-Berstain-Greene-Kruskal (DBGK) mode, Shukla-Verma mode [21], dust-drift mode [22] are also introduced.

Dust-acoustic solitary waves in the one-dimensional and unmagnetized plasma have also been investigated by several authors [23]. Most of them considered the three-component dusty plasma system consisting of ions, electrons and negatively charged dust particles [23 – 25], but both negatively as well as positively charged dust particles are present in different areas of space [26 – 28]. Fortov et al. [29] explained the mechanism by which a dust grain can be positively charged. Chow et al. [28] also explained the situations under which smaller dust particles become positively charged and larger particles become negatively charged. It was also investigated that both positively and negatively charged dust particles are simultaneously present in different space plasmas [28 – 30]. Recently Sayed and Mamun [31] investigated solitary waves in four-component plasmas where they considered both positively and negatively charged dust particles. To obtain the solitary wave solution they used the reductive perturbative technique (RPT). But few years ago, Malfliet and Wieers [32] reviewed the studies of solitary waves in plasma and found that the RPT is based on the assumption of smallness of amplitudes and so this technique can explain only small amplitude solitary waves. But there are situations where the excitation mechanism gives rise to large amplitude waves; to study such a situation one should employ a nonperturbative technique. Sagdeev's [33] pseudo-potential method is one such method to obtain solitary wave solutions. This method has been successfully applied in various cases [34 – 35].

In this paper, we consider a four-component unmagnetized dusty plasma system consisting of Boltzmann-distributed electrons, nonthermal ions and also positively (smaller size) and negatively (larger size) charged dust grains. From few observations in space plasma [36 – 38] it is seen that the ion distribution is different from the Boltzmann distribution, and in these cases the nonthermal distribution for ions is suggested. The Vela satellite [36] has observed nonthermal ions from the Earth's bow-shock, the Phobos 2 satellite [37] observed the loss of energetic ions from the upper ionosphere of Mars and the Nozomi satellite [38] observed very large velocity protons near the Earth in the vicinity of the moon. Also Lundlin et al. [37] showed that for the planet having a not so strong magnetic field, the solar wind impacting with the planetary atmosphere results in nonthermal ion flux. In view of the above observations in this model the nonthermal distribution for ions is considered. Here the existence of solitary waves is studied by Sagdeev's pseudo-potential technique. It is shown that in small amplitude approximation our result reproduces that of Sayed and Mamun [31].

The organization of this paper is as follows. In Section 2 basic equations are written for a four-component dusty plasma and Sagdeev's pseudo-potential is derived. Conditions for the existence of soliton solution are also discussed. Small amplitude approximation solutions are given in Section 3. Section 4 is kept for results and discussion and Section 5 for conclusion.

2. Basic Equations and Pseudo-Potential Approach

We consider a four-component dusty plasma consisting of Boltzmann-distributed ions and electrons and also negatively and positively charged dust grains. The basic equations are [31]:

$$\frac{\partial n_1}{\partial t}+\frac{\partial}{\partial x}(n_1u_1)=0, \tag{1}$$

$$\frac{\partial u_1}{\partial t}+u_1\frac{\partial u_1}{\partial x}=\frac{\partial \psi}{\partial x}, \tag{2}$$

$$\frac{\partial n_2}{\partial t}+\frac{\partial}{\partial x}(n_2u_2)=0, \tag{3}$$

$$\frac{\partial u_2}{\partial t}+u_2\frac{\partial u_2}{\partial x}=-\alpha\beta\frac{\partial \psi}{\partial x}, \tag{4}$$

$$\begin{aligned}\frac{\partial^2 \psi}{\partial x^2}&=n_1-(1-\mu_\mathrm{i}+\mu_\mathrm{e})n_2+\mu_\mathrm{e}\mathrm{e}^{\sigma\psi}\\&\quad-\mu_\mathrm{i}(1+\beta_1\psi+\beta_1\psi^2)\mathrm{e}^{-\psi},\end{aligned} \tag{5}$$

