Journal of Fusion Energy, Vol. 22, No. 3, September 2003 (© 2004)

Electron Acoustic Solitons

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Electron acoustic solitons in collisionless and weakly relativistic plasmas are studied. The Krylov–Bogoliubov–Mitropolsky perturbative technique is employed to obtain the nonlinear Schrodinger wave equation. We have numerically investigated modulational instability for different values of the streaming velocity. Graphs have been plotted to see the change in amplitude and inverse width by varying different plasma parameters.

KEY WORDS: Solitons; KdV; plasma; electron acoustic.

INTRODUCTION

Electrons have been found to be consisting of two distinct groups, one hot and one cold [1–3] in many types of plasmas such as those in fusion devices and in the auroral ionosphere. For analytical purposes, it is sometimes convenient to introduce the so-called two temperature electron model [2,4,5] in which the electron density is given by $n_e = n_{eh} + n_{ec}$, where $n_{eh} = n_{0h} \exp\left(\frac{e\phi}{T_h}\right)$ and $n_{ec} = n_{0c} \exp\left(\frac{e\phi}{T_c}\right)$. The unperturbed densities and temperatures of the two species of electrons are denoted by n_{0h}, T_{eh}, and n_{0c}, T_{ec}. One assumes in this model that both species of electrons are in thermal equilibrium. Such an assumption breaks down if the temperature of one species is so low that its thermal velocity becomes much less than the characteristic velocity of the problem. An example of this is the case of a cold electron beam in a hot plasma [6]. An electron acoustic (EA) wave can exist in a two-temperature plasma. It is basically an acoustic (electrostatic) wave in which the inertia is provided by the cold electrons and the restoring force comes from the pressure of hot electrons. The ions play the role of a neutralizing background, that is, the ion dynamics does not influence the EA waves because the EA wave frequency is much larger than the ion plasma frequency.

After the discovery of the existence of the EA waves, the conditions for the EA wave propagation as well as its linear properties have been investigated by several authors. Berthomier *et al.* [7] have studied EA solitons in an electron-beam plasma system. A theoretical investigation has been carried out for obliquely propagating EA solitary waves by Mamun *et al.* [8]. In this paper, the nonlinear propagation of EA waves has been studied employing the Krylov–Bogoliubov–Mitropolsky (KBM) perturbation method [9]. It plays a powerful role in describing the long-term behavior of the solution. KBM method has shown to be useful in obtaining the nonlinear Schrodinger equation for the amplitude modulation of a monochromatic plane wave as well as the reductive perturbation method or the derivative expansion method [9]. Recently, ion envelope solitons in electron–positron–ion plasmas have been studied by Salahuddin *et al.* [10] using the KBM method. Nonlinear ion acoustic waves have also been studied by several authors, as for example Refs. [11–15].

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We shall derive the nonlinear Schrodinger wave equation in this paper for an electron acoustic wave using the KBM method along with the numerical results.

The paper is organized as follows: In the next two sections, we have presented the basic equations of our model and reduced our set of equations to the NLS equation by using the KBM perturbative technique. In the "Results and Discussion" section, we have discussed the results that have been obtained by the numerical investigation. In this regard, modulational instability and the variation of the amplitude and the inverse width of the soliton with various plasma parametres have been carefully studied. In the "Conclusion" section, we have referred to some recent work on the EA solitons and also summed up the main results presented in this paper.

FORMULATION

In order to derive an expression for EA waves, the basic set of equations for cold electrons is given by the equations of motion and continuity:

$$[\partial_t + v_c \cdot \nabla]\left(\frac{v_c}{\beta}\right) - e/m_{0c}\partial_z\phi = 0, \tag{1}$$

where $\beta = 1/(1 - \frac{v_c^2}{c^2})^{1/2}$ is the relativistic factor.

$$\partial_t n_c + \nabla \cdot (n_c v_c) = 0. \tag{2}$$

The hot electrons and ions follow the Boltzmann distribution given, respectively, as

$$n_{eh} = n_{e0}\exp(-e\phi/T_h) \tag{3}$$

and

$$n_i = n_{i0}\exp(e\phi/T_i). \tag{4}$$

Ions have been assumed to follow the Bolltzmann distribution by various authors [16–18] and the system of equations is closed by Poisson's equation,

$$\partial_x^2\phi = 4\pi e(n_{i0}\exp(e\phi/T_i) - n_{e0}\exp(-e\phi/T_h) - n_c) \tag{5}$$

