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GENERAL AND APPLIED PHYSICS

Electrostatic Double Layers in a Multicomponent Drifting Plasma Having Nonthermal Electrons

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Abstract The pseudopotential technique is applied to a multicomponent plasma consisting of nonthermal electrons and warm positive and negative ions with drift motion with a view to studying ion-acoustic double layers. Conditions for the existence of such layers are obtained, two critical concentrations of negative ions being identified which control the formation and nature of the ion-acoustic double layers. The effects of nonthermal electrons, negative-ion concentration, and negative-ion temperature on the double layer formation and structure are also investigated. The nonthermal electrons and the negative ions are shown to contribute significantly to the excitation and structure of the double layers. The importance of the results in the context of magnetospheric and auroral plasmas is discussed.

Keywords Double layer · Nonthermal electrons · Sagdeev potential

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1 Introduction

A double layer (DL) in plasma consists of two oppositely charged parallel layers resulting in a strong electric field and consequent sharp change in electrical potential across the double layer. The strong field across the layer accelerates the plasma electrons and ions in opposite directions, giving rise to an electric current. Double layers (DLs) can be found in a wide variety of plasmas, from discharge tubes to space plasmas to the Birkeland current supplying the Earth's aurora. DLs occur naturally in a variety of space plasma environments and are of considerable interest in astrophysics [1]. In particular, it has been suggested that DLs are responsible for accelerating particles in the auroral region of the ionosphere [2]. It is believed that DLs play a significant role in supplying and accelerating plasma in magnetic coronal funnels [3], and various theories on the formation of solar flares involve DLs [4]. Viking and S3-3 satellite observations detected DLs in the magnetospheric regions [5] and auroral regions [6], respectively. It has also been discovered that the acoustic DLs are responsible for auroral electron precipitation. During the past two decades, the formation of DLs has raised interest because of their relevance to cosmic applications [4, 7–9], ion heating in linear turbulent heating devices [10], and confinement of plasma in tandem mirror devices [11]. Several authors have studied weak ion-acoustic DLs in different plasma systems with reductive perturbation techniques [12–20].

Given their multispecies composition, space plasmas constitute a rich laboratory for the study of DLs. In recent years, there has been considerable interest in the study of ion-acoustic DLs in multispecies plasmas including the effects of negative ions [21–24]. Negative ions, which result from electron attachment to neutral particles when an electronegative gas is introduced in an electrical gas discharge, can be found in the D region of the ionosphere [25], plasma processing reactors [26], and neutral beam sources [27]. Even a small amount of negative ions can have significant effect on the formation of nonlinear ion-acoustic wave structures [28]. In practice, ions have finite temperatures, and the ionic temperature can also significantly affect the characteristics of nonlinear ion-acoustic structures [29, 30]. The

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electron and ion distributions play a crucial role in characterizing the physics of the wave structure and can significantly influence the conditions required for the formation of solitons and double layers. On the other hand, the electron and ion distributions can be significantly affected by large-amplitude waves. The presence of non-Maxwellian electrons in plasma gives rise to many interesting characteristics in the nonlinear propagation of waves, including the excitation of ion-acoustic solitons and DLs in plasma. The solitary structure with density depression in the magnetosphere observed by the Freja [31] and Viking [5] satellites has been explained by Cairns et al. [32, 33], who assumed the electron distribution to be nonthermal. Distributions with enhanced population of energetic electrons have been observed in the magnetosphere [34]. Nonthermal distributions are commonly found in the auroral zone [35] and in many laboratory plasmas in which wave damping produces electron tails [36].

Mechanisms for the formation of nonthermal particle distributions in space plasma still constitute a central problem. One possible mechanism is the trapping and acceleration of particles in the field of large-amplitude waves. The drift motion of ions plays an important role on the formation of ion-acoustic DLs in negative-ion plasma [37].

In many physical situations, it seems therefore more realistic to consider the simultaneous presences of nonthermal electrons and warm negative ions in investigations of ion-acoustic DLs in multicomponent drifting plasmas. Nonetheless, to our knowledge, this problem has not been studied before. We are hence motivated to study the excitation and characteristics of the ion-acoustic DLs in a multicomponent drifting plasma consisting of nonthermal electrons and warm positive as well as negative ions.

The paper is organized as follows: In Section 2, the basic equations are given. In Section 3, the Sagdeev pseudo potential is derived, and the double layer solutions are obtained in the small amplitude limit. Results and discussions are presented in Section 4.

