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Schamel equation in an inhomogeneous magnetized sheared flow plasma with q-nonextensive trapped electrons

Shaukat Ali Shan† and Qamar-ul-Haque

Theoretical Physics Division (TPD), PINSTECH, P. O. Nilore, Islamabad, Pakistan

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An investigation is carried out for understanding the properties of ion–acoustic (IA) solitary waves in an inhomogeneous magnetized electron-ion plasma with field-aligned sheared flow under the impact of q-nonextensive trapped electrons. The Schamel equation and its stationary solution in the form of solitary waves are obtained for this inhomogeneous plasma. It is shown that the amplitude of IA solitary waves increases with higher trapping efficiency (β), while the width remains almost the same. Further, it is found that the amplitude of the solitary waves decreases with enhanced normalized drift speed, shear flow parameter and the population of the energetic particles. The size of the nonlinear solitary structures is calculated to be a few hundred meters and it is pointed out that the present results are useful to understand the solar wind plasma.

Keywords: sheared flow plasma, density inhomogeniety, electron trapping

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1. Introduction

The plasma species with space-dependant relative speed with reference to the rest of the plasma in a way that the variation and flowing plasma directions are different (i.e., $v_0 = v_0(x)\hat{z}$), are said to be having sheared flows. Such flows are ubiquitous in space,[1] astrophysical,[2] and laboratory plasmas.[3,4] These sheared flows behave as an additional free energy source in plasmas which can generate instabilities. The sheared-flow driven instabilities have been studied by several authors in different plasma systems.[1,5–7]

D'Angelo in his initial paper[8] considered the nonuniform density plasma and showed that the sheared flow gives rise to a purely growing instability,[8] which can appear in both naturally existing[5] and laboratory plasmas.[9–11] A few years ago,[12] it was pointed out that the density gradients are not necessary for the existence of D'Angelo instability, but in the presence of density gradients, the electrostatic drift wave becomes unstable due to shear flow. Gavrishchaka *et al.*[13] studied the shear flow driven ion acoustic wave using the kinetic model and investigated the origin of low frequency waves in the ionosphere. The impact of sheared flow ions and electrons parallel to the external magnetic field on low frequency plasma instabilities have been studied by three-dimensional (3D) electrostatic particle simulations.[6]

Nonlinear wave structures such as solitons, shocks, and double layers (DLs) are formed due to competitive balance between nonlinearity, dispersion and dissipation present in the plasma. Among the most investigated nonlinear structures are the solitary waves (IAWs). Washimi and Taniuti[14] were the first to derive the KdV equation for ion acoustic (IA) solitons in a plasma. The existence and stability of ion acoustic solitary waves for non-Maxwellian multi-component plasma were investigated.[15] The current-driven electrostatic nonlinear structures like solitons and shocks have been investigated in Saturn's magnetospheric plasmas having sheared flows, stationary dust and non-Maxwellian electrons.[16] The coupling of newly studied low-frequency electrostatic current-driven mode[16] with the electromagnetic Alfvén and drift waves has been investigated in Ref. [5], where the instability conditions and the growth rates of both inertial and kinetic Alfvén waves are estimated in the night side boundary regions of Jupiter's magnetosphere. In the presence of sheared flow, the IA waves can have different real frequencies (either smaller or larger) as compared to the stationary plasma case depending upon the direction and gradient scale lengths of the flow.[17]

The trapping of a particle is another phenomenon which can occur due to fluctuations inside the plasma. The trapping means confinement of some of the particles by the wave potential to a certain region of phase space. The particle trapping has been observed[18,19] in space as well as in laboratory plasmas. The particle trapping is basically a nonlinear phenomenon that cannot be understood by using linear theory of waves. Bernstein *et al.*[20] provided the first analytical method to construct equilibrium electrostatic structures involving particle trapping. This method is called the BGK method. Schamel developed a different method called the pseudo-potential method to construct equilibrium solutions.[21–24] This method is simpler than the BGK method. Schamel's research work is considered as a breakthrough in the theory of holes or phase space vortices. Recently, some research work has also been performed to study the effects of Maxwellian and non-Maxwellian trapping on different types of linear and nonlinear collective processes

†Corresponding author. E-mail: shaukatshan@gmail.com

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in multi-component plasmas.[25]

The solar wind originates from the solar corona which is highly inhomogeneous, therefore the solar wind is structured and has local sheared flows.[26,27] The particles of the solar wind have been found to show non-Maxwellian behavior.[28] The interaction of plasma particles of solar wind with the magnetic field in space can give rise to trapped electrons.

