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Higher Order Effects on Ion-acoustic Solitary Waves in a Multicomponent Plasma with Two-temperature Isothermal Electrons

B. Ghosh[1*], S. Banerjee[2], S. R. Majumdar[3], A. Sinhamahapatra[4]

1. Department of Physics, Jadavpur University, Kolkata-700032, India.
2. Department of Electronics, Vidyasagar College,Kolkata, India
3. Department of Physics, B N Mahavidyalaya, Itachuna, Hooghly, India
4. Department of Mathematics, B N Mahavidyalaya, Itachuna, Hooghly, India

*Corresponding author: Associate Professor. B. Ghosh, E-mail: bsdvghosh@gmail.com

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ABSTRACT

Using integral form of governing equations in terms of pseudopotential the effects of higher order nonlinearity and dispersion on the propagation of ion-acoustic solitary waves have been studied in a multicomponent plasma consisting of two types of cold positive ions and two- temperature isothermal electrons. Expressions for soliton width and Mach number as a function of soliton amplitude have been obtained including third order effects. Higher order solitons are shown to move faster than the lowest order soliton but with smaller amplitude and width.

Keywords: Solitary waves; Multicomponent plasma; Higher order effects; Two-temperature electrons

INTRODUCTION

Theoretical study of ion-acoustic waves was first undertaken by Washimi and Taniuti [1] by using a greatly simplified situation. From experimental observations [2, 3] it was found that experimental results did not match with theoretically predicted values. Thereafter, to remove the discrepancy between theoretical and experimental results, many authors [4-7] tried to incorporate physically more realistic conditions in their theoretical analyses and obtained important many important results, some of which have been experimentally verified. In some space environments and experimental situations such as hot turbulent plasmas in thermonuclear devices, hot cathode discharge plasmas, strong electron beam – plasma interaction experiments electrons can be found to have two-temperatures. The presence of two-temperature electrons in plasma gives rise to many interesting characteristics in nonlinear propagation of waves including the excitation of ion-acoustic solitary waves and double layers in plasmas [8-11]. Space plasmas are known to have multispecies composition .Such plasmas can also be produced in the laboratories. Thus it is important to study nonlinear wave propagation in multicomponent plasmas with two-temperature electrons.

Nonlinear wave propagation in multicomponent plasma with two types of ions and two-temperature electrons has been studied by a number of authors [12-16]. It has been shown that a small percentage of the cooler component of electrons leads to effects qualitatively different from those obtained for a plasma having only one-temperature electron species. In all these investigations [12-16] reductive perturbation method was used considering up to second order nonlinearity and dispersive effects. As the consideration of higher order terms give theoretical values more closer to the experimental results, researchers have also attempted to consider the contribution of third order nonlinear term in the derivation of soliton width and velocity by using a pseudopotential technique [17,18] which is different from standard perturbation technique. Here one uses integral form of governing equations in terms of pseudopotential. The advantage of this method over reductive perturbation method is that instead of solving a second order inhomogeneous differential equation at each order one has to solve a first order inhomogeneous equation at each order except at the first.

Recently this technique has been successfully used by some authors [19-21] to investigate the effects of higher order nonlinear and dispersive terms on the propagation of ion-acoustic solitary waves in different plasma systems. Das and Maunder [19] have applied this method to investigate the effects of higher order nonlinear and dispersive terms on the propagation of ion-acoustic solitary waves in a plasma containing isothermal electrons in presence of warm ions; Das, Majumdar and Paul [20] have applied this technique to study ion-acoustic solitary waves in a multicomponent plasma consisting of warm ions and two-component nonisothermal electrons. Isothermal distribution of electrons is more commonly assumed in various plasma environments. Majumdar, Paul and Roy Chowdhury [21] have considered the effects of negative ion in presence of two-temperature isothermal electrons by applying the same method.

