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EFFECTS OF NEGATIVE IONS ON THE ION–ACOUSTIC SOLITONS AND DOUBLE–LAYERS IN A RELATIVISTIC PLASMA

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Korteweg–de Vries equation for a relativistic plasma consisting of electrons, positive ions and negative ions has been derived using the reductive perturbation method for the study of ion–acoustic solitary waves. Near the critical density of negative ions for which the nonlinearity of Korteweg–de Vries equation vanishes, the modified Korteweg–de Vries equation has been derived. Formation of double layers is analysed from the mixed form of Korteweg–de Vries and modified Korteweg–de Vries equations. Profiles of ion–acoustic solitons and double layers are shown for the plasmas having (H^+, Cl^-) ions, (H^+, O^-) ions, (H^+, SF_5^-) ions and (He^+, SF_5^-) ions.

1. Introduction

Linear and nonlinear propagation of waves through a plasma consisting of electrons, positive ions and negative ions have been studied by many authors [1–6]. It has been found that negative ions have dominant role on the instability [7–9],

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wave–parameter shift [10–13] etc. of electromagnetic waves and also on the formation of ion–acoustic solitons [14–19] in plasma. Propagation of waves in a relativistic plasma having streaming ions has been found to be most interesting [20–22]. It has been observed that relativistic effect plays an important role on the formation of ion–acoustic solitons only in the presence of streaming of ions. Roychowdhury et al. [23–26] and other authors [27–32] investigated the propagation of ion–acoustic solitary waves and shocks incorporating different parameters, e.g. non–isothermality, two–temperature electrons etc. Very recently, Chakraborty et al. [33–35] considered the effect of negative ions on the formation of ion–acoustic solitons in relativistic plasmas. They have numerically estimated the width, amplitude and phase–velocity of ion–acoustic soliton for a model plasma having the negative ions which have short lifetimes (or small probability of existence).

In the present paper our motivation is to modify the results of Chakraborty et al. [33–35] for laboratory–produced negative ion–plasma, with e.g. (H^+, Cl^-) ions, (He^+, Cl^-) ions and (H^+, O^-) ions. We have also analysed the ion–acoustic solitons near the critical density of negative ions. The effect of negative ions on the ion–acoustic double layers for the laboratory plasma has also been studied.

2. *Basic equations*

We consider a collisionless, unmagnetized plasma consisting of warm electrons and cold positive and negative ions. The ions have uniform stream velocities. The velocities of the ions are relativistic. The plasma equations for the study of ion–acoustic wave are:
for positive ions:

$$\frac{\partial \overline{n}_i}{\partial \overline{t}} + \frac{\partial}{\partial \overline{x}}(\overline{n}_i \overline{u}_i) = 0, \tag{1}$$

$$\frac{\partial \overline{u}_{ir}}{\partial \overline{t}} + \overline{u}_i \frac{\partial \overline{u}_{ir}}{\partial \overline{x}} = -\frac{\partial \overline{\phi}}{\partial \overline{x}}, \tag{2}$$

and for negative ions:

$$\frac{\partial \overline{n}_j}{\partial \overline{t}} + \frac{\partial}{\partial \overline{x}}(\overline{n}_j \overline{u}_j) = 0, \tag{3}$$

$$\frac{\partial \overline{u}_{jr}}{\partial \overline{t}} + \overline{u}_j \frac{\partial \overline{u}_{jr}}{\partial \overline{x}} = \frac{1}{Q}\frac{\partial \overline{\phi}}{\partial \overline{x}}. \tag{4}$$

Poisson's equation reads

$$\frac{\partial^2 \overline{\phi}}{\partial \overline{x}^2} = n_e - \overline{n}_i + \overline{n}_j, \tag{5}$$

where

$$\overline{u}_{ir} = \frac{\overline{u}_i}{\sqrt{1 - \frac{\overline{u}_i^2}{\overline{c}^2}}},$$

$$\overline{u}_{jr} = \frac{\overline{u}_j}{\sqrt{1 - \frac{\overline{u}_j^2}{\overline{c}^2}}},$$

$$Q = \frac{m_j}{m_i},$$

$$\overline{n}_i = \frac{n_i}{n_0}, \;\; \overline{n}_j = \frac{n_j}{n_0}, \;\; \overline{\phi} = \frac{e\phi}{kT_e},$$