In this work, we use the theoretical framework of the Tsallis statistical mechanics[29] (Tsallis q-entropy) and of Tribeche *et al.*[30] to investigate the propagation of the IA solitary waves in the presence of sheared flow, density inhomogeniety, and electron-trapping for a solar wind plasma. The modification in the characteristics of solitary waves for the solar wind plasma parameters is discussed. The organization of the manuscript is as follows. In Section 2, the model equations are described. In Section 3, a nonlinear stationar solution in the form of solitary waves is presented. In Section 4, the results are discussed by plotting different figures. Section 5 is devoted to a summary.

2. Basic equations

Let us now consider an inhomogeneous, collisionless electron–ion plasma embedded in an external constant magnetic field $B_0 = B_0\hat{z}$ having density inhomogeniety along a negative $\hat{x}$ axis. It is also considered that both the ions and electrons have sheared flow i.e., $v_{i0} = v_{e0} = v_0(x)\hat{z}$ along the magnetic field lines. The ions will provide the inertia while electrons give restoring force, consequently supporting excitation of comparatively low-frequency ion acoustic wave (as compared to Langmuir wave) in the plasma under consideration. The basic set of equations for the present model include the ion continuity and momentum equations as,

$$\frac{\partial n_{\rm i}}{\partial t} + \boldsymbol{\nabla}\cdot(n_{\rm i}\boldsymbol{v}_{\rm i}), \tag{1}$$

$$\left(\frac{\partial}{\partial t} + \boldsymbol{v}_{\rm i}\cdot\boldsymbol{\nabla}\right)\boldsymbol{v}_{\rm i} = \frac{e}{m_{\rm i}}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v}_{\rm i}\times\boldsymbol{B}\right), \tag{2}$$

where $v_{\rm i}$ is the ion fluid velocity, $m_{\rm i}$ is the ionic mass, while the electric field and electrostatic potentials are denoted by E and φ, respectively. Here the symbol e represents the magnitude of electronic charge, while c is the speed of light in a vacuum. In most of the space plasmas the ions temperature is not much smaller as compared to those of electrons. Generally, in solar wind plasma, the ions temperature is less than the electrons temperature or half of it.[31] In this manuscript, the focus is on the density inhomogeniety, electron trapping, and nonextensivity of electrons, therefore for simplicity, we ignore the ions temperature. It is also necessary to clarify here that the density gradients ($\nabla n_0(x)$) are considered along the negative x axis conventionally, so that the drift velocity remains along the positive y-direction. The density gradient scale lengths for both electrons and ions are the same, and smaller than their Larmor radii. For low frequency waves under consideration, the condition $\partial_t \ll \Omega_i \ll \Omega_e$ is used. Equation (2) gives the perpendicular component of ion velocity as

$$\boldsymbol{v}_{\rm i\perp} = \frac{c}{B_0}(\boldsymbol{E}_\perp\times\hat{\boldsymbol{z}}) - \frac{1}{\Omega_{\rm i}}\left(\frac{\partial}{\partial t} + \boldsymbol{v}_{\rm i}\cdot\boldsymbol{\nabla}\right)\boldsymbol{v}_{\rm i\perp}\times\hat{z}. \tag{3}$$

The term $\Omega_{\rm i} = eB_0/cm_{\rm i}$ is defined as ion gyro-frequency. In the above Eq. (3), $\boldsymbol{v}_E = (c/B_0)(\boldsymbol{E}_\perp\times\hat{\boldsymbol{z}})$ is the electric drift and the 2nd term is named as polarization drift. Under drift approximation $\partial/\partial t \ll \Omega_{\rm i}$, the polarization drift becomes

$$\boldsymbol{v}_{\rm pi} = -\frac{c}{B_0\Omega_{\rm i}}\left[\frac{\partial}{\partial t} + \boldsymbol{v}_0(x)\cdot\boldsymbol{\nabla} + v_{\rm iz}\frac{\partial}{\partial z} + \boldsymbol{v}_E\cdot\boldsymbol{\nabla}\right]\boldsymbol{\nabla}_\perp\Phi. \tag{4}$$

