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Effect of Anisotropic Pressure of Ions on Solitary Waves in Cometary Dusty Plasmas with Kappa described Electrons

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Abstract

The propagation of solitary wavesis studied in a plasma composed of solar hot electrons, cometary photo-electrons, ions (hydrogen) and dust of both polarities.The theory of Chew, Golberger-Low (CGL) has been used to study the effect of anisotropic pressure of ions (hydrogen) on solitary waves. Both the electrons are modeled by kappa distributions. Using reductive perturbation method,the Zakharov- Kuznetsov (ZK) equation is derived for the two dimensional case and its solution is plotted for different physical parameters. From the plots it is seen that the parallel pressure has a stronger influence on the amplitude of the solitary wave structures. Further, for the proposed plasma, both positive and negative polarity solitons exist for higher and lower values of charge numbers respectively. In addition, as spectral indices increase the amplitude of the solitary structure decreases for both types of waves; however, themagnitude of the amplitude increases with an increase of Mach number.

Key words: Kappa described electrons, anisotropic ions, reductive perturbation method, ZK equation, positive and negative solitons.

Introduction

The study of plasmas with dust as a constituent is of particular interest among researchers due to its existence in different space environments like planetary rings, earth's ionosphere, asteroid zones and laboratory conditions[1-4]. Not only their omnipresence, but also the different wave modes present in dusty plasmas like Dust Acoustic Wave [6], Dust Ion Acoustic Wave [7], Dust Lattice Wave[8], etc. has attracted scientists to the study of dusty plasmas. The charging of dust grains occurs due to a number of processes like the photo-electron emission, secondary electron emission, thermionic emission, etc.[3]. Earlier, in most of the plasma environments dust particles with negative charges were observed[9-12]. However, the reports of dust with positive and negative polarities give a new dimension to the study of these plasmas [10-11].

There are a number of investigations where electrons were described by a Maxwell-Boltzmanndistributionin different space environments.However, Vasyliunas first predicted a non Maxwellian type of distribution, while analyzing solar wind data, called the "kappa distribution" [12]. The deviation from MB distribution is due to the presence of highly energetic particles in space environments in the plasma under consideration. The kappa distribution reduces to MB distribution in the limit of high spectral index value; that is when $\kappa \to \infty$ [13-16].

The presence of magnetic field strongly influences the behavior of plasma in the directions parallel and perpendicular to magnetic field[17]. CGL theory is applicable to these anisotropic plasma environments where parallel and perpendicularpressures of ions, relative to the magnetic field [18], strongly influence wave particle interactions and other dissipative effects[19]. Therefore under such situations it is important to consider the effect of ion pressure.

For reasons given above, we investigate the effect of anisotropic pressure of ions on solitary waves in a plasma composed of dust of opposite polarities, cometary photo-electrons and hot, solar wind electrons.

Basic Equations

We are interested in solitary waves in a five constituent plasma, for reasons given above. The dust components are treated as cold, while the two electron component are described by a Boltzmann-like distribution given by

$$n_s = n_{s0}\left[1+\frac{e_s\psi}{k_B T_s(\kappa_s - 3/2)}\right]^{-\kappa_s+1/2} \quad ; s = H, se, ce$$

..........(1)

In (1) s indicates the species ($s = H$ for hydrogen, $s = se$ for solar electrons and $s = ce$ for cometary photo-electrons). n denotes the density (with the subscript '0' denoting the equilibrium value), e_s the charge, T_s the temperature and κ_s the spectral index for the species 's'. k_B is the Boltzmann's constant while ψ is the potential.

The pressure tensor can be expressed as

$$\tilde{P}_i = p_{\perp i}\hat{I} + \left(p_{\parallel i} - p_{\perp i}\right)\hat{b}\hat{b}$$

where $\hat{I}$ is the unit tensor and $\hat{b}$ is unit vector along the magnetic field.