$$\overline{u}_i = \frac{u_i}{\sqrt{kT_e/m_i}}, \;\; \overline{u}_j = \frac{u_j}{\sqrt{kT_e/m_j}}, \tag{6}$$

$$\overline{x} = \frac{x}{\sqrt{kT_e/4\pi e^2 n_0}},$$

$$\bar{t} = t\sqrt{\frac{4\pi n_0 e^2}{m_{i,j}}}, \;\; \overline{c} = \frac{c}{\sqrt{kT_e/m_{i,j}}}.$$

n_e, n_i, n_j denote the densities of the electrons, positive ions and negative ions, respectively, n_0 is the unperturbed electron density, u_i and u_j are the velocities of positive and negative ions, ϕ is the electrostatic potential, k is the Boltzmann's constant and c is the velocity of light. The charge neutrality condition is $n_{i0} = 1 + n_{j0}$.

3. Derivation of Korteweg–de Vries and modified Korteweg–de Vries equations

For the study of ion–acoustic solitons and double layers, we derive the nonlinear equations from the basic Eqs. (1) to (5) using the stretched coordinates ξ and τ given below

$$\xi = \epsilon^{1/2}(x - \lambda t),$$

$$\tau = \epsilon^{3/2} t, \tag{7}$$

where ϵ is an expansion parameter and λ is the phase velocity of the wave. Moreover, we assume the field variables are perturbed in the following form (omitting the bar hereafter):

$$\begin{pmatrix} n_i \\ n_j \\ u_i \\ u_j \\ \phi \end{pmatrix} = \begin{pmatrix} n_{i0} \\ n_{j0} \\ u_{i0} \\ u_{j0} \\ \phi_0 \end{pmatrix} + \epsilon \begin{pmatrix} n_{i1} \\ n_{j1} \\ u_{i1} \\ u_{j1} \\ \phi_1 \end{pmatrix} + \epsilon^2 \begin{pmatrix} n_{i2} \\ n_{j2} \\ u_{i2} \\ u_{j2} \\ \phi_2 \end{pmatrix} + \cdots \tag{8}$$

$$(\phi_0 = 0),$$

where the first terms on the right–hand side represent the equilibrium values of the respective parameters. Second terms, third terms etc. represent the first order, second order etc. values of the parameters.

The boundary conditions which satisfy the basic equations are:

$$\begin{aligned} &\text{(i)} \quad n_e \to 1, \quad \phi \to 0 \\ &\text{(ii)} \quad n_i \to n_{i0}, \quad n_j \to n_{j0} \\ &\text{(iii)} \quad u_i \to u_{i0}, \quad u_j \to u_{j0} \end{aligned} \tag{9}$$

at $x \to \infty$.

Now, using Eqs. (7) and (8) in Eqs. (1) to (5) and equating first order power in ϵ, we obtain

$$\begin{aligned} n_{i_1} &= \frac{n_{i0}\phi_1}{r_i a_i^2}, \quad n_{j_1} = \frac{n_{j0}\phi_1}{Q r_j a_j^2}, \\ u_{i_1} &= \frac{\phi_1}{r_i a_i}, \quad u_{j_1} = \frac{\phi_1}{Q r_j a_j}, \\ \phi_1 &= n_{i_1} - n_{j_1}, \end{aligned} \tag{10}$$

where

$$a_i = \lambda - u_{i0}, \quad a_j = \lambda - u_{j0},$$

$$r_i = \frac{1 + 3u_{i0}^2}{2c^2} \ \text{ and } \ r_j = \frac{1 + 3u_{j0}^2}{2c^2}.$$

From Eq. (10), the first–order dispersion relation is obtained as

$$\frac{n_{i0}}{r_i a_i^2} + \frac{n_{j0}}{Q r_j a_j^2} = 1. \tag{11}$$

From the next higher–order equation in ϵ, we obtain

$$\frac{\partial n_{i_1}}{\partial \tau} - \lambda \frac{\partial n_{i_2}}{\partial \xi} + n_{i0} \frac{\partial u_{i_2}}{\partial \xi} + u_{i0} \frac{\partial n_{i_2}}{\partial \xi} + \frac{\partial}{\partial \xi}(n_{i_1} u_{i_1}) = 0, \tag{12}$$