Nonlinear propagation of ion-acoustic waves has also been studied by several authors in plasma with two positive ions and two-temperature isothermal electrons [22-26] by using standard reductive perturbation technique. So far as we know no one has considered the effects of higher order nonlinearity and dispersive effects on ion-acoustic solitary waves in plasmas with two positive ions and two-temperature isothermal electrons The purpose of the present paper is to address this problem. In the present investigation we have expressed soliton width and Mach number as a function of amplitude considering third order effect. We have also studied soliton behavior at the critical stage.

The paper is organized as follows: Starting from the basic equations we first derive the nonlinear evolution equation and then find solitary wave solutions at different orders. Next we consider the critical stage and finally discuss the results.

BASIC EQUATIONS

We consider a collisionless, unmagnetized plasma consisting of two types of cold positive ions and two temperature isothermal electrons The plasma dynamics in one dimension in such a system is given by the following set of dimensionless equations:

$$\frac{\partial n_{is}}{\partial t}+\frac{\partial}{\partial x}(n_{is}v_{is})=0 \qquad (1)$$

$$\frac{\partial v_{is}}{\partial t}+v_{is}\frac{\partial v_{is}}{\partial x}+\mu_{is}\frac{\partial \phi}{\partial x}=0 \qquad (2)$$

$$\frac{\partial^2\phi}{\partial x^2}=n_{el}+n_{eh}-\sum_{s=1,2}n_{is} \qquad (3)$$

Where s = 1, 2 stands for the two types of positive ions, v_{is} is the velocity of the ions having mass m_{is} and number density n_{is}. n_{el} and n_{eh} are the densities of low and high temperature electrons respectively. n_0 is the equilibrium number density of ions. k_B is the Boltzmann constant. ϕ is the electrostatic potential, $\mu_{is}=m_{i1}/m_{i2}$ is the mass ratio of two types of positive ions. T_{eff} is the effective temperature of the plasma defined by

$$T_{eff}=\frac{T_{el}.T_{eh}}{\mu T_{eh}+\nu T_{el}} \qquad (4)$$

where $\mu=n_{i10}$ and $\nu=n_{i20}$ are the unperturbed number densities of low and high temperature electrons respectively.
The charge neutrality condition in the plasma is given by

$$n_{i10}+n_{i20}=\mu+\nu=1 \qquad (5)$$

The isothermal electron densities are given by

$$n_{el}=\mu e^{\frac{\phi}{\mu+\nu\beta}} \qquad (6)$$

$$n_{eh}=\nu e^{\frac{\beta\phi}{(\mu+\nu\beta)}} \qquad (7)$$

where $\beta=T_{el}/T_{eh}$ is the ratio of temperatures of the two types of electrons.

In the above Eqs.(1)-(7) ions and electron densities are normalized with respect to the equilibrium number density of ions n_0 , the distances are normalized by the Debye length $\lambda_D=\left(k_BT_{eff}/4\pi e^2n_0\right)^{1/2}$, time by the ion plasma period $\omega_{is}^{-1}=\left(m_{is}/4\pi e^2n_0\right)^{1/2}$, velocities by ion-acoustic speed $C_{is}=\left(k_BT_{eff}/m_{is}\right)^{-\frac{1}{2}}$ and potential ϕ by k_BT_{eff}/e.

In order to get a solitary wave solution we assume that the dependent variables depend on a single independent variable ξ, where $\xi=x-Vt$ in which V is the velocity of the solitary wave. In terms of ξ, Eq. (3) can be rewritten as

$$\frac{d^2\phi}{d\xi^2}=n_{el}+n_{eh}-\sum_{s=1,2}n_{is} \qquad (8)$$

Expressing Eqs.(1) and (2) in terms of ξ and using the boundary conditions

$n_{is}\to 1,\phi\to 0$ as $\xi\to\pm\infty$

we obtain

$$\sum_{s=1,2}n_{is}=\sum_{s=1,2}n_{s0}\left(1-\frac{2\mu_{is}}{V^2}\right)^{1/2} \qquad (9)$$

