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# Impact of electron exchange-correlation on drift acoustic solitary waves

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ABSTRACT

The impact of electron exchange-correlation term on the linear and nonlinear quantum ion (QIA) acoustic drift waves in a highly degenerate plasma is investigated. An analytical approach is employed to derive the differential equation which is later on turned into Sagdeev energy integral equation that can be utilized to get drift solitons under existence conditions. It is noted that phase speed/frequency of the linear drift quantum ion acoustic (QIA) waves increases with electron exchange-correlation effect, but the amplitude of the corresponding solitons decreases with inclusion of these effects. Present study is carried out with reference to highly dense plasma environments like fast ignition inertial confinement fusion and white dwarfs etc.





High density degenerate quantum plasma exist in white dwarfs and neutron stars [1,2]. The other areas of physics where quantum degenerate plasmas can be found are: semiconductors, metals, microelectronics [3], carbon nanotubes, quantum dots and quantum wells [4–6]. The study of such plasma is necessary owing to its widespread existence in various environments like astrophysical [6] and laboratory plasmas [3]. The quantum hydrodynamic (QHD) model [7] generalizes the fluid model for the investigation of dense plasmas by taking into account different quantum effects e.g., the fermionic nature of particles, the tunneling effects, magnetic field quantization, electrons exchange and correlation effects etc.

In a number of research papers, it is shown that both linear and nonlinear plasma waves are modified under the impact of quantum effects. Hass et al. [8] pointed out the quantum ion acoustic (QIA) wave in a degenerate plasma, which looks like classical ion acoustic wave (IAW) in the limit of small quantum diffraction effects.

Different types of inhomogeneities exist in both classical and quantum plasmas e.g. density or temperature inhomogeneities etc. [10], which make the investigations of such plasmas complicated. These inhomogeneities are significant to be investigated because they can give rise to mass and energy transport. They can also produce both linear and nonlinear structures like drift solitons, shocks in dissipative plasma and double layers (DLs) [11]. The electromagnetic drift waves in a density nonuniform quantum plasma have been investigated in Ref. [12]. A dielectric response function was derived by Shokri and Rukhadze [13] considering both density and temperature inhomogeneities and discussed unstable drift waves in an electron-ion quantum plasma. Drift and ion acoustic (IA) solitons/shocks have been studied in nonuniform quantum plasma and it is shown that the amplitude and the speed of the nonlinear structures modify with quantum effects. The geometry effects on QIA shock waves in planar and nonplanar models have been elaborated by Sahu & Roychoudhury [14] within the fluid frame work. Ion acoustic [15] and drift-wave-driven vortices [16] in magnetized dense electron-ion quantum plasmas have already been investigated. It is shown in such studies that these structures are of very short spatial scales. The numerical study of dark solitons and vortices in quantum electron plasmas was carried out by Shukla and Eliason [17]. Linear and nonlinear drift waves were investigated in non-uniform quantum magneto-plasma in Ref. [18] in which they pointed out that the width of the compressive soliton decreases with increase in the quantum parameter $H_e = (\hbar\omega_{pe}/2k_B T_{Fe}$, $k_B$ is the Boltzmann constant) while it is reversed for the compressive soliton structure. Collisions of solitary pulses in quantum semiconductor degenerate plasma are investigated by taking into account the electron and hole exchange-correlation forces between the identical particles when their wave functions overlap due to the high number densities [19]. The damage to semiconductors, due to increasing temperature during the beam pumping process has been discussed [20] in which the impact of beam temperature and the streaming speed on soliton and shock-like (double layer) pulses is considered.

The role of temperature degeneracy and magnetic field quantization on the characteristics of drift waves, solitons [21] and DLs [22] have been investigated and it is shown that both types of nonlinear structures are modified by these quantum effects. Elec-

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trostatic excitations in single-walled carbon nano tubes have been investigated taking into account both the many-electron effects of exchange and correlations and the Fermi degeneracy pressure [23]. A deformed Korteweg de Vries-like equation is derived in Ref. [24] and studied the influence of exchange-correlation term on the energy carried by quantum ion-acoustic solitary waves. It is demonstrated in this investigation that the quantum ion-acoustic soliton (QIAS) energy faces a depletion/reduction due to quantum diffraction effect, which may be counteracted by the exchange-correlation effect in a degenerate plasma.