2 Basic Equations

We consider an unmagnetized collisionless plasma comprising warm positive and negative ions, and nonthermally distributed electrons. The positive and negative ions are assumed to have constant streaming motion in an equilibrium state. The nonlinear behavior of ion-acoustic waves in such a plasma may be described by the following set of normalized basic equations:

$$\frac{\partial n_s}{\partial t}+\frac{\partial}{\partial x}(n_s u_s)=0 \tag{1}$$

$$\frac{\partial u_s}{\partial t}+u_s\frac{\partial u_s}{\partial x}+\frac{\sigma_s}{Q_s n_s}\frac{\partial p_s}{\partial x}=\frac{Z_s}{Q_s}\frac{\partial \phi}{\partial x} \tag{2}$$

$$\frac{\partial p_s}{\partial t}+u_s\frac{\partial p_s}{\partial x}+3p_s\frac{\partial u_s}{\partial x}=0 \tag{3}$$

$$\frac{\partial^2 \phi}{\partial x^2}=n_{\mathrm{e}}+\sum_s Z_s n_s \tag{4}$$

Since we assume the electrons to be nonthermally distributed, the electron density n_{e} in Eq. (4) is given by [32, 33]

$$n_{\mathrm{e}}=\left(1-\beta\phi+\beta\phi^2\right)e^{\phi} \tag{5}$$

where $\beta=4p/(1+3p)$ measures the deviation from the thermalized state, and p determines the number of nonthermal electrons in the plasma.

In the above equations, the subscript s can either be i or j, representing positive and negative ions, respectively. The parameters n_s, u_s, p_s, σ_s are the concentration, velocity, pressure, and temperature of positive and negative ions, respectively. The concentration of nonthermal electrons is represented by n_{e}, ϕ denotes the electrostatic potential, Q_i=1 for positive ions, and $Q_j=m_j/m_i$, Z_i=−1 and Z_j=1. The velocities are normalized by the ion-acoustic speed $\sqrt{K_{\mathrm{B}}T_e/m_i}$, the densities by the equilibrium ion density n_{o}, all lengths by the Debye length $\sqrt{K_{\mathrm{B}}T_e/4\pi n_o e^2}$, the time variable by the ion plasma period $\omega_p^{-1}=(m_i/4\pi n_o e^2)^{1/2}$, and the potential ϕ by $K_{\mathrm{B}}T_e/e$ where K_{B} is the Boltzmann constant.

3 Double Layer Solution

To study time-independent DL structures, we make all the dependent variables depend only on a single variable

$$\eta=x-Vt \tag{6}$$

where V is the Mach number with respect to the ion-acoustic speed. We also use the steady-state condition and impose the following boundary conditions at $|x|\to\infty$:

$$\begin{aligned}
&n_s \to n_{s0} \quad (s=i,j),\\
&u_s \to u_{s0} \quad (s=i,j),\\
&p_s \to p_{s0} \quad (s=i,j),\\
&\phi \to 0,\\
&d\phi/d\eta \to 0.
\end{aligned} \tag{7}$$

The charge neutrality condition reads

$$n_{io}=1+Z_j n_{jo.} \tag{8}$$

With the transformation (6) and boundary conditions (7) in Eqs. (1)–(5), standard procedure leads to the result

$$\frac{d^2\phi}{d\eta^2}=\left(1-\beta\phi+\beta\phi^2\right)e^{\phi}$$

$$+\sum_s \frac{Z_s n_{so}^{\frac{3}{2}} Q_s^{\frac{1}{2}}}{\sqrt{12\sigma_s p_{so}}}\left[\sqrt{\left\{\left(V-u_{so}+\sqrt{\frac{3\sigma_s p_{so}}{Q_s n_{so}}}\right)^2+\frac{2Z_s\phi}{Q_s}\right\}}-\sqrt{\left\{\left(V-u_{so}-\sqrt{\frac{3\sigma_s p_{so}}{n_{so}}}\right)^2+\frac{2Z_s\phi}{Q_s}\right\}}\right] \tag{9}$$