Substituting in Eq. (8) for η_{el}, η_{eh} and $\sum n_{is}$ respectively from (6), (7) and (9) we get,

$$\frac{d^2\phi}{d\xi^2}=\Delta_1\phi+\Delta_2\phi^2+\Delta_3\phi^3+\Delta_4\phi^4 \qquad (10)$$

where,

$$\Delta_1=1-\frac{\mu_{is}}{V^2}$$

$$\Delta_2=\frac{\mu+\nu\beta^2}{2(\mu+\nu\beta)^2}-\frac{3}{2}.\frac{\mu_{is}{}^2}{V^4}$$

$$\Delta_3=\frac{\mu+\nu\beta^3}{6(\mu+\nu\beta)^3}-\frac{5}{2}.\frac{\mu_{is}{}^3}{V^6}$$

$$\Delta_4=\frac{\mu+\nu\beta^4}{24(\mu+\nu\beta)^4}-\frac{35}{8}.\frac{\mu_{is}{}^4}{V^8} \qquad (11)$$

SOLITARY WAVE SOLUTIONS AT DIFFERENT ORDERS

Integrating Eq. (10) under the conditions

$\frac{d\phi}{dx}\to 0,\phi\to 0$ as $\xi\to\pm\infty$

we get

$$\frac{\varepsilon}{2}\left(\frac{d\phi}{dx}\right)^2=\frac{1}{2}\Delta_1\phi^2+\frac{1}{3}\Delta_2\phi^3+\frac{1}{4}\Delta_3\phi^4+\frac{1}{5}\Delta_4\phi^5 \qquad (12)$$

in which we have stretched the ξ -coordinate according to the relation

$$x = \varepsilon^{\frac{1}{2}}\xi \tag{13}$$

Here ε is a small parameter measuring the weakness of dispersion. We now make the following perturbation expansions for ϕ and V

$$\phi = \varepsilon\phi^{(1)} + \varepsilon^2\phi^{(2)} + \varepsilon^3\phi^{(3)} + \cdots$$
$$V = V_0 + \varepsilon V^{(1)} + \varepsilon^2 V^{(2)} + \varepsilon^3 V^{(3)} + \cdots \tag{14}$$

From the linear dispersion relation $(\Delta_1)_0 = 0$ we get the linear velocity of the solitary wave as

$$V_0 = (\mu_{is})^{\frac{1}{2}} \tag{15}$$

Using the expansion (14) in Eqs. (11) we obtain

$$\Delta_1 = \varepsilon\delta_1^{(1)} + \varepsilon^2\delta_1^{(2)} + \varepsilon^3\delta_1^{(3)}$$
$$\Delta_2 = \delta_2^{(0)} + \varepsilon\delta_2^{(1)} + \varepsilon^2\delta_2^{(2)} + \varepsilon^3\delta_2^{(3)}$$
$$\Delta_3 = \delta_3^{(0)} + \varepsilon\delta_3^{(1)} + \ldots \tag{16}$$
$$\Delta_4 = \delta_4^{(0)}$$

Where,

$$\delta_1^{(1)} = \frac{2V^{(1)}}{V_0}, \quad \delta_1^{(2)} = \frac{2\mu_{is}}{V_0^3}\left[V^{(2)} - \frac{3}{2}\cdot\frac{V^{(1)^2}}{V_0}\right]$$

$$\delta_1^{(3)} = \frac{2\mu_{is}}{V_0^3}\left[V^{(3)} - \frac{5}{2}\cdot\frac{V^{(1)^3}}{V_0^2}\right], \quad \delta_2^{(0)} = \frac{\mu + \nu\beta^2}{2(\mu+\nu\beta)^2} - \frac{3}{2}\cdot\frac{\mu_{is}^2}{V_0^4}$$

$$\delta_2^{(1)} = \frac{6\mu_{is}V^{(1)}}{V_0^3}, \quad \delta_2^{(2)} = -\frac{6V^{(1)^2}}{V_0^3}$$

$$\delta_3^{(0)} = \frac{\mu + \nu\beta^3}{6(\mu+\nu\beta)^3} - \frac{5}{2}\cdot\frac{\mu_{is}^3}{V_0^6}, \quad \delta_3^{(1)} = \frac{16V^{(1)}}{V_0}$$

$$\delta_4^{(0)} = \frac{\mu + \nu\beta^4}{24(\mu+\nu\beta)^4} - \frac{35}{8}\cdot\frac{\mu_{is}^4}{V_0^8} \tag{17}$$