Using the CGL theory[20] parallel and perpendicular pressure can be written as

$$p_{\perp i} = p_{\perp i0}\left(\frac{n_i}{n_{i0}}\right) \text{ and } p_{\parallel i} = p_{\parallel i0}\left(\frac{n_i}{n_{i0}}\right)^3 \text{ ....(2)}$$

The equilibrium values for parallel and perpendicular pressures can be written as [17,19]

$$p_{i\perp} = n_{i0}T_{i\perp} \text{ and } p_{i\parallel} = n_{i0}T_{i\parallel}$$

The normalized form of the two continuity equations and the equations of motion for the ions, dust particles and the Poisson's equation are thus given by

$$\partial_t n_{i,1,2} + \partial_x (\nabla)_{i,1,2} = 0 \quad .....(3)$$

$$\partial_t v_1 + (v_1.\nabla)v_1 = \nabla\psi \quad .....(4)$$

$$\partial_t v_2 + (v_2.\nabla)v_2 = \alpha\beta\nabla\psi \quad .....(5)$$

$$\begin{aligned}\partial_t v_i + (v_i.\nabla)v_i &= -\alpha_i\beta_i\nabla\psi + \Omega(v_{iz}\hat{y} - v_{iy}\hat{z}) \\ &\quad -(\mathrm{p}_1 n_i\nabla n_i + \frac{\mathrm{p}2}{n_i}\nabla n_i)\beta_i\end{aligned} \quad .....(6)$$

We consider perturbations in the x-y plane [22]. From the equation (6), x, y & z components respectively can be written as follows,

$$\partial_t v_{ix} + (v_{ix}.\partial_x + v_{iy}.\partial_y)v_{ix} = -\alpha_i\beta_i\partial_x\psi + -\beta_i\,\mathrm{p}_1\, n_i\partial_x n_i .....(6a)$$

$$\partial_t v_{iy} + (v_{ix}.\partial_x + v_{iy}.\partial_y)v_{iy} = -\alpha_i\beta_i\partial_y\psi + \Omega v_{iz} -\beta_i \frac{\mathrm{p}2}{n_i}\partial_y n_i .....(6b)$$

$$\partial_t v_{iz} + (v_{ix}.\partial_x + v_{iy}.\partial_y)v_{iz} = -\Omega v_{iy} .....(6c)$$

$$\begin{aligned}\nabla^2\psi &= n_1 - (1 - z_i\mu_i + \mu_{se} + \mu_{ce})n_2 \\ &\quad + \mu_{se}(1 - \frac{\psi}{\sigma_{se}(\kappa_{se} - 3/2)})^{(-\kappa_{se}+1/2)} \\ &\quad + \mu_{ce}(1 - \frac{\psi}{\sigma_{ce}(\kappa_{ce} - 3/2)})^{(-\kappa_{ce}+1/2)} \\ &\quad -(1 - z_2\mu_2 + \mu_{se} + \mu_{ce})n_i .....(7)\end{aligned}$$

In (3) to (7) n_i, n_1 and n_2 are the ion, negative and positive dust number densities, normalized by their equilibrium values n_{i0}, n_{10} and n_{20} respectively. v_i, v_1 and v_2 are, respectively, the ions, the negatively and positively charged dust fluid speeds normalized by $\frac{z_1 k_B T_1}{m_1}$. ψ, which is now the normalized electric potential, is normalized by $\frac{k_B T_1}{e}$. x and t are normalized by the Debye length $\lambda_D = (\frac{z_1 k_B T_1}{4\pi z_1^2 e^2 n_{10}})^{1/2}$ and the inverse of the plasma frequency $\omega_{p1}^{-1} = (\frac{m_1}{4\pi z_1^2 e^2 n_{10}})^{1/2}$.

Also $\alpha_i = \frac{z_i}{z_1}$ $\alpha = \frac{z_2}{z_1}$, $\beta_i = \frac{m_1}{m_i}$, $\beta = \frac{m_1}{m_2}$, $\mu_s = \frac{n_{s0}}{z_1 n_{10}}$, $p_1 = \frac{3p_{\|i0}}{z_1 k_B T_1 n_{i0}}$, $p_2 = \frac{p_{\perp i0}}{z_1 k_B T_1 n_{i0}}$, $\sigma_s = \frac{T_s}{T_1}$

where n_{s0} is the equilibrium density for species s. T_s and T_1 are the temperatures of species s and negative dust respectively. m_i, m_1 and m_2 are, respectively, the masses of ions, negatively and positively charged dust particles while z_i, z_1 and z_2 are the corresponding charge numbers.