$$\frac{\partial n_{j_1}}{\partial \tau} - \lambda \frac{\partial n_{j_2}}{\partial \xi} + n_{j0} \frac{\partial u_{j_2}}{\partial \xi} + u_{j0} \frac{\partial n_{j_2}}{\partial \xi} + \frac{\partial}{\partial \xi}(n_{j_1} u_{j_1}) = 0, \tag{13}$$

$$r_i \frac{\partial u_{i_1}}{\partial \tau} - a_i \frac{\partial u_{i_2}}{\partial \xi} + p_i u_{i_1} \frac{\partial u_{i_1}}{\partial \xi} = 0, \tag{14}$$

$$r_j \frac{\partial u_{j_1}}{\partial \tau} - a_j \frac{\partial u_{j_2}}{\partial \xi} + p_j u_{j_1} \frac{\partial u_{j_1}}{\partial \xi} = 0, \tag{15}$$

$$\frac{\partial^2 \phi_1}{\partial \xi^2} = \phi_2 + \frac{\phi_1^2}{2} + (n_{j_2} - n_{i_2}), \tag{16}$$

where

$$p_i = 1 + \frac{9u_{i0}^2}{2c^2} - \frac{3\lambda u_{i0}}{c^2} \quad \text{and}$$

$$p_j = 1 + \frac{9u_{j0}^2}{2c^2} - \frac{3\lambda u_{j0}}{c^2}. \tag{17}$$

Eliminating ϕ_2, n_{i_2}, n_{j_2}, u_{i_2} and u_{j_2} from Eqs. (12) to (16) and using Eq. (10), we derive the following Korteweg–de Vries equation

$$\frac{\partial \phi_1}{\partial \tau} + \frac{A_{ij}}{B_{ij}} \phi_1 \frac{\partial \phi_1}{\partial \xi} + \frac{1}{2B_{ij}} \frac{\partial^3 \phi_1}{\partial \xi^3} = 0, \tag{18}$$

where,

$$A_{ij} = \frac{1}{r_i^2 a_i^2 b_i} - \frac{1}{Q^2 r_j^2 a_j^2 b_j} + \left(\frac{p_i n_{i0}}{2 r_i^3 b_i^4} - \frac{p_j n_{j0}}{2Q^2 r_j^3 b_j^4} \right) - \frac{1}{2},$$

$$B_{ij} = \frac{1}{2} \left(\frac{n_{i0}}{r_i b_i^3} + \frac{n_{j0}}{Q r_j b_j^3} + \frac{1}{r_i a_i b_i} + \frac{1}{Q r_j a_j b_j} \right), \tag{19}$$

$$b_i = \frac{(\lambda - u_{i0})^2}{n_{i0}} \text{ and } b_j = \frac{(\lambda - u_{j0})^2}{n_{j0}}.$$

From Eq. (18), it is observed that when $A_{ij} \to 0$, ion–acoustic soliton will not exist. A_{ij} will be zero for certain values of the negative–ion concentration which can be obtained from the following relation,

$$n_{jc} = \left[\frac{2n_{i0}}{a_i^4 r_i^4} (a_i r_i - p_i) - 1 \right] \cdot \left[\frac{2}{Q^2 a_j^4 r_j^4} (Q a_j r_j - p_j) \right]^{-1}. \tag{20}$$

For the study of the ion–acoustic soliton near the critical density of negative ions given by Eq. (20), we employ the stretched coordinates

$$\xi = \epsilon(x - \lambda t) \text{ and } \tau = \epsilon^3 t. \tag{21}$$

Using Eqs. (8) and (21) in Eqs. (1) to (5), the equations for the first–order of ϵ are the same as given by Eq. (10). But, for the next higher order of ϵ, we obtain

$$-a_i \frac{\partial n_{i2}}{\partial \xi} + n_{i0} \frac{\partial u_{i2}}{\partial \xi} + \frac{\partial}{\partial \xi}(n_{i_1} u_{i_1}) = 0, \tag{22}$$

$$-a_j \frac{\partial n_{j2}}{\partial \xi} + n_{j0} \frac{\partial u_{j2}}{\partial \xi} + \frac{\partial}{\partial \xi}(n_{j_1} u_{j_1}) = 0, \tag{23}$$