Substituting the expansions (14) in Eq. (10) we get a sequence of equations for $\phi^{(i)}$ and the equation for $\phi^{(i)}$ at each order becomes a first order inhomogeneous differential equation for $i > 1$.

FIRST ORDER SOLUTION

In the first order we get the following equation for $\phi^{(i)}$:

$$\frac{1}{2}\left(\frac{d\phi^{(1)}}{dx}\right)^2 = \frac{1}{2}\delta_1^{(1)}\phi^{(1)^2} + \frac{1}{3}\delta_2^{(0)}\phi^{(1)^3} \tag{18}$$

The soliton solution of this equation, which vanishes at $x = \pm\infty$ and attains a maximum at $x = 0$ is given by

$$\phi^{(1)} = \alpha_1 \sec h^2\eta \tag{19}$$

where amplitude of the first order soliton is

$$\alpha_1 = -\frac{3}{2}\frac{\delta_1^{(1)}}{\delta_2^{(0)}} = -\frac{3V^{(1)}}{V_0}\left[\frac{\mu+\nu\beta^2}{2(\mu+\nu\beta)^2} - \frac{3}{2}\cdot\frac{\mu_{is}^2}{V_0^4}\right]^{-1} \tag{20}$$

And $\eta = \frac{1}{2}\sqrt{\delta_1^{(1)}}x = \frac{1}{2}\sqrt{\frac{2V^{(1)}}{V_0}}x$ (21)

in which $V^{(1)} = -\frac{\alpha_1 V_0}{3}\left[\frac{\mu+\nu\beta^2}{2(\mu+\nu\beta)^2} - \frac{3}{2}\cdot\frac{\mu_{is}^2}{V_0^4}\right]$ (22)

The Mach number correct up to first order is

$$M_1 = \frac{V}{V_0} = 1 - \frac{\alpha_1}{3}\left[\frac{\mu+\nu\beta^2}{2(\mu+\nu\beta)^2} - \frac{3}{2}\cdot\frac{\mu_{is}^2}{V_0^4}\right] \tag{23}$$

It is important to note that the perturbed part $V^{(1)}$ of the expansion for V in (14) remains unspecified and hence the amplitude of the soliton, α_1, can be changed by varying $V^{(1)}$.

SECOND ORDER SOLUTION

Going to the next order we get the second order solution as

$$\phi^{(2)} = \left(a_2 + b_2 \sec h^2\eta\right)\sec h^2\eta \tag{24}$$

$$a_2 = \frac{2\alpha_0^2}{\delta_1^{(1)}}\left[\frac{\delta_2^1}{3} + \frac{\delta_3^0}{2}\alpha_0\right]$$

$$b_2 = -\frac{\alpha_0^3\delta_3^{(0)}}{2\delta_1^{(1)}} \tag{25}$$

$$V^{(2)} = \frac{3}{2}\frac{V^{(1)^2}}{V_0} \tag{26}$$

The solitary wave solution up to second order is

$$\phi_2 = \phi^{(1)} + \phi^{(2)}$$
$$= \alpha_2(1 + \alpha_{22}\tanh^2\eta)\sec h^2\eta \tag{27}$$

where $\alpha_2 = \alpha_1 + a_2 + b_2$ and $\alpha_{22} = -b_2/\alpha_2$.

The Mach number correct up to second order is

$$M_2 = 1 + \frac{V^{(1)}}{V_0} + \frac{V^{(1)^2}}{2V_0^2} \tag{28}$$

Where $V^{(1)}$ is given by Eq. (22).