Derivation of ZK equation

To derive ZK equations of small amplitude waves, we introduce new variables X, Y and τ as:

$X = \varepsilon^{1/2}(x - \lambda t)$; $Y = \varepsilon^{1/2} y$;

$\tau = \varepsilon^{3/2} t$.

From the above transformations we can write $\partial_x = \varepsilon^{1/2}\partial_X$; $\partial_y = \varepsilon^{1/2}\partial_Y$ and $\partial_t = \varepsilon^{3/2}\partial_\tau - \varepsilon^{1/2}\lambda\partial_X$.

For using reductive perturbation theory, various parameters can be written as

$$n_{i,1,2} = 1 + \varepsilon n_{i,1,2}^{(1)} + \varepsilon^2 n_{i,1,2}^{(2)} + \ldots\ldots\ldots\ldots (8)$$

$$v_{(i,1,2)x} = 0 + \varepsilon v_{(i,1,2)x}^{(1)} + \varepsilon^2 v_{(i,1,2)x}^{(2)} + \ldots\ldots\ldots\ldots (9)$$

$$v_{(i,1,2)\,\mathrm{y,z}} = \varepsilon^{3/2} v_{(i,1,2)y,z}^{(1)} + \varepsilon^2 v_{(i,1,2)y,z}^{(2)} + \ldots\ldots\ldots\ldots (10)$$

$$\psi = \varepsilon\psi^{(1)} + \varepsilon^2\psi^{(2)} + \ldots\ldots\ldots\ldots\ldots (11)$$

Using equations (8-11) in (3-7) and equating powers of $\varepsilon^{3/2}$:

we can get from equation (3-6)

$$n_i^{(1)} = \frac{\alpha_i\beta_i\psi^{(1)}}{\lambda^2 - p_1},\ n_1^{(1)} = \frac{-\psi^{(1)}}{\lambda^2},\qquad n_2^{(1)} = \frac{\alpha\beta}{\lambda^2}\psi^{(1)} \quad \ldots\ldots.(12)$$

and from (6b)

$$v_{iz} = \frac{\alpha_i\beta_i}{\Omega}\partial_Y\psi^{(1)} + \frac{\mathrm{p2}}{\Omega}\partial_Y n_i^{(1)} \ldots\ldots\ldots(13)$$

Similarly equating powers of $\varepsilon^{5/2}$:

$$\partial_\tau n_i^{(1)} - \lambda\partial_X n_i^{(2)} + \partial_X v_{ix}^{(2)} + \partial_X v_{iy}^{(2)} + \partial_X (\mathrm{n}_i^{(1)}\, v_i^{(1)}) = 0 \quad .....(14)$$

$$\partial_\tau v_{ix}^{(1)} - \lambda\partial_X v_{ix}^{(2)} + \alpha_i\beta_i\partial_X \psi^{(2)} + p_1\partial_X n_i^{(2)} + p_1\, \mathrm{n}_i^{(1)}\, \partial_X (\mathrm{n}_i^{(1)}) + v_{ix}^{(1)}\partial_X (v_{ix}^{(1)}) = 0 \quad ....(15)$$

$$\partial_\tau n_1^{(1)} - \lambda\partial_X n_1^{(2)} + \partial_X v_1^{(2)} + \partial_X (\mathrm{n}_1^{(1)}\, v_{1x}^{(1)}) = 0 \quad ....(16)$$

$$\partial_\tau n_2^{(1)} - \lambda\partial_X n_2^{(2)} + \partial_X v_2^{(2)} + \partial_X (\mathrm{n}_2^{(1)}\, v_{2x}^{(1)}) = 0 \quad .....(17)$$

$$\partial_\tau v_{1x}^{(1)} - \lambda\partial_X v_{1x}^{(2)} + v_{1x}^{(1)}\partial_X v_{1x}^{(1)} = \partial_X \psi^{(2)} \quad ......(18)$$

$$\partial_\tau v_{2x}^{(1)} - \lambda\partial_X v_{2x}^{(2)} + v_{2x}^{(1)}\partial_X v_{2x}^{(1)} = -\alpha\beta\partial_X \psi^{(2)} \quad .....(19)$$