where n_1 and n_2 are the negative and positive number density normalized by the equilibrium values n_{10} and n_{20}, respectively. u_1 and u_2 are the negatively and positively charged dust fluid speed normalized by $\frac{Z_1k_\mathrm{B}T_\mathrm{i}}{m_1}$. ψ, the electric potential, is normalized by $\frac{k_\mathrm{B}T_\mathrm{i}}{e}$. x and t are normalized by $\lambda_D=(\frac{Z_1k_\mathrm{B}T_\mathrm{i}}{4\pi Z_1{}^2e^2n_{10}})^{\frac{1}{2}}$ and $\omega_{p1}^{-1}=(m_1/4\pi Z_1{}^2e^2n_{10})^{\frac{1}{2}}$. $\alpha=\frac{Z_2}{Z_1}, \beta=\frac{m_1}{m_2}, \mu_\mathrm{e}=\frac{n_{\mathrm{e}0}}{Z_1n_{10}}, \mu_\mathrm{i}=\frac{n_{\mathrm{i}0}}{Z_1n_{10}}, \sigma=\frac{T_\mathrm{i}}{T_\mathrm{e}}$, where Z_1 and Z_2 are the number of electrons or protons residing on a negatively and positively charged dust particle, respectively. $\beta_1=\frac{4\alpha_1}{1+3\alpha_1}$, where α_1 is the ion nonthermal parameter that determines the number of fast (energetic) ions. m_1 and m_2 are masses of the negatively and positively charged dust particles, respectively. T_i and T_e are ion and electron temperatures, respectively, k_B is the Boltzmann constant and e is the charge of the electrons.

In order to search for solitary waves which solve (1)–(5), we introduce a linear substitution $\xi=x-Mt$ admitting only solutions which depend on space and time in the form of the wavy variable $x-Mt$. By substitution $\frac{\partial}{\partial x}=\frac{\mathrm{d}}{\mathrm{d}\xi}$ and $\frac{\partial}{\partial t}=-M\frac{\mathrm{d}}{\mathrm{d}\xi}$ (1)–(5) reduce to

$$-M\frac{\mathrm{d}n_1}{\mathrm{d}\xi}+\frac{\mathrm{d}(n_1u_1)}{\mathrm{d}\xi}=0, \tag{6}$$

$$-M\frac{\mathrm{d}u_1}{\mathrm{d}\xi}+u_1\frac{\mathrm{d}u_1}{\mathrm{d}\xi}=\frac{\mathrm{d}\psi}{\mathrm{d}\xi}, \tag{7}$$

$$-M\frac{\mathrm{d}n_2}{\mathrm{d}\xi}+\frac{\mathrm{d}(n_2u_2)}{\mathrm{d}\xi}=0, \tag{8}$$

$$-M\frac{\mathrm{d}u_2}{\mathrm{d}\xi}+u_2\frac{\mathrm{d}u_2}{\mathrm{d}\xi}=-\alpha\beta\frac{\mathrm{d}\psi}{\mathrm{d}\xi}, \tag{9}$$

$$\begin{aligned}\frac{\mathrm{d}^2\psi}{\mathrm{d}\xi^2}&=n_1-(1-\mu_\mathrm{i}+\mu_\mathrm{e})n_2+\mu_\mathrm{e}\mathrm{e}^{\sigma\psi}\\&\quad-\mu_\mathrm{i}(1+\beta_1\psi+\beta_1\psi^2)\mathrm{e}^{-\psi}.\end{aligned} \tag{10}$$

The boundary conditions are: $\psi,u_1,u_2\to 0, n_1,n_2\to 1, n_\mathrm{i}\to\mu_\mathrm{i}$ and $n_\mathrm{e}\to\mu_\mathrm{e}$ as $|\xi|\to\infty$.