THIRD ORDER SOLUTION

In the next order which is at the order ε^5 we get the following solution

$$\phi^{(3)} = \left[a_3 + b_3\tanh^2\eta + c_3\tanh^4\eta\right]\sec h^2\eta \tag{29}$$

where,

$$a_3 = \frac{2(a_2+b_2)^2}{\delta_1^{(1)}}\left(\frac{\delta_1^{(1)}}{2\alpha_1} + \delta_2^{(0)}\right) + \frac{2\alpha_1(a_2+b_2)}{\delta_1^{(1)}}\left(\delta_2^{(1)} + \frac{\delta_2^{(1)}\alpha_1}{3}\right)$$

$$+\frac{2\alpha_1}{\delta_1^{(1)}}\left[\frac{\delta_3^{(1)}\alpha_1}{4}+\delta_3^{(0)}\left(a_2+b_2\right)+\frac{\delta_4^{(0)}\alpha_1^2}{5}\right]$$

$$b_3=4b_2\left(a_2+b_2\right)\left[\frac{1}{\alpha_1}+\frac{\delta_2^{(0)}}{\delta_1^{(1)}}\right]+\frac{2b_2}{\delta_1^{(1)}}\left[\alpha_1\delta_1^{(1)}+\frac{b_2\delta_1^{(1)}}{2\alpha_1}\right]$$

$$+\frac{2\alpha_1^2}{\delta_1^{(1)}}\left[\delta_3^{(0)}\left(a_2+2b_2\right)+\frac{\alpha_1\delta_3^{(1)}}{4}+\frac{2}{5}\alpha_1^2\delta_4^{(0)}\right]$$

$$c_3=\frac{2\alpha_1^2}{3\delta_1^{(1)}}\left[\delta_3^{(0)}b_2+\frac{\alpha_1\delta_4^{(0)}}{5}\right]-\frac{2b_2^2}{3}\left[\frac{2}{\alpha_1}+\frac{\delta_2^{(0)}}{\delta_1^{(1)}}\right] \quad (30)$$

The secularity condition gives

$$V^{(3)}=-\frac{5}{2}.\frac{V^{(1)^3}}{V_0^2} \quad (31)$$

Using the solutions for $\phi^{(1)}$, $\phi^{(2)}$ and $\phi^{(3)}$ as given respectively by (19), (23) and (27) in Eq. (14) we get the following expression for ϕ correct up to order ε^3 terms

$$\phi=\alpha_3\left[1+\alpha_{23}\tanh^2\eta+\alpha_{43}\tanh^4\eta\right]\operatorname{sec}h^2\eta \quad (32)$$

$$\alpha_3=\alpha_1+a_2+b_2+a_3 \quad (33)$$

$$\alpha_{23}=\frac{b_3-b_2}{\alpha_3},\quad \alpha_{43}=\frac{c_3}{\alpha_3} \quad (34)$$

in which 'α_3' may be identified as the solitary wave amplitude correct up to ε3 terms.
Using the expressions for $V^{(1)}$, $V^{(2)}$ and $V^{(3)}$ as given respectively by (22), (26) and (31) we get from Eq. (14) the following expression for the Mach number correct up to order ε^3 terms

$$M_3=\frac{V}{V_0}=1+\frac{V^{(1)}}{V_0}+\frac{3}{2}.\frac{V^{(1)^2}}{V_0^2}-\frac{5}{2}.\frac{V^{(1)^3}}{V_0^3} \quad (35)$$

The soliton amplitude 'α_3' is a function of $V^{(1)}$ and so eliminating $V^{(1)}$ between (33) and (35) we can express M_3 as a function of soliton amplitude 'α_3'. Defining the width '*D*' of the soliton as half the value of the width of the pulse at a height of 0.42 of its amplitude, we find that the width '*D*' of the soliton can be obtained from the relation

$$D=\frac{2\eta_D}{\sqrt{\frac{V_0}{2V^{(1)}}}} \quad (36)$$

where ηD is the positive root of the following equation for η,

$$\alpha_4\tanh^6\eta+\left(\alpha_2-\alpha_4\right)\tanh^4\eta+\left(1-\alpha_2\right)\tanh^2\eta-0.58=0 \quad (37)$$

Eliminating $V^{(1)}$ between (33) and (36) we can express soliton width '*D*' as a function of the soliton amplitude 'α_3'.