Again equating power of ε^2 from (6b)and(6c)

$$v_{iy}^{(2)} = \frac{\lambda}{\Omega}\partial_X v_{iz}^{(1)}\ ;\ v_{iz}^{(2)} = \frac{-\lambda}{\Omega}\partial_X v_{iy}^{(1)} \quad .....(20)$$

Using equations (12-20), we get the ZK equation of the form

$$\frac{\partial\psi^{(1)}}{\partial\tau} + A\psi^{(1)}\frac{\partial\psi^{(1)}}{\partial X} + \frac{\partial}{\partial X}\left(B\frac{\partial^2\psi^{(1)}}{\partial X^2} + C\frac{\partial^2\psi^{(1)}}{\partial Y^2}\right) = 0 \quad ......(21)$$

where

$$A = \frac{\begin{array}{l} \{[3\alpha^2\beta^2(1 - z_i\mu_i + \mu_{se} + \mu_{ce}) - 3 + \\ (1 - z_2\mu_2 + \mu_{se} + \mu_{ce}) \\ \mathrm{X}\left(\dfrac{3\alpha_i^2\beta_i^2}{\left(1-\dfrac{p_1}{\lambda^2}\right)^3} + \dfrac{p_1\alpha_i^2\beta_i^2}{\lambda^2\left(1-\dfrac{p_1}{\lambda^2}\right)^3}\right)] \\ -\lambda^4[\dfrac{\mu_{se}}{\sigma_{se}^2}\{\dfrac{(\kappa_{se}-1/2)(\kappa_{se}+1/2)}{(\kappa_{se}-3/2)^2}\} + \\ \dfrac{\mu_{ce}}{\sigma_{ce}^2}\{\dfrac{(\kappa_{ce}-1/2)(\kappa_{ce}+1/2)}{(\kappa_{ce}-3/2)^2}\}]\} \end{array}}{\begin{array}{l} 2\lambda(1 + \alpha\beta(1 - z_i\mu_i + \mu_{se} + \mu_{ce}) + \\ (1 - z_2\mu_2 + \mu_{se} + \mu_{ce})\dfrac{2\alpha_i\beta_i}{\left(1-\dfrac{p_1}{\lambda^2}\right)^2} \end{array}}$$

$$B = \frac{\lambda^3}{\begin{array}{l} 2\lambda(1 + \alpha\beta(1 - z_i\mu_i + \mu_{se} + \mu_{ce}) + \\ (1 - z_2\mu_2 + \mu_{se} + \mu_{ce})\dfrac{2\alpha_i\beta_i}{\left(1-\dfrac{p_1}{\lambda^2}\right)^2} \end{array}}$$

$$C = \frac{\lambda^3\left(\begin{array}{l} (1 + (1 - z_2\mu_2 + \mu_{se} + \mu_{ce}) \\ \mathrm{X}\left(\dfrac{\lambda^2\alpha_i\beta_i}{\Omega^2(\lambda^2 - p_1)} + \dfrac{\lambda^2 p_2\alpha_i\beta_i}{\Omega^2(\lambda^2 - p_1)^2}\right) \end{array}\right)}{\begin{array}{l} 2\lambda(1 + \alpha\beta(1 - z_i\mu_i + \mu_{se} + \mu_{ce}) + \\ (1 - z_2\mu_2 + \mu_{se} + \mu_{ce})\dfrac{2\alpha_i\beta_i}{\left(1-\dfrac{p_1}{\lambda^2}\right)^2} \end{array}}$$

