RESEARCH ARTICLE

Frontiers in Advanced Materials Research

DOI: 10.34256/famr2414

Possibility of formation of stationary structures in relativistically degenerate magnetized quantum plasma with exchange-correlation energy

Chinmay Das [a], Pooja Thakur [b], Deepsikha Mahanta [c], Parthasona Maji [d], Saptarshi Ghosh [e,b], Krishna Bulchandani [f,b], Harshit Jain [g,b]

[a] Department of Mathematics, Kabi Jagadram Roy Govt. General Degree College, Mejia, Bankura-722143, West Bengal, India

[b] Institute of Natural Sciences and Applied Technology, Kolkata-700032, India

[c] Department of Mathematics, Gauhati University, Guwahati-781014, India

[d] Department of Physics, Amity University, Newtown, Kolkata, West Bengal-700135, India

[e] Department of Physics, Ramakrishna Mission Residential College (Autonomous), Narendrapur, Kolkata, West Bengal-700103, India

[f] St. Xavier's College, Mumbai-400001, Maharashtra, India

[g] Jawahar Navodaya Vidyalaya, Lalitpur, Uttar Pradesh-284403, India

* Corresponding Author: chinmaydas.mtmh@gmail.com

Received: 09-03-2024, Revised: 20-04-2024, Accepted: 25-04-2024, Published: 15-05-2024

Abstract: In the present paper we have studied the possibility of stationary structure formation in ion acoustic wave in a relaivistically degenerate quantum plasma in presence of magnetic field quantum diffraction parameter and localized exchange correlation energy. Recent authors include exchange correlation term in many plasma configurations including quantum and relativistic regime. We have analyzed the applicability of certain mathematical tools like the Sagdeev pseudo-potential method in dealing with the analysis of the formation and properties of large amplitude solitary structures, double layers, shocks etc. The findings of this paper will help future researchers to select analytical methods while studying wave phenomena in plasma.

Keywords: Ion acoustic wave, quantum diffraction, exchange correlation energy, relativistic degeneracy, Sagdeev pseudo-potential method

1. Introduction

Over the past few years there has been considerable study of quantum diffraction and quantum statistical effects on different plasma phenomena. The relativistic degeneracy pressure played an important role in many astrophysical situations, the degeneracy pressure arise out of extreme high density and the quantum diffraction effect comes into play due to the overlapping of de-Broglie waves of particles thus giving rise to a pressure due to the exclusion principle. Quantum plasma is characterized by high density and low temperature in contrast to the classical thermal plasma. The coupling parameter is the main distinction between quantum and classical regime. It (coupling parameter Γ) is defined as the ratio of the potential to the kinetic energy. The potential energy as given by the Coulomb interaction of charge particles is

$$U_{pot} \approx e^2 \frac{n_{j0}^{1/3}}{\varepsilon_0} \tag{1}$$

The classical and quantum kinetic energies are given by (1)

$$K_{cl} = k_B T \tag{2}$$

and

$$K_{Qj} = k_B T_{Fj} \tag{3}$$

respectively, where T_{Fj} is Fermi temperature is given by

$$T_{Fj} = \frac{\hbar^2}{2m_j} \frac{\left(3\pi^2 n_{j0}\right)^{\frac{2}{3}}}{k_B} \tag{4}$$

The classical and quantum coupling parameter are thus given by

$$\Gamma_{j,cl} = 2.1 \times 10^{-7} \frac{n_{j0}^{1/3}}{T} \tag{5}$$

$$\Gamma_{j,Q} = 10^{11} \times \frac{n_{j0}^{1/3}}{2} \tag{6}$$

From equations (5) & (6) it is clear that where classical weakly coupled plasmas are generally dilute in the quantum range, weakly coupled plasmas are obtained in dense plasma. Thus whether a system behaves classically or quantum mechanically, it is ascertained by the degeneracy parameter $\chi = \frac{T_F}{T}$ and accordingly the Vlasov or Winger formations are used. Quantum plasma is often studied with the help of Winger Poisson or the Schrodinger Poisson model. The quantum hydrodynamic model traces its origin to the Schrodinger Poisson model. It assumes the plasma to be a fluid with quantum properties. The hydrodynamic model equations represent the density and momentum of these quantum particles. Early researcher like Bohm

[1-5] and Madelung [6] carried out a elegant treatment by introducing Eikonal representation for wave functions evolved in the non-stationary Schrodinger equation. The inclusion of Bohm potential or quantum diffraction parameter H, which is the ratio of plasma energy to the Fermi energy is therefore crucial in the energy equation in this quantum regime .

The introduction of an additional exchange correlation potential has been of very recent in interest. It is valid only for a static case. In statistical terms, the exchange correlation is introduced as a part of the free energy functions in addition to the ideal non-interacting term. While deriving expression related to the Fermi pressure and the Bohm potential, the exchange correlation is neglected. However, the exchange correlation free energy term was introduced in local field correction [7-9]. Groth et al [10] has provided an accurate picturisation of exchange correlation terms in finite temperature case.