Equation (1) is the momentum equation of the cold electrons for a weakly relativistic case incorporating the effect of streaming of the cold electrons. n_c, n_{eh}, and n_i are the number densities of cold and hot electrons and ions, respectively. v_c is the velocity of the cold electrons, ϕ is the electrostatic potential, T_{eh}, T_i are the temperatures of the hot electrons and ions respectively, m_0 is the rest mass of the cold electrons and $\pm e$ is the charge of the electrons and ions.

The quasineutrality condition at plasma equilibrium is satisfied through

$$n_{0h} + n_{0c} = n_{0i}, \tag{6}$$

where n_{e0}, n_{c0}, and n_{i0} are the unperturbed number densities of hot and cold electrons and ions respectively.We expand all the physical quantities n_c, v_c, and ϕ in terms of the perturbation parameter-ϵ, as

$$\begin{bmatrix} n_c \\ v_c \\ \phi \end{bmatrix} = \begin{bmatrix} n_0 \\ v_0 \\ 0 \end{bmatrix} + \epsilon\begin{bmatrix} n_1(a,\bar{a},\psi) \\ v_1(a,\bar{a},\psi) \\ \phi_1(a,\bar{a},\psi) \end{bmatrix} + \epsilon^2\begin{bmatrix} n_2(a,\bar{a},\psi) \\ v_2(a,\bar{a},\psi) \\ \phi_2(a,\bar{a},\psi) \end{bmatrix} + \epsilon^3\begin{bmatrix} n_3(a,\bar{a},\psi) \\ v_3(a,\bar{a},\psi) \\ \phi_3(a,\bar{a},\psi) \end{bmatrix} + \cdots \tag{7}$$

While employing the KBM perturbation method, we assumed that n_1, v_1 , ϕ_1, and all higher orders in ϵ quantities depend on x and t only through $a, \bar{a}$, and ψ where a, and $\bar{a}$ are the complex amplitudes and ψ is the phase factor defined as $\psi = kx - \omega t$. Here k and ω are the wave number and frequency, respectively. The time and space derivatives of the complex amplitude are slowly varying functions of x and t and are given by

$$\partial_t a = \epsilon A_1(a,\bar{a}) + \epsilon^2 A_2(a,\bar{a}) + \epsilon^3 A_3(a,\bar{a}) + \cdots \tag{8}$$

$$\partial_x a = \epsilon B_1(a,\bar{a}) + \epsilon^2 B_2(a,\bar{a}) + \epsilon^3 B_3(a,\bar{a}) + \cdots \tag{9}$$

The unknown $A's$ and $B's$ are arbitrary functions and are used to eliminate the secular terms that appear subsequently.

Substituting equations (7),(8) and (9) into equations(1), (2) and (5), we obtain the linear dispersion relation of EA waves by collecting terms of ϵ-order and eliminating all terms in favor of ϕ_1 and further by assuming a starting solution of the form:

$$\phi_1 = ae^{i\psi} + \bar{a}e^{-i\psi},$$

which gives the first order solutions:

$$n_1 = \left(\frac{-1}{4\pi e\lambda_s^2}\right)(1 + k^2\lambda_s^2)(ae^{i\psi} + \bar{a}e^{-i\psi}) \tag{11}$$

and

$$v_1 = \left(\frac{-(\omega - kv_0)}{4\pi en_0k\lambda_s^2}\right)(1 + k^2\lambda_s^2)(ae^{i\psi} + \bar{a}e^{-i\psi}) \tag{12}$$

and leads to the dispersion relation given by:

$$(\omega - kv_0) = kc_{es}\left(\frac{\delta}{\sigma(1 + k^2\lambda_s^2)}\right)^{1/2}, \tag{13}$$

where

$$\sigma = 1 + \frac{3v_0^2}{2c^2},$$

$$c_{es} = \left(\frac{T_i}{m_0(1 + \delta + \alpha)}\right)^{1/2},$$

$$\lambda_s = \left(\frac{T_i}{4\pi n_{0h}e^2(1 + \delta + \alpha)}\right)^{1/2},$$