CRITICAL CASE

The nonlinear coefficient $\delta_2^{(0)}$ in Eq. (18) which is an integral form of KdV equation, may be either positive or negative depending on the relative values of μ (unperturbed number density of cooler component of electron) and β (the ratio of temperature of cooler component of electron and hotter component of electron). If the coefficient $\delta_2^{(0)}$ is positive a compressional soliton solution is obtained. On the other hand if the nonlinear coefficient $\delta_2^{(0)}$ becomes negative refractive soliton solution is obtained. In the critical case the nonlinear coefficient $\delta_2^{(0)}$ vanishes and the soliton becomes a *sechη* profile instead of the usual $sech^2\eta$ profile. To study the critical state $\delta_2^{(0)}=0$ we make the following perturbation expansion for ϕ and V:

$$\phi=\varepsilon^{\frac{1}{2}}\phi^{(1)}+\varepsilon\phi^{(2)}+\varepsilon^{\frac{3}{2}}\phi^{(1)}+\cdots$$

$$V=V_0+\varepsilon V^{(1)}+\varepsilon^2V^{(2)}+\varepsilon^3V^{(3)}+\cdots \quad (38)$$

$$x=\varepsilon^{1/2}\xi \quad (39)$$

Substituting all these in the energy Eq. (10) we get in the first order

$$\left(\frac{d\phi^{(1)}}{dx}\right)^2=\delta_1^{(1)}\phi^{(1)^2}+\frac{1}{2}\delta_3^{(0)}\phi^{(1)^4} \quad (40)$$

It has a solution of the form

$$\phi^{(1)}=A\operatorname{sech}\eta \quad (41)$$

Where

$$A^2=-\frac{2\delta_1^{(1)}}{\delta_3^{(0)}} \text{ and } \quad \eta=\frac{1}{2}\sqrt{\delta_1^{(1)}}x \quad (42)$$

In the critical case $\delta_2^{(0)}=0$ and hence

$$\frac{\mu+\nu\beta^2}{2(\mu+\nu\beta)^2}-\frac{3}{2}.\frac{\mu_{is}^2}{V_0^4}=0 \quad (43)$$

Using the relation $V_0=(\mu_{is})^{1/2}$, we get a quadratic equation in β

$$\nu\left(1-3\nu\right)\beta^2-6\mu\nu\beta+\mu\left(1-3\mu\right)=0 \quad (44)$$

Hence in the critical stage the value of β is given by

$$\beta_c=\frac{6\mu\nu\pm\sqrt{36\mu^2\nu^2-4\nu\left(1-3\nu\right).\mu\left(1-3\mu\right)}}{2\nu\left(1-3\nu\right)} \quad (45)$$

RESULTS AND DISCUSSIONS

In this paper we have studied higher order nonlinear and dispersive effects on the amplitude, Mach number and width of the soliton in a multicomponent plasma containing two cold ions and two-temperature isothermal electrons by carrying out calculations up to third order. The secularity conditions at each order gives corrections to the velocity of the solitary wave at the corresponding higher order. It is shown that higher order nonlinear and dispersion terms have significant contributions to the formation of solitons in the plasma under consideration. The nonlinear coefficient $\delta_2^{(0)}$ in Eq. (18) is a function of μ (or ν) and β. The sign of $\delta_2^{(0)}$ depends on the relative values of μ(or ν) and β . When $\delta_2^{(0)}$ is positive a compressional soliton solution is obtained and when $\delta_2^{(0)}$ becomes negative a rarefactive soliton is obtained. Keeping all other parameters fixed if we slowly increase the value of β the state of soliton changes from compressional mode to rarefactive mode. To investigate all these effects and the characteristics of solitary waves numerical calculations are made for two different positive ion pairs, namely (H^+, He^+) and (He^+, Ar^+) for which μ_{is} = 0.25 and 0.10 respectively.