Solution of the ZK Equation

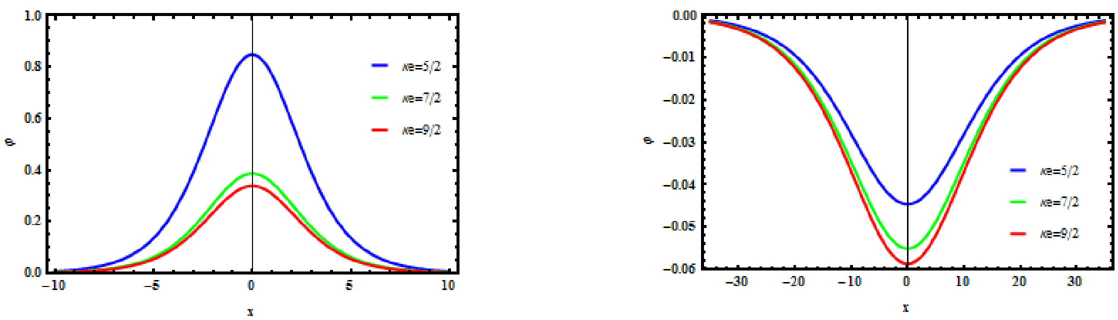
The solution of the ZKequation can be written as

$$\psi = \psi_m Sech^2(\frac{\chi}{\omega})$$

where $\chi = l\mathrm{X} + lY - u_0\tau$, $\psi_m = \dfrac{3u_0}{lA}$ is the amplitude and $\omega = 2\sqrt{\dfrac{l^3B + l_x l_y^2 C}{u_0}}$ is the width of the soliton.

Discussions

Though our equations are valid for arbitrary values of charge numbers z_1 and z_2 on the dust particles we are interested, in this paper, on parameters relevant to comet Halley. The density of hydrogen ions observed at comet Halley was $4.95\,\mathrm{cm}^{-3}$ at a temperature of $8 \times 10^4 K$. The solar electron temperature was $2 \times 10^5\,\mathrm{K}$ [25]. The negatively charged ions were detected at an energy of 1eV, with densities $\leq 1\,\mathrm{cm}^{-3}$ in the 7-19 amu peak [26]. Therefore we choose a majority ion density $n_{i0} = 4.95\,\mathrm{cm}^{-3}$ and temperature $T_i = 8 \times 10^4 K$, hot electron temperature $T_{se} = 2 \times 10^5\,\mathrm{K}$ and photo-electron temperature $T_{ce} = 2 \times 10^4\,\mathrm{K}$. Negatively and positively charged oxygen ions are considered in lieu of negatively and positively charged dust with densities of $n_{10} = 0.05\,\mathrm{cm}^{-3}$ and $n_{20} = 0.5\,\mathrm{cm}^{-3}$ respectively. The temperature of negatively and positively charged oxygen is taken as $T_1 = 1.16 \times 10^4 K$ [26].



(A) (B)

Figure 1 ψ vs.x for different kappa values

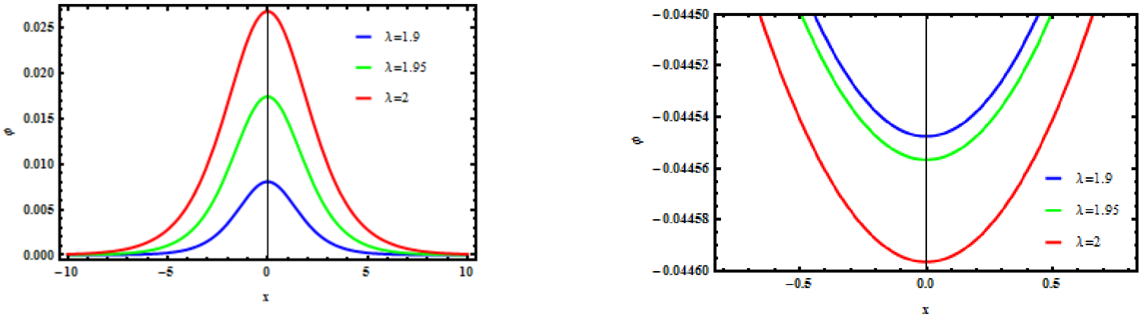
Figure 1 depicts the variation of the amplitudes ofsolitary waves for different kappa values:ie. figure 1A shows the variation of compressive solitary waves ($z_2 = 6$) and figure 1B for rarefactivesolitary wave ($z_2 = 1$) for different kappa values. The other common parameters used are:

$\lambda = 2$, $u_0 = 0.1$, $n_{10} = 0.05\,\mathrm{cm}^{-3}$, $n_{20} = 0.5\,\mathrm{cm}^{-3}$, $n_{i0} = 4.95\,\mathrm{cm}^{-3}$, $T_{ce} = 2 \times 10^4\,\mathrm{K}$, $T_{se} = 2 \times 10^5\,\mathrm{K}$, $T_i = 8 \times 10^4 K$, $T_1 = 1.16 \times 10^4 K$, $z_1 = z_i = 1$, $\kappa_{ce} = 5/2$, $\kappa_{se} = 11/2$ and $B_0 = 8 * 10^{-5} G$.

From the figures, it is seen that amplitude of the compressive solitary waves decreases as kappa indices increase, while the magnitude of the amplitude of the rarefactivesolitary wave increases as kappa decreases.

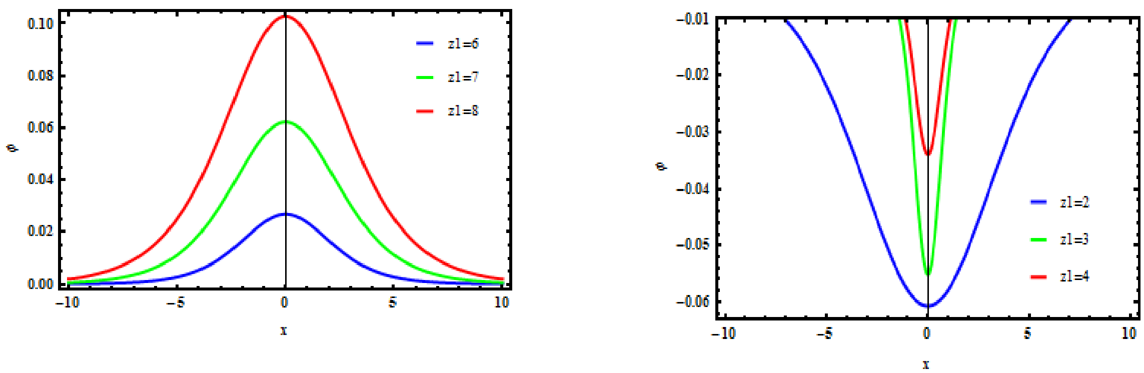
Figure 2 shows the variation of solitaryprofile for different Mach numbers; figure 2A is for compressive and figure 2B for rarefactivesolitons. The parameters used are same as figure 1 except

$z_1 = 6$, $z_2 = 1$, $\kappa_{ce} = 5/2$ (for figure 2A) and $z_1 = z_2 = 1$ $\kappa_{ce} = 5/2$ (for figure 2B). From the figures it is seen that as the Mach number increase, magnitude of the amplitude of both solitary waves increases.



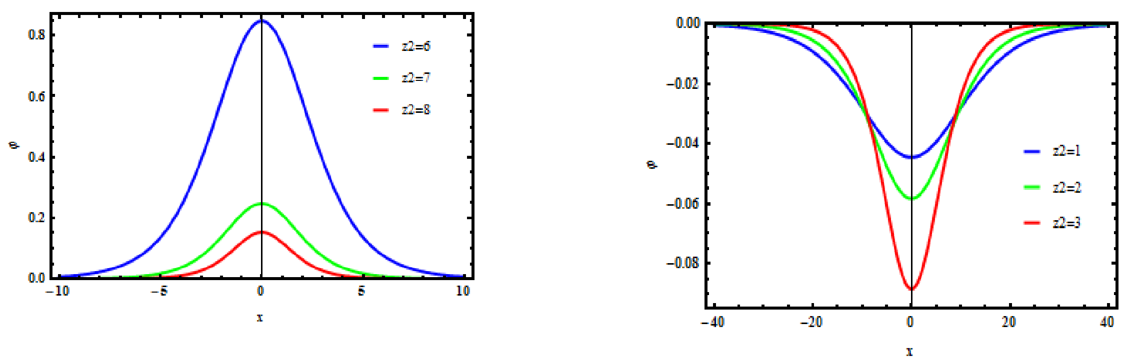
(A) (B)

Figure 2 ψ vs. x for different λ lamda values



(A) (B)

Figure 3 ψ vs. x for different negative dust charge numbers.