The qualitative nature of the solution of Eq. (9) can be most easily seen by introducing the Sagdeev potential [38]. Equation (9) can be written in the form

$$\frac{d^2\phi}{d\eta^2} == -\frac{\partial\psi}{\partial\phi} = -\psi'(\phi) \tag{10}$$

where the Sagdeev potential $\psi(\phi)$ is given by

$$\psi(\phi) = (1+3\beta) - e^{\phi} + \beta(\phi-1)e^{\phi} - \beta\left(\phi^2 - 2\phi + 2\right)e^{\phi}$$

$$-\sum_s \frac{Q_s^{\frac{3}{2}} n_{so}^{\frac{3}{2}}}{3\sqrt{12\sigma_s p_{so}}}\left[\left\{\left(V-u_{so}+\sqrt{\frac{3\sigma_s p_{so}}{Q_s n_{so}}}\right)^2+\frac{2Z_s\phi}{Q_s}\right\}^{\frac{3}{2}}-\left\{\left(V-u_{so}-\sqrt{\frac{3\sigma_s p_{so}}{Q_s n_{so}}}\right)^2+\frac{2Z_s\phi}{Q_s}\right\}^{\frac{3}{2}}-\left(V-u_{so}+\sqrt{\frac{3\sigma_s p_{so}}{Q_s n_{so}}}\right)^3+\left(V-u_{so}-\sqrt{\frac{3\sigma_s p_{so}}{Q_s n_{so}}}\right)^3\right] \tag{11}$$

Considering the small amplitude theory $(|\phi| < 1)$ one may expand the Sagdeev potential up to the fourth order in ϕ, which yields

$$\frac{d^2\phi}{d\eta^2} = S_1\phi + S_2\phi^2 + S_3\phi^3 + \ldots.. \tag{12}$$

and

$$\psi(\phi) = -\frac{1}{2}S_1\phi^2 - \frac{1}{3}S_2\phi^3 - \frac{1}{4}S_3\phi^4 - \ldots., \tag{13}$$

where

$$\begin{aligned}
S_1 &= (1-\beta) - \sum_s \frac{Z_s^2 n_{so}}{Q_s(V-u_{so})^2 - \frac{3\sigma_s p_{so}}{n_{so}}}\\
S_2 &= \tfrac{1}{2}\left[1 - \sum_s \frac{Z_s^3 n_{so}^{\frac{3}{2}}}{2Q_s^{\frac{3}{2}}\sqrt{3\sigma_s p_{so}}}\left\{\left(V-u_{so}+\sqrt{\frac{3\sigma_s p_{so}}{Q_s n_{so}}}\right)^{-3}-\left(V-u_{so}-\sqrt{\frac{3\sigma_s p_{so}}{Q_s n_{so}}}\right)^{-3}\right\}\right]\\
S_3 &= \tfrac{1}{6}\left[(1+3\beta) + \sum_s \frac{3Z_s^4 n_{so}^{\frac{3}{2}}}{2Q_s^{\frac{5}{2}}\sqrt{3\sigma_s p_{so}}}\left\{\left(V-u_{so}+\sqrt{\frac{3\sigma_s p_{so}}{Q_s n_{so}}}\right)^{-5}-\left(V-u_{so}-\sqrt{\frac{3\sigma_s p_{so}}{Q_s n_{so}}}\right)^{-5}\right\}\right]
\end{aligned} \tag{14}$$

Integrating Eq. (10) with respect to η, we obtain the so-called energy equation,

$$\frac{1}{2}\left(\frac{d\phi}{d\eta}\right)^2 + \psi(\phi) = 0 \tag{15}$$

where we have used the boundary conditions $\phi \to 0$, $d\phi/d\eta \to 0$, and $d^2\phi/d\eta^2 \to 0$. Equation (15) describes the motion of a pseudoparticle of unit mass with velocity $d\phi/d\eta$ and position ϕ in a potential $\psi(\phi)$. The first term on the right-hand side of Eq. (15) can be regarded as the kinetic energy of the pseudoparticle. Since the kinetic energy is always nonnegative, it follows that $\psi(\phi) \le 0$ for the entire motion, zero being the maximum value of $\psi(\phi)$. Equation (10) shows that $\psi'(\phi)$ is the force on the particle at the position ϕ. Equation (15) may also be regarded as an anharmonic oscillator equation, provided that we interpret ϕ and η as space and time coordinates, respectively.

For the double layer solution of Eq. (15), the Sagdeev potential $\psi(\phi)$ should be negative between $\phi = 0$ and ϕ_m, where ϕ_m is some extremum value of the potential ϕ, called the amplitude of the DL. Double layer solutions $\psi(\phi)$ must additionally satisfy the following boundary conditions:

1. $\psi(\phi) = 0, \psi'(\phi) = 0,$ and $\psi''(\phi) < 0$ at $\phi = 0$ (16)

2. $\psi\ (\phi) = 0,\ \psi'(\phi) = 0,$ and $\psi''(\phi) < 0$ at $\phi = \phi_{\mathrm{m}}(\neq 0)$. (17)

3. $\psi(\phi) < 0$ for $0 < |\phi| < |\phi_m|$ (18)

When the above conditions are satisfied, $\phi = 0$ is an unstable equilibrium position. The pseudoparticle is not reflected at $\phi = \phi_m$ because the pseudo force and the pseudo velocity vanish. Instead, it goes to another state producing an asymmetrical double layer with a net potential drop ϕ_m.