$$\alpha = \frac{T_i}{T_h},$$

and

$$\delta = \frac{n_{0c}}{n_{0h}}$$

are the relativistic factor, modified EA speed, modified Debye length respectively. v_0 is the weakly relativistic streaming velocity of the cold electrons, α is the ratio of ion to hot electron temperature ratio, and δ is the ratio of number density of cold electrons to hot electrons. In the limit $\sigma = 1$ and $v_0 = 0$, we retrieve the dispersion relation as obtained in Ref. [18] for a modified EA mode.

We note here that group velocity for the EA wave is given by:

$$v_g = v_0 \pm \frac{c_{es}}{(\sigma/\delta)^{1/2}(1 + \lambda_s^2k^2)^{3/2}}. \tag{14}$$

HIGHER ORDER TERMS AND THE NLS EQUATION

In this section, we shall collect the ϵ^2-*order* terms and ϵ^3-*order* terms by substituting equations (7), (8) and (9) in equaitons (1), (2) and (5), respectively. For ϵ^2-*order*, we eliminate the second order variables in favor of ϕ_2 and further by setting the secular terms equal to zero we get $A_{1+}v_gB_1 = 0$ and obtain the following solution for ϕ_2:

$$\phi_2 = c_1 + c_2(e^{i\psi} + e^{-i\psi}) + \alpha_1a^2e^{2i\psi} + \text{c.c} + \gamma_1. \tag{15}$$

Here c_1, c_2, and $\gamma_1$are the integration constants.

By using the above results, we obtain explicit expressions of n_2 and v_2, which are

$$n_2 = \alpha_2a^2e^{2i\psi} + \left(\frac{ik}{2\pi e}B_1 - \alpha_3c_2\right)e^{i\psi} + \gamma_2\alpha_4 + \frac{n_{i0}e^2}{T_i^2}a\bar{a} + \text{c.c} \tag{16}$$

and

$$v_2 = \alpha_5a^2e^{2i\psi} + \left[\frac{-ie(1 + k^2\lambda_s^2)}{m_0\delta kc_{es}^2}(A_1 + v_0B_1) + i\alpha_6B_1 - \alpha_7c_2\right]e^{i\psi} - \alpha_8\gamma_2 + \gamma_3 + \text{c.c}, \tag{17}$$

where

$$\alpha_1 = \frac{\frac{3v_0e^2k(1+k^2\lambda_s^2)}{2\sigma^{3/2}m_0^2c^2c_{es}} - \frac{3ke^2(1+k^2\lambda_s^2)}{2m_0^2\delta c_{es}^2} - \frac{\delta kc_{es}^2n_{i0}e^2}{2n_0T_i^2(1+k^2\lambda_s^2)}}{\frac{ek(1+4k^2\lambda_s^2)}{m_0(1+k^2\lambda_s^2)} - \frac{ek}{m_0}},$$

$$\alpha_2 = \frac{n_{i0}e^2}{2T_i^2} - \left(\frac{k^2}{\pi e} + \frac{1}{4\pi e\lambda_s^2}\right)\alpha_1,$$

$$\alpha_3 = \frac{k^2}{4\pi e} + \frac{1}{4\pi e\lambda_s^2},$$

$$\alpha_4 = -\frac{1}{4\pi e\lambda_s^2},$$

$$\alpha_5=\left[\frac{-e^2(1+k^2\lambda_s^2)^{3/2}}{m_0^2\sigma^{1/2}\delta^{3/2}c_{es}^3} - \left\{\frac{\delta^{1/2}k^2c_{es}}{\pi e n_0\sigma^{1/2}(1+k^2\lambda_s^2)^{1/2}}+\frac{\delta^{1/2}c_{es}}{4\pi e n_0\sigma^{1/2}\lambda_s^2(1+k^2\lambda_s^2)^{1/2}} + \frac{\delta^{1/2}e^2 n_{i0}c_{es}}{2\sigma^{1/2}n_0T_i^2(1+k^2\lambda_s^2)}\right\}\alpha_1\right],$$