Here, we investigate the influence of electron exchange-correlation on the linear and nonlinear characteristics of inhomogeneous magnetized plasmas. The quantum forces on ions have been neglected due to their large inertia. The frequency/phase speed variation of linear waves and the changes in the amplitude/speed of the nonlinear structures with electron exchange correlation effects is discussed.

We consider electron-ion plasma model, in which electrons behave quantum mechanically and ions are assumed to be classical. Furthermore, it is an assumption that the dense electron-ion plasma is inhomogeneous and fixed in a external magnetic field $\mathbf{B_0} = B_0\,\hat{\mathbf{z}}$ (where $B_0$ is the magnitude of constant magnetic field and $\hat{z}$ is the unit vector along $z$-direction). The density inhomogeneity in plasma is assumed along $-x$-direction. By employing QHD model, the momentum equation for electrons is: [9,24,25],

$$m_e n_e\left(\frac{\partial}{\partial t} + \mathbf{v}_e\cdot\nabla\right)\mathbf{v}_e = -e n_e\left(\mathbf{E} + \frac{1}{c}\mathbf{v_e}\times\mathbf{B_0}\right) - \nabla p_{fe} + \left(\frac{1}{9}\right)\frac{\hbar^2 n_e}{2m_e}\nabla\left(\frac{\nabla^2\sqrt{n_e}}{\sqrt{n_e}}\right) - e n_e\nabla\varphi_{xc}, \tag{1}$$

where $\mathbf{E} = -\nabla\varphi$ is the electrostatic electric field ($\varphi$, the electrostatic potential), $\hbar = h/2\pi$ ($h$ is a Plank's constant), $n_e$ and $m_e$ are number density and mass of the electron respectively. The factor "1/9" appearing in Bohm potential term is included in order to remove the discrepancy that exist in the kinetic and fluid wave theory studied for the fully degenerate electrons plasmas [25]. The inclusion of additional factor "1/9" is in good agreement with kinetic theory for ion acoustic wave as pointed in Ref. [25]. But here we are studying the coupled drift-ion acoustic waves, therefore it is necessary to clarify that this factor "1/9" may or may not be in good agreement with kinetic theory for the present case. The quantum behavior of electrons in Eq. (1) appears in different terms, the quantum degeneracy of electrons appears through Fermi pressure $p_{fe}$, the quantum tunneling effects come through Bohm potential term (4th term on right hand side) and exchange correlation effects ($\varphi_{xc}$) due to 1/2 spin in the last term on right hand side. The Fermonic nature of electrons is represented by 3-dimensional equation of state of Fermi gas as [26],

$$p_e = \frac{m_e v_{Fe}^2}{5 n_{e0}^{2/3}} n_e^{5/3}, \tag{2}$$

where $v_{Fe}$ is the electrons Fermi velocity that is defined in terms of Fermi temperature ($T_{Fe}$) of electrons as: $m_e v_{Fe}^2 = 2k_B T_{Fe}$.

A quantum hydrodynamic fluid model, derived from the Wigner–Poisson equations, is used to study the ultra-fast electron dynamics in thin metal films where exchange and correlation effects [28] are incorporated. The exchange-correlation term is: $\varphi_{xc} = \varphi_x + \varphi_c$, where $\varphi_x$ is the electron exchange potential and $\varphi_c$ is the electrons correlation potential given as

$$\varphi_x \simeq -0.985\frac{e^2}{\varepsilon} n_e^{1/3} \tag{3}$$

and

$$\varphi_c \simeq 0.03349\frac{e^2}{\varepsilon\, a_B}\left[1 + \ln\left|1 + 18.376\, a_B n_e^{1/3}\right|\right] \tag{4}$$