The parallel component of the ion momentum equation can be expressed as

$$\left(\frac{\partial}{\partial t} + v_0\frac{\partial}{\partial z} + v_{\rm iz}\frac{\partial}{\partial z}\right)v_{iz} = \frac{cv_0'}{B_0}\frac{\partial\varphi}{\partial y} - \frac{e}{m_{\rm i}}\frac{\partial\varphi}{\partial z}, \tag{5}$$

where $v_0' = {\rm d}v_0(x)/{\rm d}x$. If we write the total ions density $n_{\rm i} = n_{\rm i0} + \tilde{n}_{\rm i}$ (where $n_{\rm i0}$ is the equilibrium density and $\tilde{n}_{\rm i}$ is the perturbed number density of ions) and considering the electric drift ($\boldsymbol{v}_E$) to be dominant as compared to the polarization drift ($\boldsymbol{v}_{\rm pi}$), then the continuity equation for ions can be rewritten as follows:

$$\left(\frac{\partial}{\partial t} + \boldsymbol{v}_0\cdot\boldsymbol{\nabla}\right)\tilde{n}_{\rm i} + \boldsymbol{v}_E\cdot\boldsymbol{\nabla}_\perp n_{\rm i0} + n_{\rm i0}\boldsymbol{\nabla}_\perp\cdot\boldsymbol{v}_{\rm pi} + (n_{\rm i0}+\tilde{n}_{\rm i})\frac{\partial v_{\rm iz}}{\partial z} + v_{\rm iz}\frac{\partial\tilde{n}_{\rm i}}{\partial z} = 0. \tag{6}$$

If there are free (that means the kinetic energy is greater than the wave potential energy) and the trapped electrons (this means the kinetic energy is less than the wave potential energy) present in a plasma, then one can employ the concept of a separatrix[21–23] in the distribution function which separates the free electrons from the trapped ones. On the basis of this idea, the total distribution function for the one-dimensional (1D) case can be written as the following equation

$$f_{\rm e}(x,v) = f_{\rm ef}(x,v) + f_{\rm et}(x,v), \tag{7}$$

where $f_{\rm ef}(x,v)$ stands for the free electron distribution function and $f_{\rm et}(x,v)$ shows the trapped electron distribution function. The observations of suprathermal particles in space and laboratory plasmas lead to the conclusion that the plasma particles deviate from thermal velocity distributions. A similar situation also arises in solar wind plasma, where the pres-

ence of such highly energetic electrons have been reported.[28] In the present study, we consider the most general distribution q-nonextensive distribution which gives κ-distribution in the limiting case if one replaces the factor $(1-q)$ by κ.[32] This is the reason why we choose the one-dimensional equilibrium q-distribution function for free electrons in a collisionless plasma as[33]

$$f_{\rm ef}(x,v) = C_q\left[1-(q-1)\left(\frac{m_{\rm e}v^2}{2K_{\rm B}T_{\rm ef}}-\frac{e\varphi}{K_{\rm B}T_{\rm ef}}\right)\right]^{1/(q-1)} \tag{8}$$

for $v > \sqrt{2e\varphi/m_{\rm e}}$, where the constant of normalization is[34,35]

$$C_q = n_{\rm e0}(\Gamma[1/(1-q)]/\Gamma[1/(1-q)-1/2])\sqrt{m_e(1-q)/2\pi K_{\rm B}T_{\rm ef}} \text{ for } 1/3<q<1$$

and

$$C_q = n_{\rm e0}\left(\frac{1+q}{2}\right)\{\Gamma[1/(1-q)+1/2]/\Gamma[1/(1-q)]\}\sqrt{m_e(q-1)/2\pi K_{\rm B}T_{\rm ef}}$$

for $q>1$. The trapped electrons are bounced back and forth in the trough of the potential well and obey the following distribution[30,36]

$$f_{\rm et}(x,v) = C_q\left[1-(q-1)\left\{\frac{m_{\rm e}v^2}{2K_{\rm B}T_{\rm et}}-\frac{e\varphi}{K_{\rm B}T_{\rm et}}\right\}\right]^{1/(q-1)}, \tag{9}$$

or

$$f_{\rm et}(x,v) = C_q\left\{1-(q-1)\left[\frac{m_{\rm e}v^2}{2K_{\rm B}T_{\rm ef}(T_{\rm et}/T_{\rm ef})}-\frac{e\varphi}{K_{\rm B}T_{\rm ef}(T_{\rm et}/T_{\rm ef})}\right]\right\}^{1/(q-1)},$$

or

$$f_{\rm et}(x,v) = C_q\left[1-\beta(q-1)\left\{\frac{m_{\rm e}v^2}{2K_{\rm B}T_{\rm ef}}-\frac{e\varphi}{K_{\rm B}T_{\rm ef}}\right\}\right]^{1/(q-1)} \tag{10}$$