From (6) we get

$$n_1=\frac{M}{M-u_1}. \tag{11}$$

Similarly from (8) we get

$$n_2=\frac{M}{M-u_2}. \tag{12}$$

From (7) we get

$$\psi=-Mu_1+\frac{u_1^2}{2}, \tag{13}$$

and from (9) we get

$$\alpha\beta\psi = Mu_2 - \frac{u_2^2}{2}. \tag{14}$$

Now using (11)–(14) in (10) we get

$$\frac{\mathrm{d}^2\psi}{\mathrm{d}\xi^2} = -\frac{\partial V(\psi)}{\partial\psi}, \tag{15}$$

where

$$\begin{aligned} V(\psi) &= M^2\left[1-\left(1+\frac{2\psi}{M^2}\right)^{\frac{1}{2}}\right] \\ &+ \frac{M^2}{\alpha\beta}(1-\mu_\mathrm{i}+\mu_\mathrm{e})\left[1-\left(1-\frac{2\alpha\beta\psi}{M^2}\right)^{\frac{1}{2}}\right] \\ &+ \frac{\mu_\mathrm{e}}{\sigma}(1-\mathrm{e}^{\sigma\psi}) \\ &+ \mu_\mathrm{i}[1+3\beta_1-(1+3\beta_1+3\beta_1\psi+\beta_1\psi^2)\mathrm{e}^{-\psi}]. \end{aligned} \tag{16}$$

Multiplying both sides of (15) by $2\frac{\mathrm{d}\psi}{\mathrm{d}\xi}$ and integrating w. r. t. ξ with the boundary conditions $|\xi| \to \infty, V \to 0$ and $\frac{\mathrm{d}\psi}{\mathrm{d}\xi} \to 0$, we get

$$V(\psi) + \frac{1}{2}\left(\frac{\mathrm{d}\psi}{\mathrm{d}\xi}\right)^2 = 0. \tag{17}$$

Equation (15) can be considered as a motion of a particle (whose pseudo-position is ψ at pseudo-time ξ) with pseudo-velocity $\mathrm{d}\psi/\mathrm{d}\xi$ in a pseudo-potential well $V(\psi)$. That is why Sagdeev's potential is called pseudo-potential. Hence the conditions for the existence of solitary wave solutions are:

(i) $V(\psi)$ has a double root at $\psi = 0$. Moreover $V(\psi)$ has a local maximum at $\psi = 0$, i. e. $\mathrm{d}V/\mathrm{d}\psi = 0$ at $\psi = 0$ and $\mathrm{d}^2V/\mathrm{d}\psi^2 < 0$ at $\psi = 0$.

(ii) There exists a nonzero ψ_m, the maximum (or minimum) value of ψ, where $V(\psi_m) = 0$. ψ_m is the amplitude of the solitary wave. If ψ_m is positively charged then the solitary wave is called compressive solitary wave, and if ψ_m is negatively then the solitary wave is called rarefractive solitary wave.

(iii) $V(\psi)$ is negatively in the interval $(0, \psi_m)$.

3. Small Amplitude Approximation

To obtain Korteweg-de Vries (KdV)-type solutions we use the small amplitude approximation of $V(\psi)$ and expand $V(\psi)$ about $\psi = 0$. Using the boundary condition $V \to 0$ and $\frac{\mathrm{d}V}{\mathrm{d}\psi} \to 0$ as $\psi \to 0$, we get

$$V(\psi) = A_1\frac{\psi^2}{2} + A_2\frac{\psi^3}{6}, \tag{18}$$

when

$$A_1 = \frac{1}{M^2} + (1-\mu_\mathrm{i}+\mu_\mathrm{e})\frac{\alpha\beta}{M^2} - \sigma\mu_\mathrm{e} + (\beta_1-1)\mu_\mathrm{i}, \tag{19}$$

$$\begin{aligned} A_2 = &-\frac{3}{M^4} + (1-\mu_\mathrm{i}+\mu_\mathrm{e})\frac{3\alpha^2\beta^2}{M^4} \\ &- \sigma^2\mu_\mathrm{e} - (1+4\beta_1)\mu_\mathrm{i}. \end{aligned} \tag{20}$$