Applying the boundary conditions (16) and (17), from Eq. (13) we find that

$$\phi_m = -\frac{2S_2}{3S_3} \tag{19}$$

and

$$\psi(\phi) = -\frac{S_3}{4}\phi^2(\phi_m - \phi)^2. \tag{20}$$

The DL solution of Eq. (15) satisfying (20) is given by

$$\phi = \frac{\phi_m}{2}\left[1 - \tan h\left(\sqrt{S_3/8.\phi_m.\eta}\right)\right] \tag{21}$$

Equation (19) relates the amplitude ϕ_m of the DL to the ratio between the coefficients S_2 and S_3 of the quadratic and cubic terms on the right-hand side of Eq. (12). A double layer can only exist for positive S_3, i.e., for plasma parameters satisfying the following condition:

$$1 + 3\beta > \sum_s \frac{3Z_s^4 n_{so}^{\frac{3}{2}}}{2Q_s^{\frac{5}{2}}\sqrt{3\sigma_s p_{so}}}\left\{\left(V - u_{so} - \sqrt{\frac{3\sigma_s p_{so}}{Q_s n_{so}}}\right)^{-5} - \left(V - u_{so} + \sqrt{\frac{3\sigma_s p_{so}}{Q_s n_{so}}}\right)^{-5}\right\} \tag{22}$$

From Eqs. (19) and (21), it follows that the sign of S_2 determines the nature of the DL. If S_2 is positive (negative), a rarefactive (compressive) DL is formed. Since S_2 is independent of β, the nature of DL, whether compressive or rarefactive, remains invariant under changes in β. For a cold ion plasma (σ_i=σ_j=0), S_2 is negative, and only compressive DLs can be formed.

The width of the DL is given by

$$w = 2\sqrt{S_3/8/|\phi_m|} \tag{23}$$

Note that the nature, amplitude, and width of the DLs depend on the plasma parameters, i.e., on the density of negative ions, drift velocity of the ions, the ionic temperature, and the nonthermal parameter β, through the coefficients S_2 and S_3.

4 Results and Discussion

We have investigated the occurrence of ion-acoustic double layers in a multicomponent warm drifting plasma having nonthermal electrons. Our analysis reveals that both compressive and rarefactive DLs exist in the plasma under consideration for selected ranges of the plasma parameters.

As an example, we have considered a H^+ plasma with O_2^- negative ions, which is expected to occur in the D region of the ionosphere. For this plasma, we have numerically evaluated the double layer amplitude ϕ_m and width w as functions of the nonthermal parameter β and negative-ion number density n_{j0} at different ionic temperatures. We have found the nonthermal electrons and the negative ions to drastically affect the existence regions and nature of the ion-acoustic double layers in warm drifting plasmas. Equation (14) shows that the coefficients S_2 and S_3 depend on the negative-ion concentration, temperature, nonthermal parameter, drift velocity, and other plasma parameters. For a given set of parameters, the coefficient S_2 is positive for small negative-ion concentrations n_{j0}, but becomes negative as the negative-ion concentration n_{j0} exceeds a certain critical value $n_{j01,}$ where n_{j01} corresponds to the case S_2=0. Since S_2 is independent of β, the value of n_{j01} is also independent of β. A second critical value n_{j02} can be found such that the coefficient S_3 is positive for n_{jo}<n_{j02}, negative for n_{jo}> n_{j02}, and equal to zero for n_{jo}=n_{j02}. Hence, the system may support rarefactive double layers in the range 0<n_{jo}<n_{j01} and compressive double layers in the range n_{jo1}<n_{j0}<n_{j02}.