$$\alpha_6 = \left[\frac{\delta^{1/2}kc_{es}}{2\pi e n_0\sigma^{1/2}(1+k^2\lambda_s^2)^{1/2}} - \frac{e(1+k^2\lambda_s^2)^{1/2}}{m_0\sigma^{1/2}\delta^{1/2}kc_{es}}\right],$$

$$\alpha_7 = \left[\frac{\delta^{1/2}k^2c_{es}}{4\pi e n_0\sigma^{1/2}(1+k^2\lambda_s^2)^{1/2}} + \frac{\delta^{1/2}c_{es}}{4\pi e n_0\sigma^{1/2}\lambda_s^2(1+k^2\lambda_s^2)^{1/2}}\right],$$

$$\alpha_8 = \frac{\delta^{1/2}c_{es}}{4\pi e n_0\sigma^{1/2}\lambda_s^2(1+k^2\lambda_s^2)^{1/2}},$$

and

$$\gamma_2 = c_1 + \gamma_1.$$

The constants of integration γ_2 and γ_3 are assumed to be real and arbitrary with respect to ψ, and they depend on a and $\bar{a}$ alone.

The constants γ_2 and γ_3 are obtained from the ϵ^3-*order* terms in the following manner. We collect ϵ^3-*order* terms and eliminate all unknowns in favor of ϕ_3 and the removal of the secularity producing constant terms yield the following expressions for γ_2 and γ_3:

$$\gamma_2=\left[\frac{\left\{\frac{12v_0e(1+k^2\lambda_s^2)}{c^2\sigma^2\delta c_{es}^2m_0}\pm\frac{e\lambda_s^2}{\left(\frac{\sigma}{\delta}\right)^{\frac{1}{2}\frac{1}{2}}(1+k^2\lambda_s^2)^{3/2}\lambda_i^2T_i\delta c_{es}}\mp\frac{(1+k^2\lambda_s^2)^{3/2}}{2\sigma^{1/2}\delta^{1/2}\lambda_s^2 e n_0 c_{es}}\right\}}{\left\{\frac{\mp 1}{\sigma^{1/2}\delta^{1/2}c_{es}(1+k^2\lambda_s^2)^{3/2}}\mp\frac{(1+k^2\lambda_s^2)^{3/2}}{\sigma^{1/2}\delta^{1/2}c_{es}}\right\}}\right] \times a\bar{a}+R_1 \quad (18)$$

and

$$\gamma_3 = \left[\frac{\alpha_9}{\left(\frac{1}{(1+k^2\lambda_s^2)^3}\mp 1\right)} \mp \frac{3v_0e^2(1+k^2\lambda_s^2)}{m_0^2c^2\sigma^2c_{es}^2\delta^{3/2}}\right]a\bar{a} + R_2. \quad (19)$$

Here,

$$\alpha_9 = \left(\frac{3v_0(1+k^2\lambda_s^2)}{4\pi m_0c^2\lambda_s^2\sigma^2} \pm \frac{c_{es}\delta^{1/2}}{4\pi\sigma^{1/2}\lambda_i^2T_i(1+k^2\lambda_s^2)^{3/2}} \mp \frac{(1+k^2\lambda_s^2)^{3/2}}{2\sigma^{1/2}\delta^{1/2}m_0\lambda_s^2c_{es}}\right)\left(\frac{1}{n_0(1+k^2\lambda_s^2)} - \frac{1}{n_0}\right).$$

On the other hand, the removal of the secularity producing resonant terms yield:

$$\mathrm{i}(A_2 + v_gB_2) + P\left(B_1\partial_a + \overline{B_1}\partial_{\bar{a}}\right)B_1 = Qa^2\bar{a} + Ra \quad (20)$$