$$-a_i r_i \frac{\partial u_{i2}}{\partial \xi} + p_i u_{i_1} \frac{\partial u_{i1}}{\partial \xi} = -\frac{\partial \phi_2}{\partial \xi}, \tag{24}$$

$$-a_j r_j \frac{\partial u_{j2}}{\partial \xi} + p_j u_{j_1} \frac{\partial u_{j1}}{\partial \xi} = \frac{1}{Q} \frac{\partial \phi_2}{\partial \xi}, \tag{25}$$

$$\phi_2 + \frac{\phi_1^2}{2} + n_{j2} - n_{i2} = 0. \tag{26}$$

Eliminating ϕ_2, n_{i_2}, n_{j_2}, u_{i_2} and u_{j_2} from Eqs. (22) to (26) and using Eq. (10), we finally obtain the modified Korteweg–de Vries equation

$$\frac{\partial \phi_1}{\partial \tau} + \frac{A'_{ij}}{2B_{ij}} \phi_1^2 \frac{\partial \phi_1}{\partial \xi} + \frac{1}{2B_{ij}} \frac{\partial^3 \phi_1}{\partial \xi^3} = 0, \tag{27}$$

where

$$A'_{ij} = \frac{1}{2} A_{ij}.$$

From Eqs. (18) and (27) we derive the following combined form of modified Korteweg–de Vries equation:

$$\frac{\partial \phi_1}{\partial \tau} + \frac{A_{ij}}{B_{ij}} \phi_1 \frac{\partial \phi_1}{\partial \xi} + \frac{A'_{ij}}{2B_{ij}} \phi_1^2 \frac{\partial \phi_1}{\partial \xi} + \frac{1}{2B_{ij}} \frac{\partial^3 \phi_1}{\partial \xi^3} = 0. \tag{28}$$

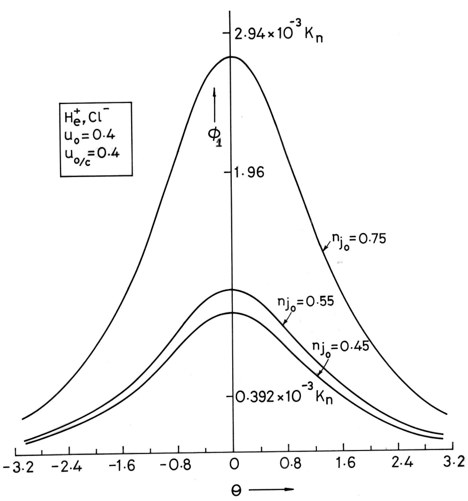
4. Ion–acoustic solitary wave

Equation (27) gives the ion–acoustic solitary wave solution at the critical density of negative ions,

$$\phi_1 = A \,\mathrm{sech}\, \left(\mu \xi - \frac{U \tau}{\delta} \right) = A \,\mathrm{sech}\, \Theta, \tag{29}$$

where A and δ are the amplitude and width of the soliton, respectively, given by

$$A = 2\sqrt{3} \frac{U}{\delta} \frac{1}{A'_{ij}} \tag{30}$$



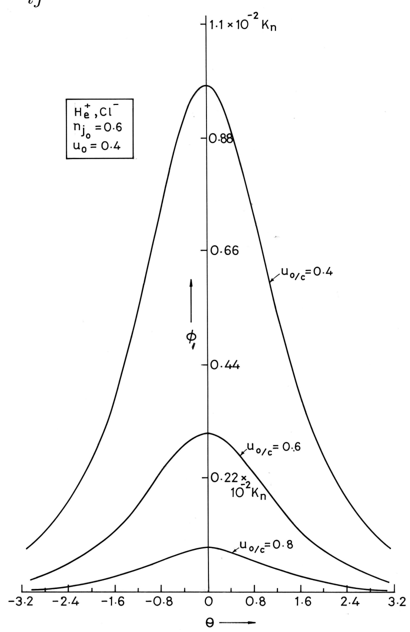


Fig. 1. Form of the solitary wave in the case when the ions are He$^+$, Cl$^-$ *for various values of* n_{j0}.