for $v \le \sqrt{2e\varphi/m_{\rm e}}$, where $\beta = T_{\rm ef}/T_{\rm et}$ is a parameter, which measures the proportion of trapped electrons.[21,37] The parameter q stands for the strength of electrons nonextensivity. Note that the symbols $T_{\rm et}$, $T_{\rm ef}$ in Eqs. (8–10) are the electrons' trapped and free kinetic temperatures that they would have for the case $q\to 1$ (equivalent to Maxwellian case). It may be useful to note that for $\beta>0$ and $q>1$ or $1/3<q<1$, the distribution function (7) exhibits thermal cutoffs. The latter, whenever they exist, are summarized as follows: the hot electron number density with trapped electrons in the case $1/3<q<1$ can be expressed as[36]

$$n_{\rm e} = n_{\rm eo}\left\{1+\frac{1+q}{2}\Phi-\frac{4(1-\beta)(1-q)^{1/2}}{3\sqrt{\pi}}\frac{\Gamma[1/(1-q)]}{\Gamma[(1+q)/(2-2q)]}\Phi^{3/2}\right\}, \tag{11}$$

where $\Gamma[1/(1-q)]$ is the standard gamma function of its argument and $\Phi = e\varphi/K_{\rm B}T_{\rm ef}$ is the normalized electrostatic potential. It is worth mentioning here that the equilibrium flow velocity will not appear for electrons explicitly, since we have ignored their inertia. To close the system we will use the quasineutrality ($\tilde{n}_{\rm e}\simeq\tilde{n}_{\rm i}$) where $\tilde{n}_{\rm e}$, $\tilde{n}_{\rm i}$ are the perturbed number densities of electrons and ions respectively.

3. Nonlinear analysis

In order to obtain the nonlinear solution of the set of model equations, we define a moving frame $\eta = y+\alpha z-ut$, where y and z are the Cartesian coordinates, u represents the speed of solitary wave, and α is the angle between the external magnetic field B_0 and the propagation direction. Both the temporal and the spatial coordinates may be transformed into a single variable (η) by using the differentials as follows:

$$\partial/\partial t = -u\partial/\partial\eta,\ \ \partial/\partial z = \alpha\partial/\partial\eta,\ \ \partial/\partial y = \partial/\partial\eta.$$

Using this transformation, the ion continuity Eq. (6) in the η frame can be written as

$$-g\frac{\partial n_{\rm i}}{\partial\eta}+gn_{\rm i0}\rho_{\rm s}^2\frac{\partial^3\Phi}{\partial\eta^3}+v_{*\rm n}\frac{\partial\Phi}{\partial\eta}+\alpha n_{\rm i0}\frac{\partial v_{\rm iz}}{\partial\eta}=0, \tag{12}$$

where $g=(u-\alpha v_0)$, and

$$v_{*\rm n} = -(cK_{\rm B}T_{\rm ef}/eB_0)\kappa_n$$

is the drift speed and $\kappa_n = \nabla\ln n_0$ is the inverse of the density inhomogeniety scale-length. The parallel component of ions momentum equation Eq. (5) gives

$$\frac{\partial v_{\rm iz}}{\partial\eta} = \frac{(\alpha-S_{\rm i})c_{\rm s}^2}{g}\frac{\partial\Phi}{\partial\eta}, \tag{13}$$

where $c_{\rm s} = \sqrt{K_{\rm B}T_{\rm ef}/m_{\rm i}}$ is the ion acoustic speed and

$$S_{\rm i} = (1/\Omega_{\rm i})\,{\rm d}v_0(x)/{\rm d}x.$$

Using Eqs. (6), (12), and (13) along with the quasi-neutrality condition ($\tilde{n}_e \simeq \tilde{n}_i$), we obtain,

$$\left[\frac{1+q}{2}-\frac{v_{*n}}{(u-\alpha v_0)}-\frac{\alpha(\alpha-S_i)c_s^2}{(u-\alpha v_0)^2}\right]\frac{\partial\Phi}{\partial\eta}+2\left[\frac{(\beta-1)(1-q)^{1/2}}{\sqrt{\pi}}\frac{\Gamma[1/(1-q)]}{\Gamma[(1+q)/(2-2q)]}\right]\sqrt{\Phi}\frac{\partial\Phi}{\partial\eta}-\rho_s^2\frac{\partial^3\Phi}{\partial\eta^3}=0. \tag{14}$$