Hence the KdV-type soliton solution is given by

$$\psi = \psi_0 \mathrm{sech}^2\frac{\xi}{\delta}, \tag{21}$$

where

$$\psi_0 = -\frac{3A_1}{A_2} \tag{22}$$

is the amplitude of the solitary wave and

$$\delta = \frac{2}{\sqrt{-A_1}} \tag{23}$$

is the width of the solitary wave. Neglecting the nonthermal effect of ions (i. e. putting $\beta_1 = 0$), (18)–(20) will become

$$V(\psi) = A_1\frac{\psi^2}{2} + A_2\frac{\psi^3}{6}, \tag{24}$$

where

$$A_1 = \frac{1}{M^2} + (1-\mu_\mathrm{i}+\mu_\mathrm{e})\frac{\alpha\beta}{M^2} - \sigma\mu_\mathrm{e} - \mu_\mathrm{i}, \tag{25}$$

$$A_2 = -\frac{3}{M^4} + (1-\mu_\mathrm{i}+\mu_\mathrm{e})\frac{3\alpha^2\beta^2}{M^4} - \sigma^2\mu_\mathrm{e} - \mu_\mathrm{i}. \tag{26}$$

Sayed and Mamun [31] studied this model for small amplitude solitary waves using the RPT and they obtained the KdV equation as

$$\frac{\partial\psi_1}{\partial\tau} + A\psi_1\frac{\partial\psi_1}{\partial\xi} + B\frac{\partial^3\psi_1}{\partial\xi^3} = 0, \tag{27}$$

where

$$\begin{aligned} A = \frac{1}{2V_0[(1-\mu_\mathrm{i}+\mu_\mathrm{e})\alpha\beta]}\big[&(1-\mu_\mathrm{i}+\mu_\mathrm{e})3\alpha^2\beta^2 \\ &-3-{V_0}^4(\mu_\mathrm{e}\sigma^2-\mu_\mathrm{i})\big] \end{aligned} \tag{28}$$

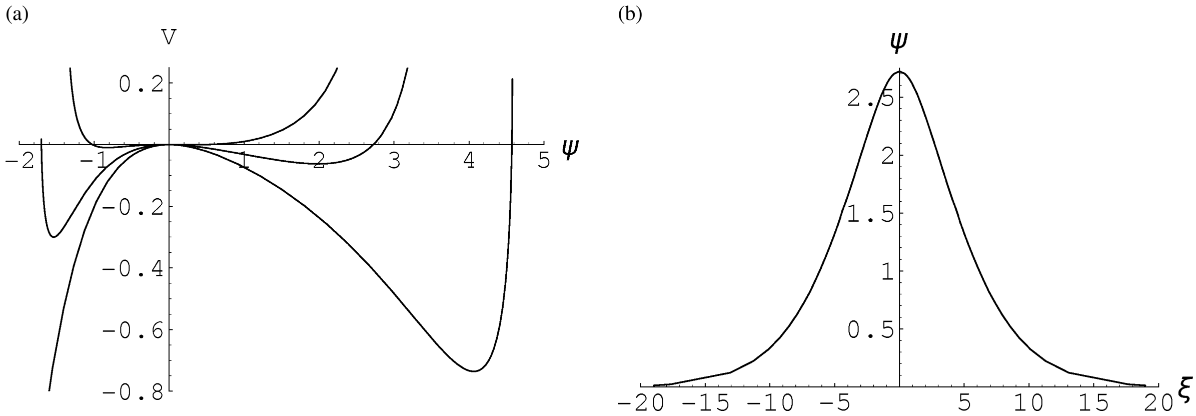

Fig. 1. (a) Plot of V vs. ψ for $M = 1.65$, 1.85 and 2.14, and (b) plot of ψ vs. ξ for $M = 1.85$. The other parameters are: $\alpha = 0.01, \beta = 50, \mu_i = 0.5, \mu_e = 0.2, \sigma = 0.5$ and $\alpha_1 = 0.05$.