(A) (B)

Figure 4 ψ vs. x for different positive dust charge numbers

Figure 3 shows the variation of solitary wave amplitudes for different negative dust charge numbers. It is seen that in the proposed plasma supports both kind of solitary waves; ie. compressive (figure 3A) and rarefactive(figure 3B) for higher and lower negative charge numbers respectively. The other parameters remain same as figure 1. From the plots, it is seen that as negative charge number increases the amplitude of the solitary wave increases for both type of solitary waves.

Figure 4 shows the effect of the variation of the values of positive dust charge numbers on the solitary wave. As in the previous case (figure 3), it is seen that the higher and lower values of charge number supports both kind of solitary waves. However, the variation on positive dust charge numbers affects the value of amplitude of solitaryprofilesoppositely: that is as positive dust charge number increases the amplitude of compressive solitary wave decreases, while the magnitude of the amplitude of the rarefactivesolitary wave increases.

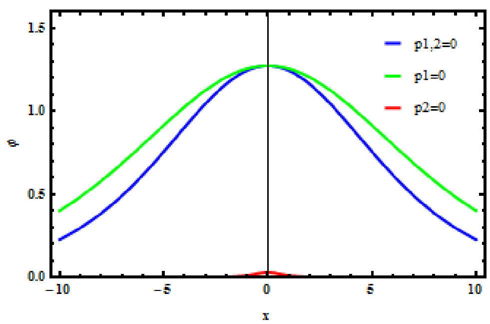


Figure 5 ψ vs. x for different pressure values of ions

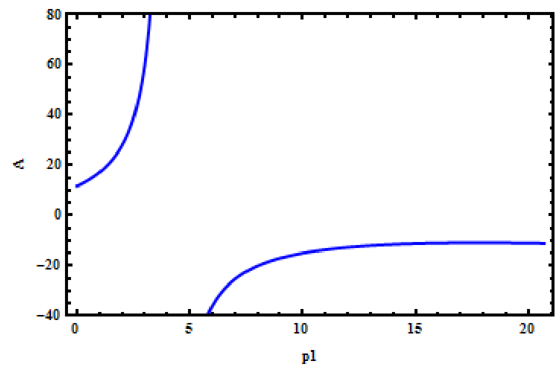


Figure 6 A (nonlinearity coefficient) vs. p_1 (parallel pressure of ions)

The effect of pressure anisotropy of ions is studied next in figure 5. It is seen that for the cases of $p_1 = p_2 = 0$ and $p_1 = 0$, $(p_2 \neq 0)$, do not effect very much the amplitude of the solitary waves; but for the case of $p_2 = 0$ (and $p_1 \neq 0$), the amplitude of the solitary wave decreases very much: that is parallel pressure has a significant effect on the amplitude of the solitary wave.

Finally figure 6, depicts the variation of nonlinear coefficient for different values of parallel pressure. From the figure, it is seen that for given set of values, both type of solitary waves ($A > 0$;compressiveand $A < 0$; rarefactive) can be observed. However, rarefactivesolitary wave can exist for larger values of parallel pressure of ions.

Conclusions

We have studied the effect of anisotropic pressure of ions on solitary wave profiles in a five component dusty plasma consisting of kappa described photo-electrons and hot electrons negatively and positively charged oxygen ions and ions. Solitary structures are obtained from ZK equations. From the plots it is seen that the parallel pressure has a stronger influence on the amplitude of the solitary wave structures. Further, for the proposed plasma, both positive and negative polarity solitons exist for higher and lower values of charge numbers respectively. In addition, as spectral indices increases the magnitude of the amplitude of the solitary structure varies oppositely; however, themagnitude of the amplitude increases with an increase of Mach number for both type of solitons.

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