If we normalize the space variable η with ρ_s (i.e., $\eta/\rho_s \to \xi$) and velocity with c_s then the expression (14) becomes

$$\frac{\partial\Phi}{\partial\xi}-A\sqrt{\Phi}\frac{\partial\Phi}{\partial\xi}-B\frac{\partial^3\Phi}{\partial\xi^3}=0, \tag{15}$$

where $A=B_1/A_1$, $B=1/A_1$, and

$$A_1=\frac{1+q}{2}-\frac{v_{*n}}{(M-\alpha v_{0n})}-\frac{\alpha(\alpha-S_i)}{(M-\alpha v_{0n})^2},$$

$$B_1=\frac{2(1-\beta)(1-q)^{1/2}}{\sqrt{\pi}}\frac{\Gamma[1/(1-q)]}{\Gamma[(1+q)/(2-2q)]},$$

where $M=u/c_s$, v_{*n} is the normalized drift speed and v_{0n} is the normalized flow speed. Equation (15) is the Schamel equation which has a stronger nonlinearity as compared to that appearing in the standard KdV equation. The factors A and B are the coefficients of the nonlinear and dispersion terms, respectively. The stationary solution of Eq. (15) can give rise to two types of structures depending upon the sign of the coefficient A associated with the nonlinear term i.e, for $A>0$, equation (15) gives a compressive type of soliton while for $A<0$ it yields a refractive soliton. The dispersion produces a spread in the group of waves while nonlinearity causes the wave steepening. Consequently, a balance between nonlinearity and dispersion can form a stable pulse (the soliton). Using the boundary conditions i.e., $\Phi \to 0$ and $\partial\Phi/\partial\xi \to 0$ at $\xi \to \pm\infty$, equation (15) admits a solitary wave solution of the form

$$\Phi=\Phi_m \operatorname{sech}^4\left(\frac{\xi}{\Delta}\right), \tag{16}$$

where $\Phi_m=(15/8A)^2$ is the amplitude and $\Delta=\sqrt{16B}$ is the width of the solitary waves. The expressions for the coefficients A and B clearly show the dependence on the entropic index (q) and electron trapping effects (β), consequently these parameters affect the amplitude (Φ_m) and width (Δ) of the expected solitons. The illustration and discussion of the effect of parameters q and β on IA solitary waves in an inhomogeneous electron–ion plasma will be presented in the following Section 4.

4. Results and discussion

It is well known that the solar corona is highly structured, i.e., sheared flows are common[38] and the plasma enters into corona from lower regions with inhomogeneous flows. When a stream of highly energetic charged particles is forced out from the outermost atmosphere (corona) of the Sun and is dragged along with the Sun's magnetic fields, a flow of highly magnetized solar plasma is generated that is known as solar wind. The Sun unleashes a huge amount of mass, mostly consisting of electrons and protons having energies ranging from 1.0 keV to 10 keV, as well as being accompanied by magnetic fields out into space.[39] These are termed as coronal mass ejection (CME). During the CME processes, the magnetic field is dragged along with the solar wind. The coronal mass which is gravitationally bound to the Sun, escapes under enormous thermal kinetic pressures. This scenario has motivated us to illustrate our research work with solar wind parameters to show the impact of trapping on IA wave dispersion properties due to the sheared flow. The plasma parameters used in this study are given below: the magnetic field strength $B_0=0.2$ Gs (the unit 1 Gs $=10^{-4}$ T), the temperature in energy units, i.e., $T_{ef}=50$ eV, $n_{e0}\simeq n_{i0}\simeq 30$ cm^{-3}, and $v_0 \sim 2\times10^7$ cm/s.[40] The density inhomogeniety scale length and shear in the flow are not exactly known, therefore these scales are approximated with ρ_s. The selected solar wind parameters correspond to $\rho_s \simeq 3612$ cm, $c_s \simeq 6.9\times10^6$ cm/s, and the shear flow parameter

$$S_i=\frac{1}{\Omega_i}\frac{dv_0(x)}{dx}=\frac{v_0}{\Omega_i}\frac{1}{L_v}\simeq 0.1,$$

where

$$L_v=\kappa_v^{-1}\sim 10^5 \text{ cm}, \quad \kappa_v=\frac{1}{v_0}\left|\frac{dv_0(x)}{dx}\right|.$$

Figure 1 is plotted by varying the trapping efficiency factor β ($=0.05, 0.15, 0.3$) which shows that the higher amplitude soliton is formed for $\beta=0.3$ (that is, a higher proportion of the electrons are trapped), whereas the width remains unaffected. In other words, we can say that for $\beta=0.3$, the amplitude of the solitary wave is increased as the case in comparison with that for $\beta=0.05$ and $\beta=0.15$. In this case, the width of the solitary structures is few ρ_s, since the space is normalized with ρ_s therefore the size of the nonlinear structures is calculated to be a few hundred meters. The speed of the structures is above the ion acoustic speed (c_s) which means nonlinear structures are supersonic (i.e., $M>1$ and Doppler shifted speed $M-\alpha v_{0n}>1$).