This is the NLS equation. The dispersion coefficient P, the nonlinearity interaction coefficient Q, and linear interaction coefficient R are given as:

$$P = -3/2\left(\frac{kc_{es}\lambda_s^2}{\left(\frac{\sigma}{\delta}\right)^{\frac{1}{2}\frac{1}{2}}(1+k^2\lambda_s^2)^{5/2}}\right) = \frac{1}{2}\frac{\mathrm{d}v_g}{\mathrm{d}k}, \quad (21)$$

and

$$Q = \left[\begin{array}{c} \mp\frac{3e^2k(1+k^2\lambda_s^2)^{1/2}}{4\sigma^{5/2}\delta^{\frac{1}{2}\frac{1}{2}}c_{es}c^2m_0^2} + \frac{3v_0ke^2(1+k^2\lambda_s^2)}{2\sigma^2c^2m_0^2\delta c_{es}^2} - \left\{\frac{\pm 3v_0kc_{es}\delta^{1/2}}{2c^2\sigma^{1/2}(1+k^2\lambda_s^2)^{1/2}} - k\right\}\alpha_5 \pm \left(\frac{\delta^{1/2}kc_{es}}{2n_0\sigma^{1/2}(1+k^2\lambda_s^2)^{1/2}}\right)\alpha_2 \\ \pm\frac{\delta^{1/2}kc_{es}}{8\pi n_0\sigma^{1/2}T_i\lambda_i^2(1+k^2\lambda_s^2)^{1/2}} \mp \left(\frac{\delta^{1/2}kc_{es}\lambda_s^2}{2\sigma^{1/2}(1+k^2\lambda_s^2)^{3/2}}\right)\left\{\frac{2\pi e^4n_{h0}}{T_h^3}\left(1+\frac{1+\delta}{\alpha^3}\right) + \frac{4\pi n_{h0}e^3}{T_h^2}\left(1-\frac{1+\delta}{\alpha^2}\right)\alpha_1\right\} \\ -\left(\frac{k}{2\sigma}+\frac{k}{2}\mp\frac{3v_0k\delta^{1/2}c_{es}}{2c^2\sigma^{3/2}(1+k^2\lambda_s^2)^{1/2}}\right)(\alpha_8\theta-\eta) \pm \frac{kc_{es}\delta^{1/2}}{2\sigma^{1/2}n_0(1+k^2\lambda_s^2)^{1/2}}\alpha_4\theta \\ \pm\frac{kc_{es}\delta^{1/2}\lambda_s^2}{2\sigma^{1/2}(1+k^2\lambda_s^2)^{3/2}}\left\{\frac{4\pi n_{h0}e^3}{T_h^2}\left(1-\frac{1+\delta}{\alpha^2}\right)\theta\right\} \end{array}\right], \quad (22)$$

$$R = \begin{bmatrix} -\left\{\frac{k}{2\sigma} + \frac{k}{2} \mp \frac{3v_0 k\delta^{1/2} c_{\mathrm{es}}}{2c^2\sigma^{3/2}(1+k^2\lambda_{\mathrm{s}}^2)^{1/2}}\right\}\alpha_8 \\ \pm\left\{\frac{kc_{\mathrm{es}}\delta^{1/2}}{2\sigma^{1/2} n_0 (1+k^2\lambda_{\mathrm{s}}^2)^{1/2}}\right\}\alpha_4. \\ \pm\frac{kc_{\mathrm{es}}\delta^{1/2}\lambda_{\mathrm{s}}^2}{2\sigma^{1/2}(1+k^2\lambda_{\mathrm{s}}^2)^{3/2}}\left\{\frac{4\pi n_{\mathrm{h0}} e^3}{T_{\mathrm{h}}^2}\left(1 - \frac{1+\delta}{\alpha^2}\right)\right\} \end{bmatrix} R_1 + \left[\left\{\frac{k}{2\sigma} + \frac{k}{2} \mp \frac{3v_0 k\delta^{1/2} c_{\mathrm{es}}}{2c^2\sigma^{3/2}(1+k^2\lambda_{\mathrm{s}}^2)^{1/2}}\right\}\alpha_8\right] R_2. \quad (23)$$