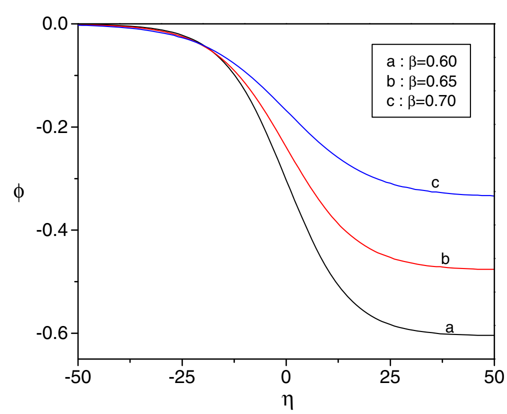

Fig. 1 (Color online) The rarefactive DL potential profile for different values of the nonthermal parameter (β). Curves a, b, and c refer to three different values β=0.60, 0.65, and 0.70, respectively

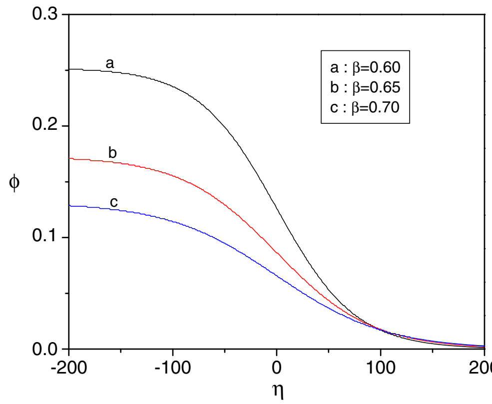

Fig. 2 (Color online) The compressive DL potential profile for different values of the nonthermal parameter (β). Curves *a*, *b*, and *c* refer to three different values β=0.60, 0.65, and 0.70, respectively

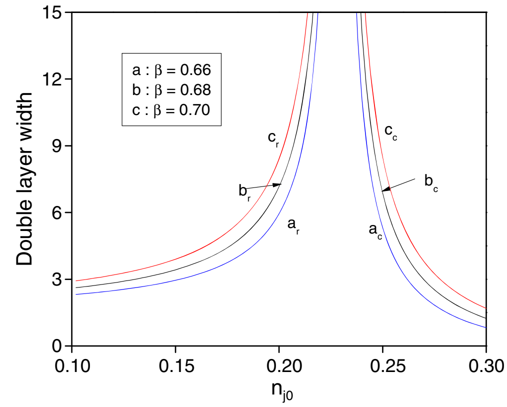

Fig. 4 (Color online) Variation of DL width with negative-ion concentration (n_{j0}) for different values of the nonthermal parameter (β). Curves *a*, *b*, and *c* refer to three different values β=0.66, 0.68, and 0.70, respectively. The subscripts *c* and *r* refer to compressive and rarefactive double layers, respectively

No double layer formation is possible for $n_{jo}>n_{j02}$. The critical values of n_{j0} depend on various plasma parameters.

In the limiting case $n_{j0}\rightarrow 0$, $\beta\rightarrow 0$, i.e., with no negative ions and a single Maxwellian distribution of electrons, no DL solution becomes possible, a result in agreement with that reported by Goswami and Bujarbarua [12]. However, a DL solution is possible even in the absence of negative ions when the electrons are described by non-Maxwellian distributions. For a plasma containing double Maxwellian distributed electrons, both compressive and rarefactive DL solutions are obtained, even in the absence of negative ions [12]. In our case, with nonthermal electrons ($\beta\neq 0$), only rarefactive DL solutions are obtained in the absence of any negative ion ($n_{jo}\neq 0$). Thus, ion-acoustic double layers, compressive and rarefactive, can only be formed in a multicomponent plasma system only for certain restricted values of plasma parameters.

The rarefactive and compressive DL potential profiles for different nonthermal parameters (β) are shown in Figs. 1 and 2, respectively.

We have calculated the amplitude and width of the ion-acoustic DLs using Eqs. (19) and (23), respectively, for different nonthermal parameters, negative-ion concentrations, and temperatures for H^+ plasmas with O_2^- negative ions. The dependence of the DL amplitude on the negative-ion concentration for different nonthermal parameters is shown in Fig. 3. The DL is rarefactive for small n_{j0} up to certain critical value n_{j01}. At very low n_{j0}, the DL amplitude is almost independent of n_{j0}. For n_{jo} approaching n_{j01}, the DL amplitude decreases rapidly towards zero. Beyond n_{j01}, compressive DLs are formed whose amplitude increases rapidly with the negative-ion concentration.