Quantum plasma is often reported to be observed at astrophysical plasma mainly in white dwarfs, neutron stars etc. [11-16]. Here, in these environment the planetary magnetic field is very strong and therefore give rise to additional magnetic properties. In such environment the density is so high that it give rise to something known as relativistic degeneracy pressure [17]. Such pressure provides the necessary restoring force to the oscillatory particles. Now keeping all this in mind we want to investigate the possibility of the formation of solitary structures, double layers or shocks in the presence of exchange correlation in such dense quantum plasma [18-25]. We have learnt from previous findings that dense plasma showing quantum diffraction effects are weakly coupled. Now we want to study the applicability of exchange correlation energy in local scale that might exit under such conditions and be instrumental in influencing the stationary structure. Apparently is seems that such a term in the free energy will not allow the formation of nonlinear solitary wave structures or anything equivalent to it due to the exchange correlation.

The motivation of the present paper is to mathematically investigate such possibility of the absence of it and find out a route for further study. The paper is organized in the following way- in the second section we introduce the set of dynamic equations with all components of momentum equations viz. the restoring term, the exchange correlation term, the quantum Bohm Potential terms. We also use proper normalization in the aforesaid regime to simplify the equations. In this section we have two subsections for weakly relativistic and ultra relativistic degeneracy cases and obtained the standard nonlinear differential equations in terms of pseudo-potential as prescribed by Sagdeev. In these subsections we find the expression for pseudo-potential in terms of the ion density. In the next section we discus the results from the plots for the pseudo-potential tuned for various parameters. Finally we discuss the possibilities of the formation of stationary structures and conclude with some remarks for future study. Related works are available for reference [26-28]

2. Basic Equations

We consider a two component electron-ion plasma in presence of external magnetic field. The system is similar to a dense plasma in the core and near the vicinity of neutron stars and white dwarfs. For simplicity we take the magnetic field in the z-direction i.e. $\vec{\mathbf{B}} = \mathbf{B_0}\hat{\mathbf{z}}$. We include the quantum diffraction term for electrons and exclude it for ions. The set of unnormalized basic equations are given by [29-36]:

$$\frac{\partial n_j}{\partial t} + \vec{\nabla}\cdot\left(n_j \vec{v_j}\right) = 0 \tag{7}$$

$$\frac{\partial \vec{v}_j}{\partial t} + \left(\vec{v_j}\cdot\vec{\nabla}\right)\vec{v}_j = \frac{e}{m_j}\left[-\vec{\nabla}\varphi + \frac{1}{c}\vec{v}_j \times \vec{B}\right] - \frac{\vec{\nabla} p_j}{m_j n_j} + \frac{1}{m_j}\vec{\nabla} U_{xcj} + \frac{\hbar^2}{2m_j^2}\vec{\nabla}\left(\frac{\nabla^2\sqrt{n_j}}{\sqrt{n_j}}\right) \tag{8}$$

$$\nabla^2\varphi = \frac{e}{\epsilon_L}\left(n_e - n_i\right) \tag{9}$$

Where $\varphi, n_j, v_j, m_j, p_j, c, U_{xcj}$ are the electrostatic potential, number density, velocity, mass, pressure, velocity of light in vacuum and interaction exchange potential for the j th species namely j= i(ion), e(electron) and ϵ_L is the effective linear dielectric constant.

The exchange correlation potential is given by [19]

$$U_{xcj} = -0.985\frac{e^2}{\epsilon_L} n_j^{\frac{1}{3}}\left[1 + \frac{0.034}{n_j^{\frac{1}{3}}\alpha_B^*}\ln\left(1 + 18.37 n_j^{\frac{1}{3}}\alpha_B^*\right)\right] \tag{10}$$

for jth species. where n_{0j} is the equilibrium densities of jth species and $\alpha_B^* = \frac{\epsilon_L \hbar^2}{m_j^* e^2}$ is the Bohr radius. For simplicity the latter equation we can write

$$U_{xcj} = -1.6\frac{e^2}{\epsilon_L} n_j^{\frac{1}{3}} + 5.65\frac{\hbar^2}{m_j} n_j^{\frac{2}{3}} \tag{11}$$

Since $1.837 n_j^{\frac{1}{3}} \alpha_B^* << 1$.