In the above expressions for P, Q, and R, θ and ϕ are given by

$$\theta = \left[\frac{\left\{\frac{12v_0 \mathrm{e}(1+k^2\lambda_{\mathrm{s}}^2)}{c^2\sigma^2\delta c_{\mathrm{es}}^2 m_0} \pm \frac{e\lambda_{\mathrm{s}}^2}{\left(\frac{\sigma}{\delta}\right)^{\frac{1}{2}\frac{1}{2}}(1+k^2\lambda_{\mathrm{s}}^2)^{3/2}\lambda_{\mathrm{i}}^2 T_{\mathrm{i}}\delta c_{\mathrm{es}}} \mp \frac{(1+k^2\lambda_{\mathrm{s}}^2)^{3/2}}{2\sigma^{1/2}\delta^{1/2}\lambda_{\mathrm{s}}^2 e n_0 c_{\mathrm{es}}}\right\}}{\left\{\frac{\mp 1}{\sigma^{1/2}\delta^{1/2}c_{\mathrm{es}}(1+k^2\lambda_{\mathrm{s}}^2)^{3/2}} \mp \frac{(1+k^2\lambda_{\mathrm{s}}^2)^{3/2}}{\sigma^{1/2}\delta^{1/2}c_{\mathrm{es}}}\right\}}\right] a\bar{a}$$

and

$$\eta = \left[\frac{\alpha_9}{\left(\frac{1}{(1+k^2\lambda_{\mathrm{s}}^2)^3} \mp 1\right)} \mp \frac{3v_0 e^2(1+k^2\lambda_{\mathrm{s}}^2)}{m_0^2 c^2\sigma^2 c_{\mathrm{es}}^2\delta^{3/2}}\right] a\bar{a}.$$

RESULTS AND DISCUSSION

In the present paper, we have used the multiple scale method, that is, the KBM method to obtain the nonlinear Schrodinger equation for collisionless and weakly relativistic plasmas. We know that the NLS equation leads to the formation of the envelope solitons when the wave becomes modulationally unstable. We have investigated the modulational instability and it has been found that beyond a critical wave number $k > k_{\mathrm{c}}$, the nonlinear wave becomes modulationally unstable and soliton formation takes place (Figure 1). Figure 1 also shows that the critical wave number k_{c} decreases with the increasing streaming velocity. Graphs have also plotted between inverse width and amplitude of the soliton against various plasma parameters. The values of the plasma parameters namely cold electrons, hot electrons and ion number densities, ion temperature and hot electron temperature are $0.5/\mathrm{cm}^3$, $2.5/\mathrm{cm}^3$, $1.75/\mathrm{cm}^3$, 175 eV, and 250 eV respectively and they correspond to the dayside auroral zone [8]. The numerical investigation has shown that the inverse width κ of the soliton has a complex relationship with the wave number for different values of the streaming velocity while the amplitude of the soliton has been found to have an inverse relationship with the wave number for different values of the streaming velocity (Figures 2 and 3). Moreover, Figures 4 and 5 show that the amplitude of the soliton increases while the inverse width κ of the soliton decreases with the increasing number density of the cold electrons for different values of the streaming velocity.

CONCLUSION

In this paper, we have solved the problem of 1D EA in a collisionless and weakly relativistic

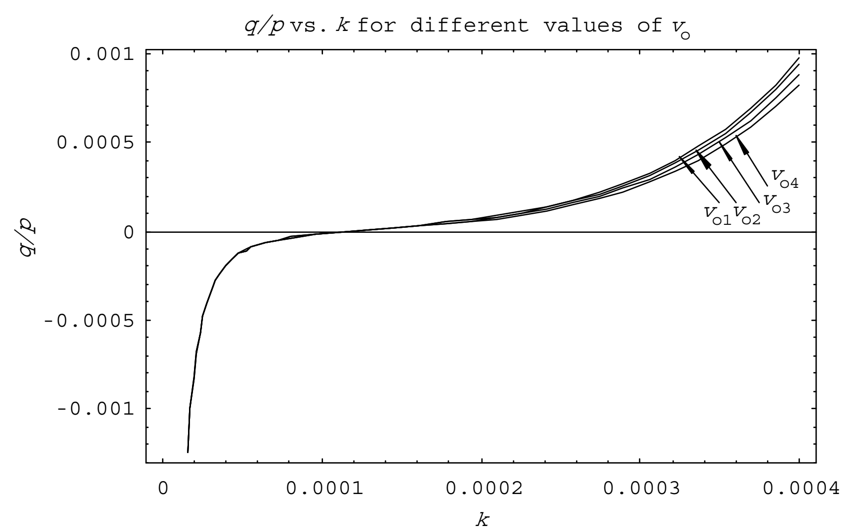

Fig. 1. $\frac{q}{p}$ versus k for $v_{01} = \frac{c}{10}$, $v_{02} = \frac{2c}{10}$, $v_{03} = \frac{3c}{10}$, and $v_{04} = \frac{4c}{10}$.