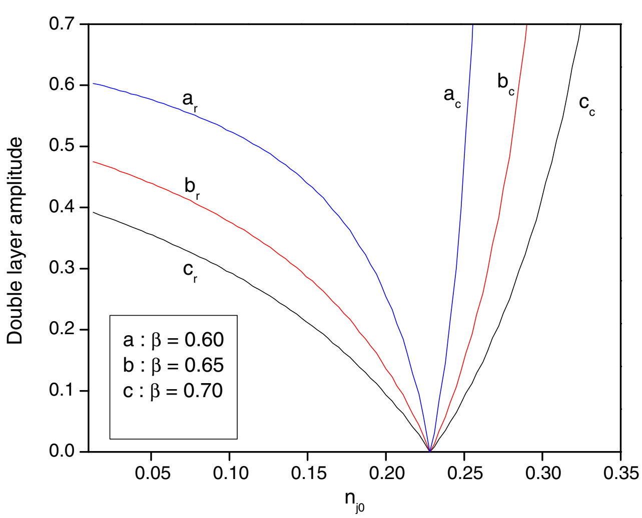

Fig. 3 (Color online) Variation of DL amplitude with negative-ion concentration (n_{j0}) for different values of the nonthermal parameter (β). Curves *a*, *b*, and *c* refer to three different values β=0.60, 0.65, and 0.70, respectively. The subscripts *c* and *r* refer to compressive and rarefactive double layers, respectively

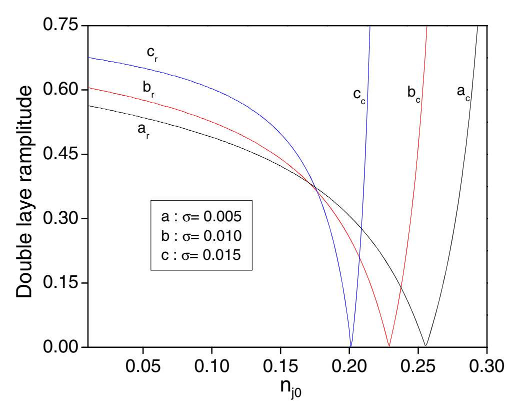

Fig. 5 (Color online) Variation of DL amplitude with negative-ion concentration (n_{j0}) for different values of negative-ion temperature (σ_j). Curves *a*, *b*, and *c* refer to three different values σ_j=0.005, 0.010, and 0.015, respectively. The subscripts *c* and *r* refer to compressive and rarefactive double layers, respectively

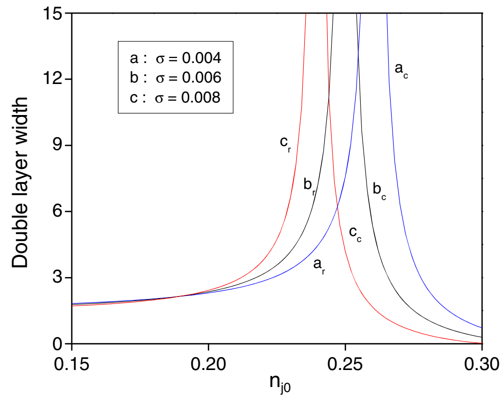

Fig. 6 (Color online) Variation of DL width with negative-ion concentration for different values of negative-ion temperature (σ_j). Curves *a*, *b*, and *c* refer to three different values σ_j=0.004, 0.006, and 0.008, respectively. The subscripts *c* and *r* refer to compressive and rarefactive double layers, respectively

While the critical value n_{j01} is independent of the nonthermal parameter, the amplitudes of both the rarefactive and compressive DLs decrease as the nonthermal parameter grows. Figure 4 shows the DL width as a function of the negative-ion concentration for diverse nonthermal parameters. The DL width increases rapidly as the negative-ion concentration approaches the critical value n_{j01}. The widths of both the rarefactive and compressive DLs increase with the nonthermal parameter. Figure 5 shows the DL amplitude as a function of the negative-ion concentration for different ionic temperatures. Clearly, the critical negative-ion density n_{j01}, which determines the nature of DLs, decreases as the ionic temperature grows. The ionic temperature also raises the amplitude of the DL.

Figure 6 shows the DL width as a function of the negative-ion concentration, for various negative-ion temperatures. The width of rarefactive (compressive) DLs increases (decreases) as the negative-ion concentration grows and as the ionic temperature rises.

5 Conclusions

We have shown that the negative-ion concentration, negative-ion temperature, and nonthermal parameter significantly affect the conditions for existence and the structure of ion-acoustic DLs. For negative-ion concentrations approaching the critical value n_{j02}, the DL amplitude becomes so large that the assumption of weak DL becomes invalid.

Finally, we would like to point out that the type of plasma considered in the present work exists in space and also can be produced in the laboratory. We expect the present study to be useful in the understanding of auroral and magnetospheric plasmas.

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