$$B = \frac{V_0{}^3}{2\left[1 + (1 + \mu_e - \mu_i)\,\alpha\beta\right]}. \tag{29}$$

V_0, the phase speed of the DAW, is given by

$$V_0^2 = \frac{1 + (1 + \mu_e - \mu_i)\,\alpha\beta}{\sigma\mu_e + \mu_i}. \tag{30}$$

To get the steady-state solution they used the transformation $\xi = \eta - U_0\tau$ and the usual boundary conditions, where U_0 is the velocity of the frame of the transformed coordinate. By usual technique one obtains

$$\frac{d^2\psi_1}{d\xi^2} = \frac{2}{B}(U_0\psi_1 - \frac{\psi_1^2}{2}) = -\frac{\partial V_1}{\partial \psi_1}, \tag{31}$$

where

$$V_1(\psi_1) = -\frac{U_0}{B}\psi_1^2 + \frac{1}{3B}\psi_1^3. \tag{32}$$

Now to compare the small amplitude approximation of $V(\psi)$ of (24) with the values of $V_1(\psi_1)$ of (32) obtained by the RPT [31], we first replace M by $V_0 + U_0$ when U_0 is small. Then keeping only first-order terms (in U_0) it can easily be verified that $V(\psi)$ in (24) reduces to $V_1(\psi_1)$ given in (32). Hence $V_1(\psi_1)$ obtained by the RPT in [31] is nothing but a small amplitude approximation of $V(\psi)$ of (24).

4. Results and Discussion

Figure 1a shows the plot of $V(\psi)$ vs. ψ for $M = 1.65$, 1.85 and 2.14. The other parameters are $\alpha = 0.01, \beta = 50, \mu_i = 0.5, \mu_e = 0.2, \sigma = 0.5, \alpha_1 = 0.05$. It can be seen that $V(\psi)$ crosses the ψ axis for negative values of ψ for $1.65 \le M \le 1.85$. Hence rarefractive solitary waves exist for $1.65 \le M \le 1.85$. For $M = 1.85$, $V(\psi)$ crosses the ψ axis at $\psi = -1.703$. Hence $|\psi_{\min}| = \psi_0 = 1.703$ is the amplitude of the rarefractive solitary waves. It is also seen from this figure that the amplitude of the solitary waves increases with the increase of velocity.

The shape of the solitary wave is obtained from the formula

$$\pm\xi = \int_{\psi 0}^{\psi} \frac{1}{\sqrt{-2V(\psi)}}, \tag{33}$$

and Fig. 1b depicts the rarefractive soliton solution $\psi(\xi)$ plotted against ξ for $M = 1.85$. The other parameters are the same as those in Figure 1a.

Figure 2a shows the plot of $V(\psi)$ vs. ψ for $M = 1.6$, 1.98 and 2.14. The other parameters are $\alpha = 0.01, \beta = 50, \mu_i = 0.5, \mu_e = 0.2, \sigma = 0.5, \alpha_1 = 0.04$.

It can be seen that $V(\psi)$ crosses the ψ axis for positive values of ψ for $1.6 \le M \le 1.98$. Hence compressive solitary waves exist for $1.6 \le M \le 1.98$. For $M = 1.75$, $V(\psi)$ crosses the ψ axis at $\psi = 2.643$. Hence $|\psi_{\min}| = \psi_0 = 2.643$ is the amplitude of the compressive solitary waves. It is also seen from this figure that the amplitude of the solitary waves increases with the increase of velocity.