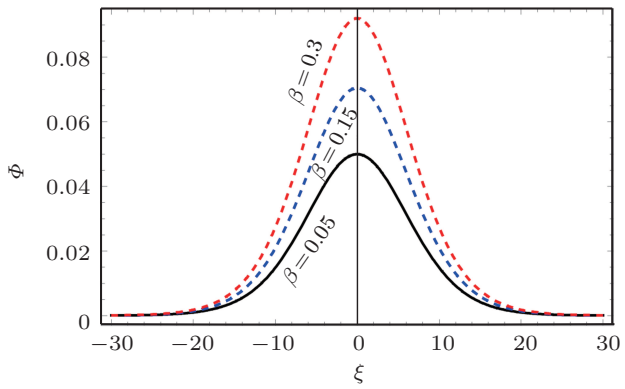


Fig. 1. (color online) The soliton profile for varying $\beta = 0.05$ (solid curve), $\beta = 0.15$ (blue dashed curve), $\beta = 0.3$ (red dotted curve) with other fixed parameters $\alpha = 0.1$, $q = 0.4$, $S_{\rm i} = 1.04 \times 10^{-1}$, $M = 3.9$, $v_{*\rm n} = 0.7$, and $v_{0\rm n} = 2.88$.

Figure 2 shows small amplitude solitary waves for different values of entropic index $q(= 0.4, 0.5, 0.6)$, and it indicates the nonlinear structures with depreciated amplitude and unchanged width at lower values of q. The smaller values of entropic index "q" mean the larger concentration of higher energetic particles deviating more from the Maxwellian behavior. So this figure 2 helps us to conclude that increased population of energetic particles again play a destructive role in the formation of small amplitude IA solitons. The other very important parameter which needs attention is the sheared flow parallel to the ambient magnetic field $B_0\hat{z}$.

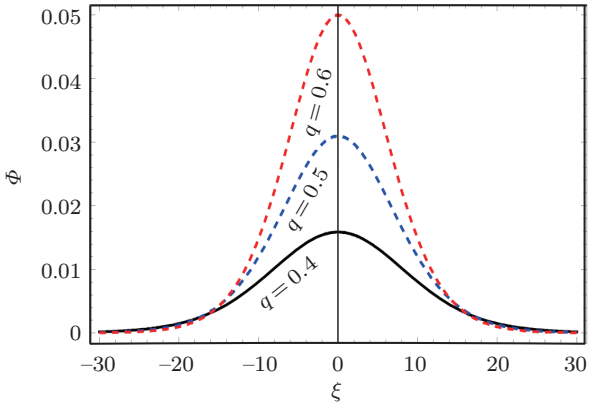


Fig. 2. (color online) The soliton profile for different entropic index $q = 0.4$ (solid curve), $q = 0.5$ (blue dashed curve), $q = 0.6$ (red dotted curve) with other fixed parameters $\alpha = 0.1$, $\beta = 0.05$, $S_{\rm i} = 1.04 \times 10^{-1}$, $M = 3.9$, $v_{*\rm n} = 0.7$, and $v_{0\rm n} = 2.88$.

Figure 3 shows the nonlinear structure profile corresponding to three different values of sheared flow parameter $S_{\rm i}(= 1.04 \times 10^{-1},\ 1.09 \times 10^{-1},\ 1.14 \times 10^{-1})$, indicating that the amplitude of the soliton is depreciated with increased value of $S_{\rm i}$. It means that the sheared flow parameter plays a destructive role in the formation of soliton structures. The reason is that the increased free energy in the form of sheared flow reduces the structure speed M consequently it reduces the amplitude of the solitons. Therefore, it can be concluded that these flows can it make possible for some of the solitary structures to disappear and at the same time it becomes a source for the emergence of some of the new solitary structures at relatively higher values of M.