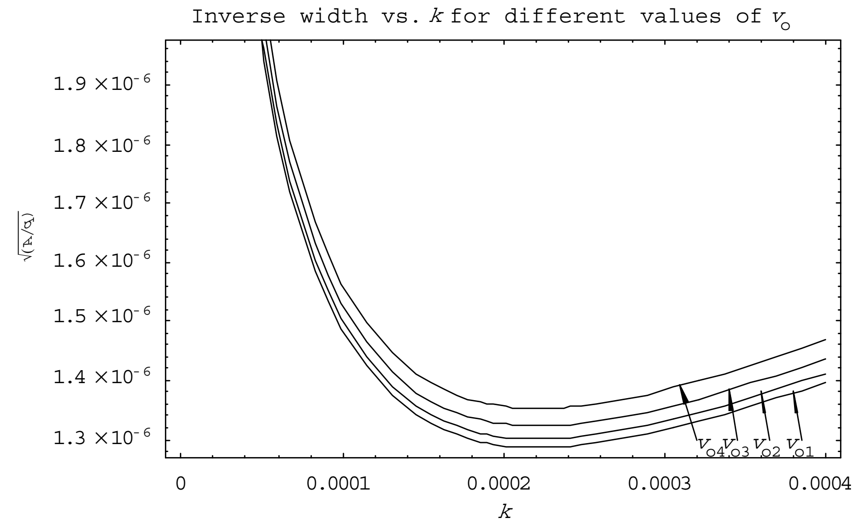

Fig. 2. Inverse width $\sqrt{\frac{A}{p}}$ versus k for $v_{01} = \frac{c}{10}, v_{02} = \frac{2c}{10}, v_{03} = \frac{3c}{10}$, and $v_{04} = \frac{4c}{10}$.

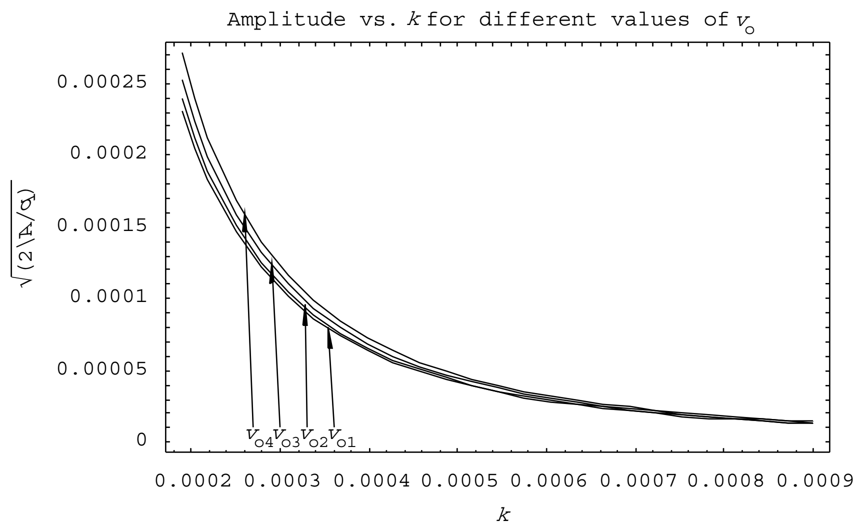

Fig. 3. Amplitude $\sqrt{\frac{2A}{p}}$ versus k for $v_{01} = \frac{c}{10}, v_{02} = \frac{2c}{10}, v_{03} = \frac{3c}{10}$, and $v_{04} = \frac{4c}{10}$.

plasma. KBM perturbation method has been employed to reduce our fluid equations into NLS. The variation of the EA solitons with the various plasma parameters have been numerically investigated. The values of the parameters correspond to the dayside auroral zone as mentioned above. It has been found that the amplitude and the inverse width of the soliton undergo significant changes with the variation of different plasma parameters.The linear EA mode has been clearly identified in the auroral cusp [19, 20] and in the large scale auroral radiating cavity [21] where electrons are accelerated downwards to produce visible auroras in the ionosphere. The observed solitary waves were, however, not interpreted in terms of EA solitons because they were known to form the potential wells [22–24]. Recently, Berthomier *et al.* [7] have shown that that the presence of electron beam in the plasma allows the existence of potential humps and electron density holes ans stressed to make a further anaysis to identify these structures as EA solitons. We, therefore, conclude by saying that our endeavor should be useful in order to understand the salient features of EA soliton in the Space plasmas with special reference to the auroral region.