Using the same technique the shape of the solitary wave is found and Fig. 2b depicts the compressive soliton solution $\psi(\xi)$ plotted against ξ for $M = 1.75$. The other parameters are the same as those in Figure 2a.

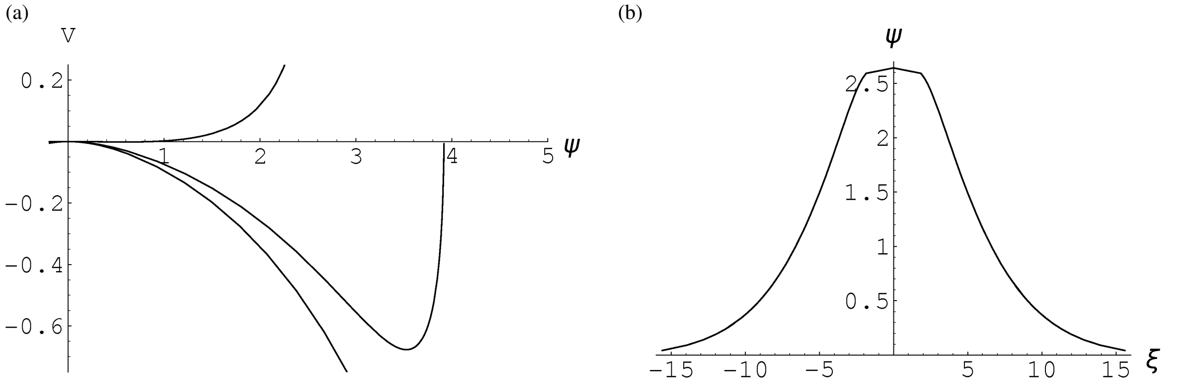

Fig. 2. (a) Plot of V vs. ψ for $M = 1.6$, 1.98 and 2.14, and (b) plot of ψ vs. ξ for $M = 1.75$. The other parameters are: $\alpha = 0.01, \beta = 50, \mu_i = 0.5, \mu_e = 0.2, \sigma = 0.5$ and $\alpha_1 = 0.04$.

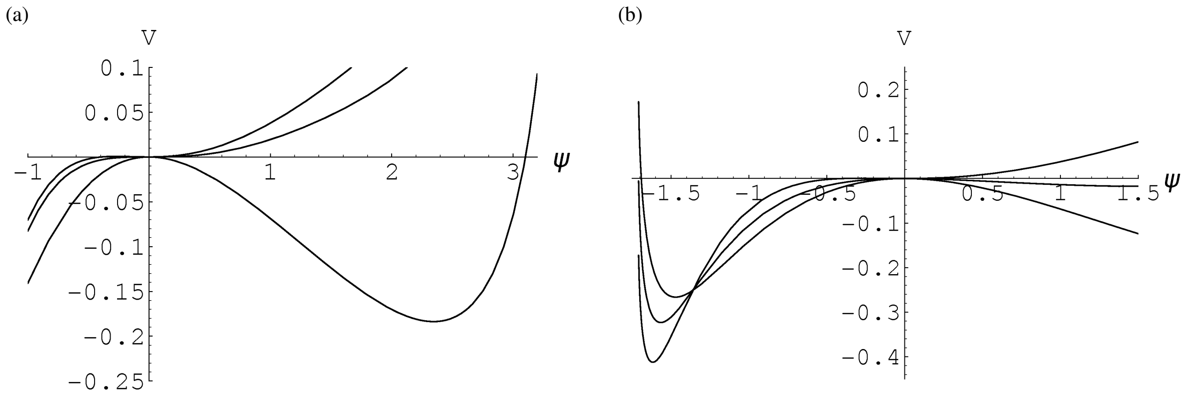

Fig. 3. (a) Plot of V vs. ψ for $\alpha_1 = 0$, 0.15, 0.16, and (b) plot of ψ vs. ξ for $\alpha_1 = 0,\ 0.1,\ 0.11$. The other parameters are the same as those in Figure 1.