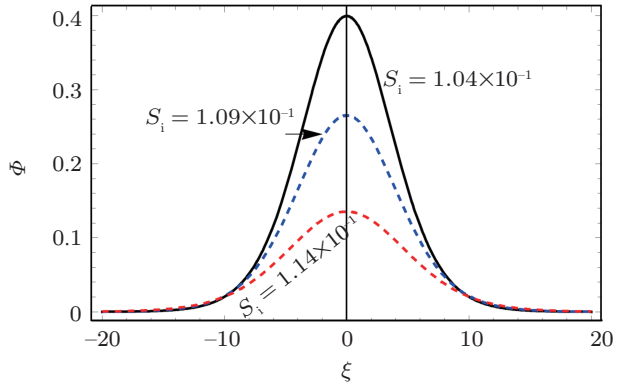


Fig. 3. (color online) The soliton profile for varied $S_i = 1.04 \times 10^{-1}$ (solid curve), $S_{\rm i} = 1.09 \times 10^{-1}$ (blue dashed curve), $S_{\rm i} = 1.14 \times 10^{-1}$ (red dotted curve) with other fixed parameters $\alpha = 0.1$, $q = 0.4$, $\beta = 0.05$, $M = 3.9$, $v_{*\rm n} = 0.7$, and $v_{0\rm n} = 2.88$.

As the plasma system is inhomogeneous, so we have included Fig. 4, which has been constructed by giving variation in normalized drift speed $v_{*\rm n} = 0.6,\ 0.65,\ 0.7$. It is evident from this figure that an increase in the normalized drift speed $v_{*\rm n}$ reduces the amplitude of the solitons.

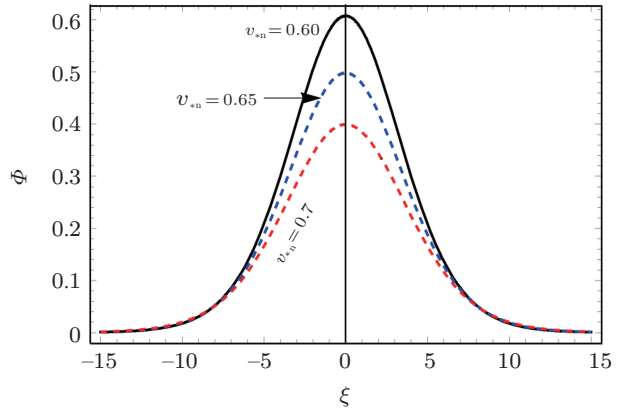


Fig. 4. (color online) The soliton profile for varied $v_{*\rm n} = 0.6$ (solid curve), $v_{*\rm n} = 0.65$ (blue dashed curve), $v_{*\rm n} = 0.7$ (red dotted curve) with other fixed parameters $\alpha = 0.1$, $q = 0.4$, $\beta = 0.05$, $M = 3.9$, $S_{\rm i} = 1.04 \times 10^{-1}$ and $v_{0\rm n} = 2.88$.

The above discussion shows that the amplitude of the solitary system has the tendency to be modified due to various plasma parameters, so figure 5 has been made a part of the study which shows the dependence of amplitude ($\Phi_{\rm m}$) on different parameters like normalized structure speed M, electron trapping efficiency β, nonextensivity factor q, angle α, normalized drift speed $v_{*\rm n}$, and the normalized flow speed $v_{0\rm n}$. All these results imply that the nonlinear solitary structures are modified under the impact of nonextensivity, trapping efficiency, and sheared flow in an inhomogeneous electron–ion plasma system.