where $a_B = \varepsilon\hbar^2/e^2 m_e$ is the Bohr atomic radius and "$\varepsilon$" is a relative dielectric constant. It is important to mention here that the contribution of electrons exchange-correlation term in the QHD model is incorporated in a very simple way [19,20], but in this manner the basic features remain qualitatively correct. However, the exact study of these quantum effects can be done either by kinetic theory [29] or Density Function Theory (DFT) [27]. DFT has the advantage to estimate the complicated things, which are very difficult to handle with kinetic theory. The numerical value of the coefficient of exchange potential term for ion acoustic wave is used 6.52 instead of 0.985 which shows a good agreement of real frequency between kinetic theory and DFT [29]. Since the frequency range of drift and ion acoustic wave is similar and we are using the fluid theory, therefore the same numerical values of coefficients of exchange-correlation as Refs. [19,20] are utilized. Here, we investigate low-frequency waves i.e., $\partial_t \ll \Omega_j$ ($\Omega_j$ is the cyclotron frequency of ions and electrons) which justifies to ignore the inertia of electrons. Thus the parallel component of Eq. (1), for inertialess electrons gives,

$$\frac{\partial\Phi}{\partial z} - \frac{2}{5}\frac{\partial n_e^{5/3}}{\partial z} + \frac{H_e^2}{18}\frac{\partial}{\partial z}\left(\frac{\nabla_\perp^2\sqrt{n_e}}{\sqrt{n_e}}\right) - \frac{\partial(\alpha_1 n_e^{1/3} + \alpha_2 n_e^{2/3})}{\partial z} = 0, \tag{5}$$

where $H_e = \hbar\omega_{pe}/2k_B T_{Fe}$ is a quantum parameter which represents the ratio between the electron plasmon energy and the electron Fermi energy.

$$\alpha_1 = -1.6\frac{e^2}{\varepsilon} n_{e0}^{1/3},\ \alpha_2 = 5.65\frac{\hbar^2}{m_e} n_{e0}^{2/3} \tag{6}$$

We start with finding the electron number density from Eq. (5). After integrating Eq. (5) and using the Taylor series expansion for various terms, we get

$$n_e = -\frac{\Phi}{A_{xc}} + \frac{H_e^2}{36 A_{xc}^2}\nabla_\perp^2\Phi = \beta_1\Phi + \beta_2\nabla_\perp^2\Phi, \tag{7}$$

where $A_{xc} = (\alpha_1/3 + 2\alpha_2/3 - 2/3)$, $\beta_1 = -1/A_{xc}$ and $\beta_2 = H_e^2/36A_{xc}^2$. The ions are taken to be cold and non-degenerate owing to massive ($m_i \gg m_e$) as compared to degenerate electrons, hence the continuity and momentum equations for ions can be expressed as

$$\frac{\partial n_i}{\partial t} + \nabla\cdot(n_i\mathbf{v}_i) = 0 \tag{8}$$

$$\left(\frac{\partial}{\partial t} + \mathbf{v}_i\cdot\nabla\right)\mathbf{v}_i = \frac{e}{m_i}\left(\mathbf{E} + \frac{\mathbf{v}_i\times\mathbf{B}}{c}\right) \tag{9}$$

The Poisson's equation is given as

$$\nabla^2\varphi = 4\pi e(n_i - n_e) \tag{10}$$

The perpendicular component of ion momentum equation (9) gives,

$$\mathbf{v}_{i\perp} = \frac{c}{B_0}(\mathbf{E}_\perp\times\hat{\mathbf{z}}) - \frac{c}{B_0\Omega_i}\left(\frac{\partial}{\partial t} + \mathbf{v}_i\cdot\nabla\right)\nabla_\perp\varphi = \mathbf{v}_E + \mathbf{v}_{pi}. \tag{11}$$

In the above expression (11), $\Omega_i = eB_0/cm_i$ is defined as ion gyrofrequency, $\mathbf{v}_E = \frac{c}{B_0}(\mathbf{E}_\perp\times\hat{\mathbf{z}})$ is the electric drift and the second term is named as polarization drift $\mathbf{v}_{pi}$. The drift approximation $\partial/\partial t \ll \Omega_i$ has been used in arriving at Eq. (11).