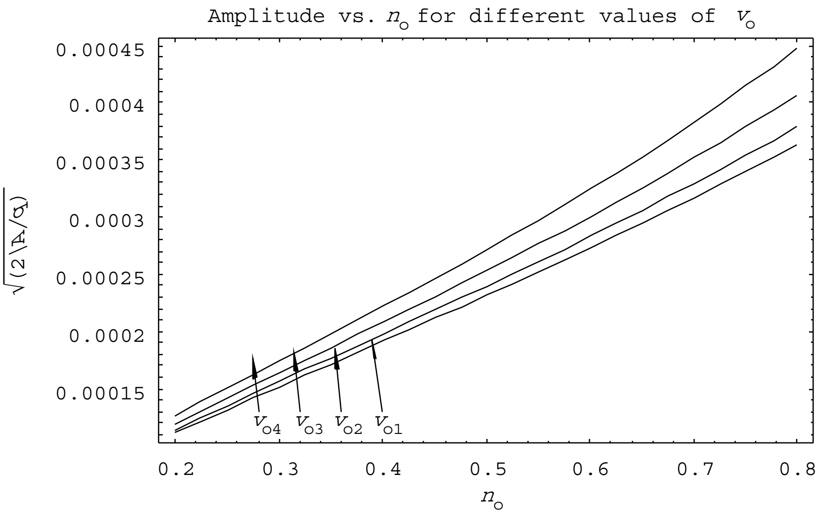

Fig. 4. Amplitude $\sqrt{\frac{2A}{p}}$ versus n_0 for $v_{01} = \frac{c}{10}, v_{02} = \frac{2c}{10}, v_{03} = \frac{3c}{10}$, and $v_{04} = \frac{4c}{10}$.

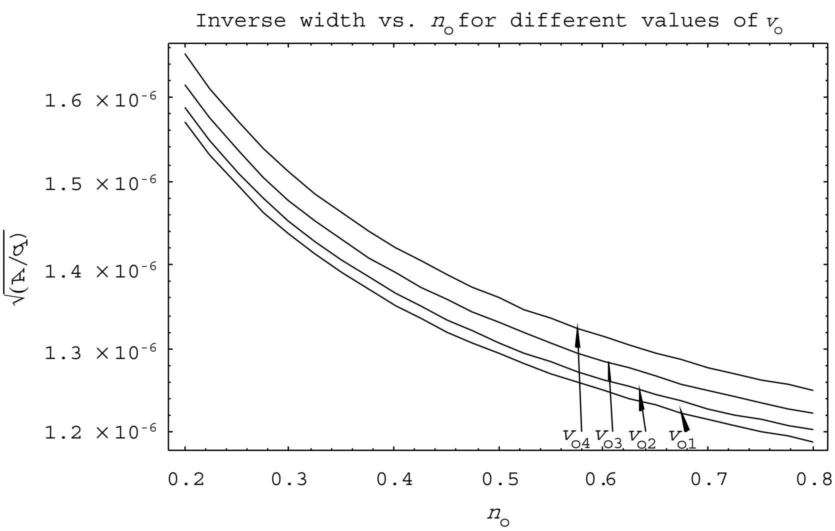

Fig. 5. Inverse width $\sqrt{\frac{A}{p}}$ versus n_0 for $v_{01} = \frac{c}{10}, v_{02} = \frac{2c}{10}, v_{03} = \frac{3c}{10}$, and $v_{04} = \frac{4c}{10}$.

ACKNOWLEDGMENTS

One of the authors W. M. would like to thank Ministry of Science and Technology, Pakistan for granting him the Split PhD Scholarship under which this research work has been carried out.

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