To see the effect of β_1 on the existence of solitary waves Figs. 3a and 3b are drawn. M is taken as 1.85. The other parameters are the same as those in Figure 1. In Fig. 3a $V(\psi)$ is plotted against ψ for $\alpha_1 = 0$, 0.15 and 0.16. Here it can be seen that soliton solutions exist for $\alpha_1 = 0$ and 0.15. But for $\alpha_1 = 0.16$ $V(\psi)$ does not satisfy the conditions for existence of soliton solution. So a compressive soliton exists for $0 \le \beta \le 0.15$. Similarly in Fig. 3b $V(\psi)$ is plotted against ψ for $\beta = 0$, 0.1 and 0.11, and it is seen that a rarefractive soliton solution exists for $0 \le \beta \le 0.1$.

To see the effect of α_1 on the amplitude of the compressive and rarefractive solitary waves Figs. 4a and 4b are drawn. Here the amplitude of the solitary wave $|\psi_0|$ is plotted against α_1. The parameters of Figs. 4a and b are same as those in Fig. 3a and b, respectively. Here it is seen that the amplitude of the compressive solitary wave decreases drastically with the increase of α_1 but the amplitude of the rarefractive solitary wave increases very slowly with the increase of α_1. Hence α_1 has a significant effect on the speed and shape of solitary waves in four-component plasmas. It can also be shown that the amplitude of the solitary waves also depends upon other parameters.

5. Conclusion

The existence of both the rarefractive and compressive solitary waves in four-component dusty plasmas is investigated using Sagdeev's pseudo-potential approach. Nonthermal ion distribution is considered. It is seen that our result completely agrees with the RPT result obtained by Sayed and Mamun [31] provided one consideres to neglect the Boltzmann distribution for ions. The shape of the solitary wave is determined using the integration (33). It is shown that α_1, the ion thermal parameter that determines the number of

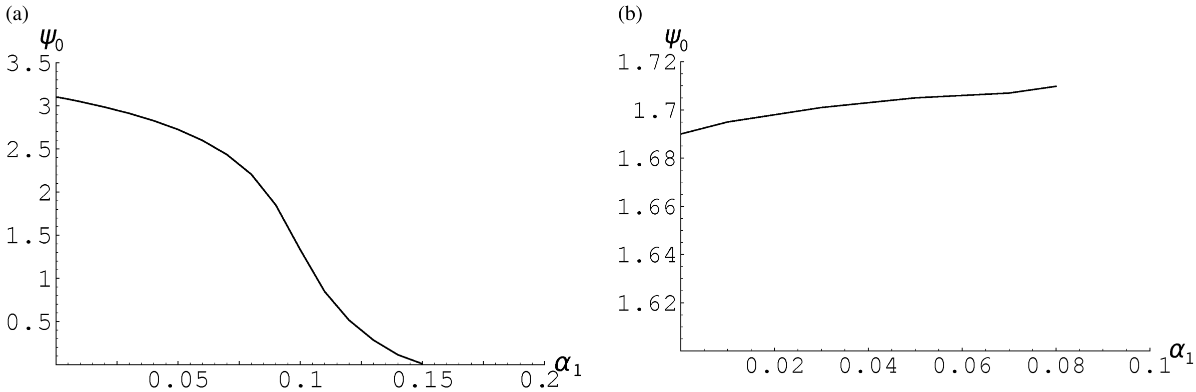

Fig. 4. (a) and (b) Plot of $|\psi_0|$ against α_1 with the parameters of Fig. 3a and b, respectively.

fast ions, has a significant effect on the amplitude of the solitary wave. Sakanaka and Spassovska [39] and Sakanaka and Shukla [40] studied large amplitude double layers in four-component dusty plasmas. Work in this direction is in progress considering nonthermal distribution of ions.

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