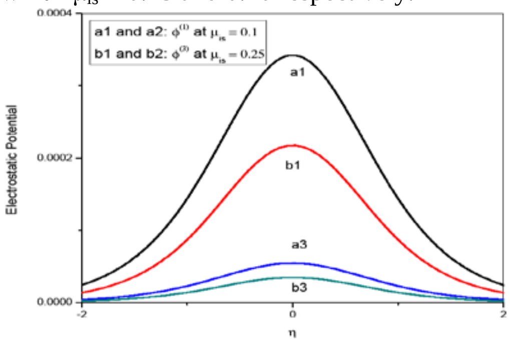

Fig 1: Solitary wvae profile in first and third orders for two different mass ratio. The curves labeled a_1 and b_1 corresponds to 1st order and curves labeled a_3 and b_3 corresponds to 3rd order. Other parameters: μ = 0.1, ν = 0.9, β = 0.15, v_0 = 0.1, $V^{(1)}$ = 0.0017.

In Fig. 1 we have plotted both the lowest and higher order solitary wave solutions. We note that the higher order correction terms give a negative contribution to the solitary wave profile. Higher order solution has smaller amplitude and width than that of the lowest order soliton. Also we note that higher values of the mass ratio μis make the soliton amplitude and width smaller.

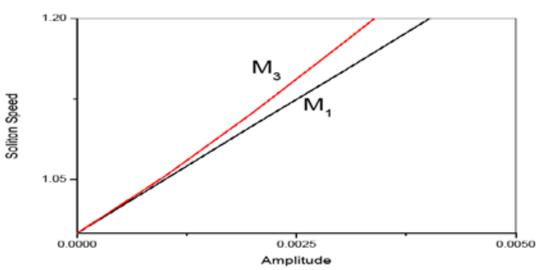

Fig 2: Dependence of solitons speed on solitons amplitude in 1st and 3rd order. Parameters: μ = 0.1, ν = 0.9, β = 0.15, v0 = 0.1.

Dependence of Mach number on soliton amplitude has been shown in Fig. 2. We find that higher order solitons move faster than the lowest order solitons. Higher values of the mass ratio, $\mu_{is,}$ make the Mach number smaller.

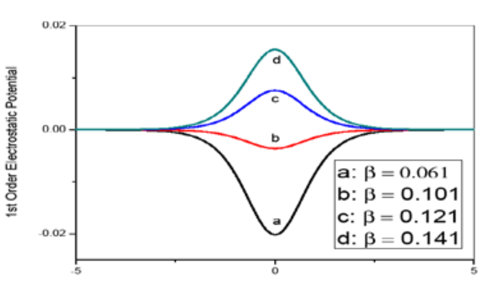

Fig 3: Compressive and rarefactive solitons depending on the values of the ratio of the temperatures of the two types of electrons: μ = 0.1, ν = 0.9, β = 0.15, v_0 = 0.3, $V^{(1)}$ = 0.0015.

In Fig.3 we show that formation of both compressive and rarefactive type of solitons is possible depending on the values of the ratio of the temperatures of the two types of electrons, β, .Keeping all other parameters fixed if this temperature ratio is slowly increased the nature of the soliton changes from compresional mode to rarefactive mode at certain critical value. We have considered the critical case separately. At critical stage the soliton has *sech* profile as given by Eq. (41), instead of the usual $sech^2$ as given by Eq. (19).

Finally we would like to point out that the results presented in the paper may be useful in the study of nonlinear wave phenomena in many space plasma environments. The mathematical technique used here has advantage over other conventional methods and may be adopted to study higher order nonlinear and dispersive effects on solitary waves in other plasma environments.

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