Fig. 2. The structure of the solitary wave when the ion are He$^+$, Cl$^-$ *for different values of* u_0/c *(right).*

and

$$\delta = \sqrt{\frac{\mu^3}{2B_{ij}U}}. \tag{31}$$

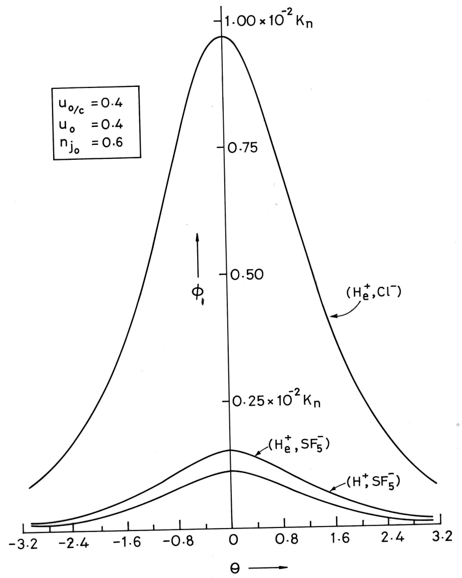


Fig. 3. The variation of the soliton profile with the ion content of the plasma.

From Eqs. (29)–(31), it is observed that the negative ions and the relativistic stream velocity of the ions have important role on the formation of ion–acoustic soliton in the plasma. To see the effect of negative ions and stream velocity on the solitons, we consider the plasmas having (H^+, SF_5^-), (He^+, Cl^-) and (He^+, SF_5^-) ions with different streaming velocities. Using the solitary wave solution (29) near the critical density of negative ions, the potential ϕ_1 is estimated and plotted in Figs. 1, 2 and 3. It is seen that for the increase of negative ion concentration (n_{j0}), the potential ϕ_1 increases. But, for the increase of mass ratio Q and u_0/c, the potential ϕ decreases. It is to be noted that the critical densities n_{jc} of negative ions for the non–existence of solitons are:

(i)	$n_{jc} = 0.74$	for $Q = 9$ (He^+, Cl^-),	$u_0 = 0.4$,	$u_0/c = 0.3$,
(ii)	$n_{jc} = 0.8$	for $Q = 16$ (H^+, O^-),	$u_0 = 0.4$,	$u_0/c = 0.3$,
(iii)	$n_{jc} = 0.85$	for $Q = 35.5$ (H^+, Cl^-),	$u_0 = 0.4$,	$u_0/c = 0.4$,
(iv)	$n_{jc} = 0.57$	for $Q = 9$ (He^+, Cl^-),	$u_0 = 0.6$,	$u_0/c = 0.5$,
(v)	$n_{jc} = 0.6$	for $Q = 9$ (He^+, Cl^-),	$u_0 = 0.9$,	$u_0/c = 0.8$.

4.1. Ion–acoustic double layers

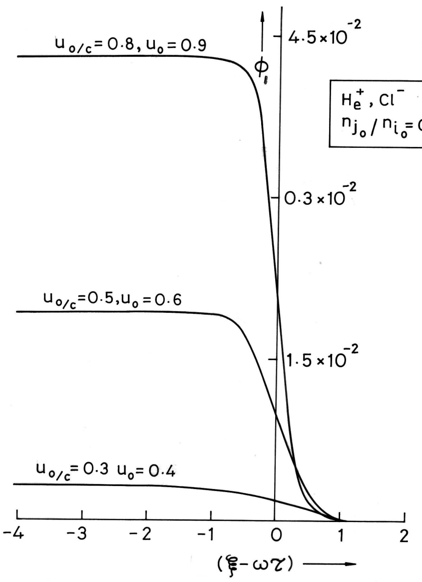
Equation (28) represents the ion–acoustic double layers in the plasma near critical density of negative ions. Solution of Eq. (28) for the double layers is

$$\phi_1 = \frac{1}{2}\Theta(A_{ij})\phi_m(1 - \tanh X), \tag{32}$$

where

$$X = \sqrt{-\frac{B_{ij}}{48}}\phi_m(\xi - \omega t). \tag{33}$$

It is seen that the quantities A_{ij} and B_{ij} depend on the plasma parameters i.e., density of negative ions, relativistic effect, streaming velocities of ions etc. To investigate the ion–acoustic double layers for various negative ion–plasmas having (H^+, O^-) ions, (H^+, Cl^-) ions and (He^+, Cl^-) ions, we have plotted Eq. (32) in Figs. 4, 5 and 6. In Fig. 4, it is seen that potential ϕ_1 is larger for large values of u_0/c and ϕ_1 falls more rapidly than at lower values of u_0/c, i.e. $u_0/c = 0.5$ and 0.3. Figure 5 shows that double layers are more prominent when the concentration of negative ions is large. But, from Fig. 6, we see that for small values of Q, strong double layers are generated.