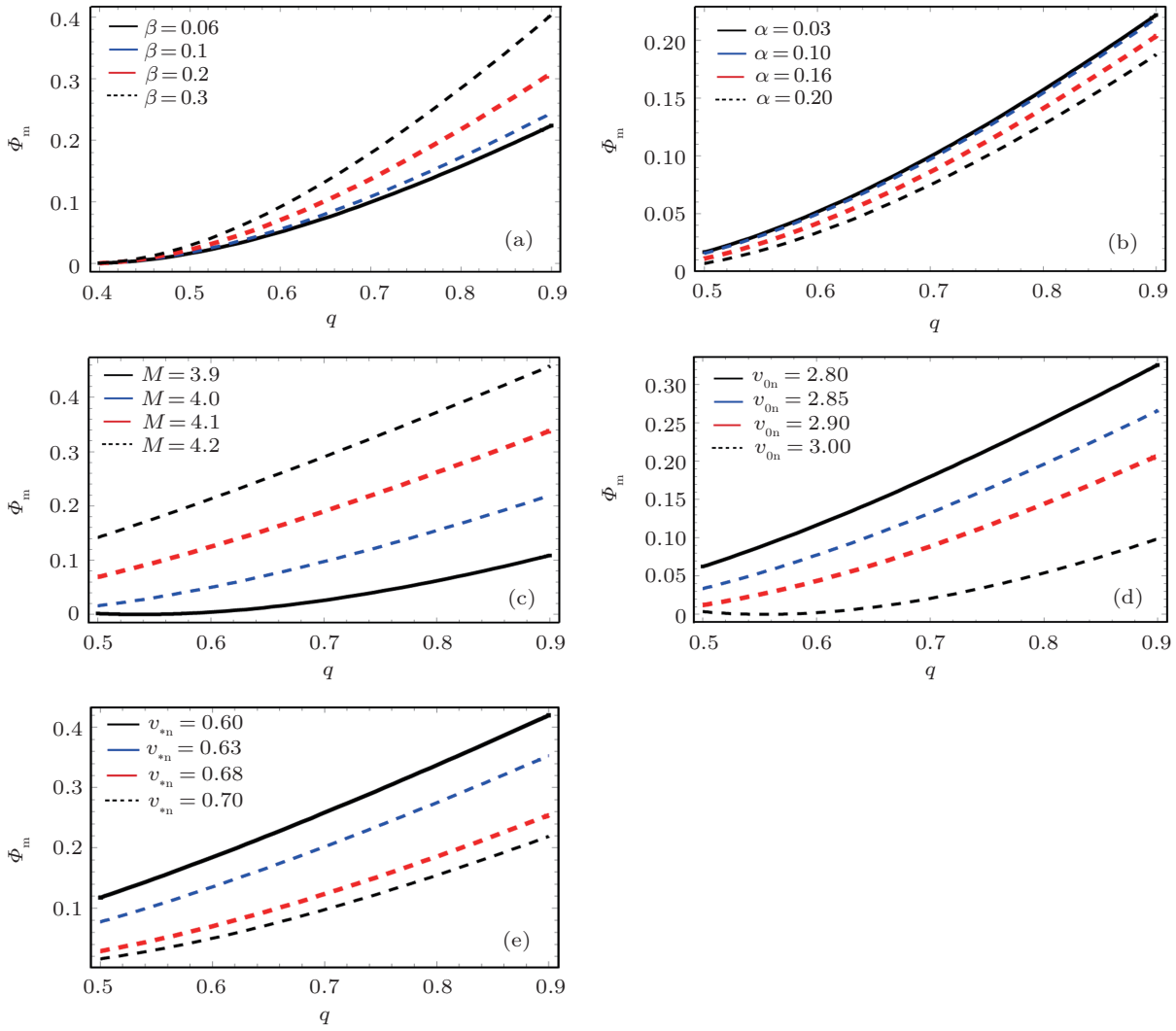


Fig. 5. (color online) Dependence of the maximum amplitude $\Phi_{\rm m}$ of solitary waves on various parameters (a) $\alpha = 0.1$, $M = 3.9$, $v_{*\rm n} = 0.7$, and $v_{0\rm n} = 2.88$; (b) $M = 3.9$, $v_{*\rm n} = 0.7$, $\beta = 0.05$, and $v_{0\rm n} = 2.88$; (c) $\alpha = 0.1$, $v_{*\rm n} = 0.7$, $\beta = 0.05$, and $v_{0\rm n} = 2.88$; (d) $\alpha = 0.1$, $M = 3.9$, $\beta = 0.05$, and $v_{*\rm n} = 0.7$; (e) $\alpha = 0.1$, $M = 3.9$, $\beta = 0.05$, and $v_{0n} = 2.88$.

5. Summary

Schamel equation is derived for an inhomogeneous magnetized electron–ion plasma by taking into account field-aligned sheared flow, electron trapping and nonextensivity effects. The q-nonextensive distribution introduced in Ref. [30] to incorporate the trapping efficiency β, is employed to study the ion acoustic solitary waves. For illustration, the Solar wind plasma parameters are used to show the characteristics of solitary structures. It is observed that the increased energetic particle population and sheared flow reduces the amplitude of the nonlinear structures while the width remains unaffected. On the other hand, the enhanced proportion of trapped electrons generates solitary structures with higher amplitude. It is obvious from the illustrations obtained with the help of suitable parameters that the width of the solitary structures is a few $\rho_{\rm s}$ and the size of the nonlinear structures is estimated to be a few hundred meters. Since most plasma environments have density inhomogeniety and sheared flow, therefore the present results can be useful to understand both the space and laboratory plasmas.

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