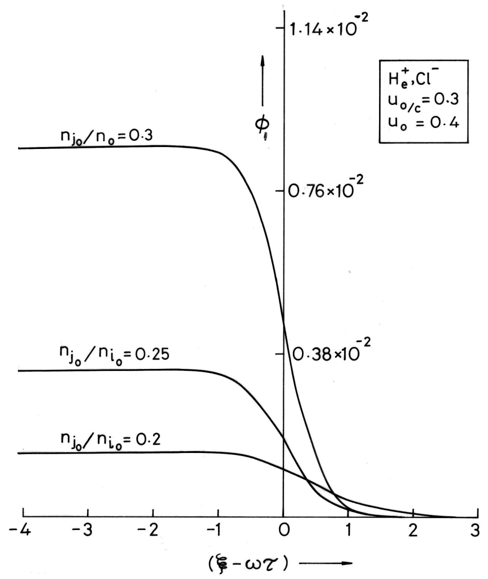


Fig. 4. The structure of the shock wave in the case of He^+, Cl^- *for* $n_{j0}/n_{i0} = 0.2$.

Fig. 5. The same form of the shock wave for various u_0/c *values (right).*

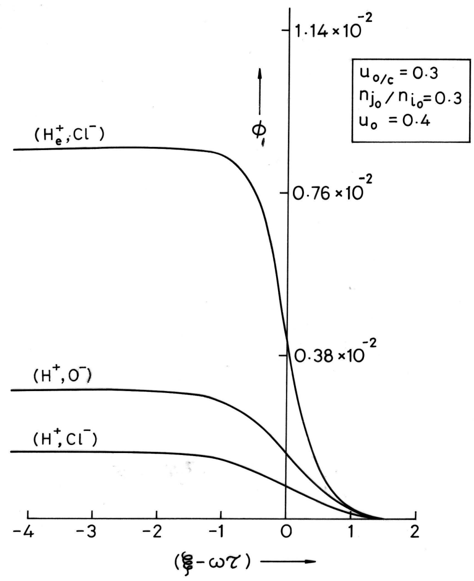


Fig. 6. Variation of the shock profile with ion content.

5. Concluding remarks

From our present study, we observe that negative ions have significant role on the formation of ion–acoustic solitons and double layers in a relativistic plasma having streaming of ions. We have only shown the profile of solitary waves and double layers. But, graphical representation of width and amplitude of the solitary wave will also show the importance of negative ions in the plasma. The effects of ionic temperatures are important for the occurence of solitons and double layers in a plasma [36–39]. So, inclusion of ionic temperature in our present analysis would give some fascinating characteristic of solitary and double layers in relativistic plasma. Experimental observations of ion–acoustic solitary wave in plasma were made by Ikezi et al. [40] and other authors [41–44]. In a negative–ion plasma, Nakamura et al. [45,46] and other authors [47,48] experimentally observed the ion–acoustic soliton and shocks. In astrophysical plasma and in laser–induced laboratory plasma, relativistic ions have been detected. However, ion–acoustic solitons and double layers in relativistic plasma have not yet been investigated in the laboratory. So, we are unable to compare our present theoretical results with experimental observations.

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UTJECAJ NEGATIVNIH IONA NA IONSKO–AKUSTIČNE SOLITONE I DVOJNE SLOJEVE U RELATIVISTIČKOJ PLAZMI

Izveli smo Korteweg–de Vriesovu jednadžbu za relativističku plazmu koja se sastoji od elektrona i pozitivnih i negativnih iona, primjenom perturbacijske metode za ionsko–akustičke solitonske valove. Za područje oko kritične gustoće negativnih iona izveli smo modificiranu Korteweg–de Vriesovu jednadžbu. Analizu stvaranja dvojnih slojeva načinili smo miješanom nemodificiranom i modificiranom Korteweg–de Vriesovom jednadžbom. Prikazujemo profile ionsko–akustičkih solitona za plazmu s (H^+, Cl^-), (H^+, O^-), (H^+, SF_5^-) i (He^+, SF_5^-) ionima.