We now normalize the quantities by $x \to \frac{\omega_{pe}}{v_{th}} x, t \to \omega_{pe} t, \varphi \to \frac{e\varphi}{2k_B T_e}, n_j \to \frac{n_j}{n_0}, v_j \to \frac{v_j}{v_{th}}$, here subscript 0 denotes at equilibrium state $\left(n_{0i} = n_{0e} = n_0\right)$ for the jth species. Using these above conditions and considering that electrons are inertialess and exchange correlation for ion of our such system are ignored, (since ions are much heavier than electrons) one can write the dynamic equations in one dimension as:

$$\frac{\partial n_e}{\partial t} + \frac{\partial \left(n_e v_e\right)}{\partial x} = 0 \tag{12}$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial \left(n_i v_i\right)}{\partial x} = 0 \tag{13}$$

$$0 = \frac{\partial \varphi}{\partial x} + \frac{v_{e\perp}}{\rho_s} - \frac{A_e}{n_e}\frac{\partial p_e}{\partial x} - \epsilon_1 \frac{\partial n_e^{\frac{1}{3}}}{\partial x} + \epsilon_2 \frac{\partial n_e^{\frac{2}{3}}}{\partial x} + \frac{H^2}{2}\frac{\partial}{\partial x}\left(\frac{1}{\sqrt{n_e}}\frac{\partial^2 \sqrt{n_e}}{\partial x^2}\right) \tag{14}$$

$$\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial x} = -\mu \frac{\partial \varphi}{\partial x} - \frac{A_i}{n_i}\frac{\partial p_i}{\partial x} \tag{15}$$

and

$$\frac{\partial^2 \varphi}{\partial x^2} = \left(n_e - n_i\right) \tag{16}$$

Where $k_B, T_e, v_{th}, v_{e\perp}, \omega_{pe}$ are the Boltzmann constant, electron temperature, electron thermal velocity, velocity of the electron along y-axis, electron plasma frequency, $H = \frac{\hbar \omega_{pe}}{\sqrt{2k_B T_e m_e v_{th}^2}}$, $\rho_s = \frac{2k_B T_e \omega_{pe} c}{e B_0 v_{th}^2}$, $\epsilon_1 = \frac{1.6 e^2 n_0^{\frac{1}{3}}}{\epsilon_L 2k_B T_e}$, $\epsilon_2 = \frac{5.65 \hbar^2 n_0^{\frac{2}{3}}}{2k_B T_e m_e}$, $\mu = \frac{m_e}{m_i}$ and $A_j, j = e, i$ to be incorporated accordingly. Similar treatment can be found in works by different authors [37-42]

Our purpose is to study the possibility for obtaining stationary solutions for the ion acoustic wave in such plasma. For this we apply following transformation $\xi = x - Mt$ where M is a Mach number.

2.1 Weakly Relativistic Degenerate Case

The weakly relativistic degeneracy pressure for jth species of plasma particles is given by

$$p_j = \frac{1}{20}\left(\frac{\pi}{3}\right)^{\frac{2}{3}} \frac{h^2}{m_j} n_j^{\frac{5}{3}} \tag{17}$$

Here $A_e = \frac{1}{8}\left(\frac{3}{\pi}\right)^{\frac{2}{3}} \frac{h^2 n_0^{\frac{2}{3}}}{2k_B T_e m_e}$ and $A_i = \frac{1}{8}\left(\frac{3}{\pi}\right)^{\frac{2}{3}} \frac{h^2 n_0^{\frac{2}{3}}}{m_i^2 v_{th}^2}$.

Integrating equation (13), (14) & (15) and applying the boundary $n_e \to 1, n_i \to 1, v_i \to 0, \varphi \to 0$ as $\xi \to \pm\infty$ and neglecting small order terms (2nd term on the rhs of equation (14)), we obtained

$$v_i = M\left(1 - \frac{1}{n_i}\right) \tag{18}$$

$$\varphi - A_e n_e^{\frac{2}{3}} - \epsilon_1 n_e^{\frac{1}{3}} + \epsilon_2 n_e^{\frac{2}{3}} + \frac{H^2}{2}\frac{1}{\sqrt{n_e}}\frac{d^2\sqrt{n_e}}{d\xi^2} + d_1 = 0 \tag{19}$$

Where $d_1 = \epsilon_1 + A_e - \epsilon_2$ and

$$\varphi = \frac{1}{\mu}\left[A_i\left(1 - n_i^{\frac{2}{3}}\right) + Mv_i - \frac{v_i^2}{2}\right] \tag{20}$$

Using equation (18) in (20) then we have

$$\varphi = \frac{1}{\mu}\left[A_i\left(1 - n_i^{\frac{2}{3}}\right) + \frac{M^2}{2}\left(1 - \frac{1}{n_i^2}\right)\right] \tag{21}$$

Now employing quasi-neutrality conditions $n_i \approx n_e \approx n$ and put $r^2 = n$ we obtain from equations (19) & (21)

$$\frac{H^2}{2}\frac{d^2 r}{d\xi^2} - \left(A_e + \frac{A_i}{\mu} - \epsilon_2\right) r^{\frac{7}{3}} - \epsilon_1 r^{\frac{5}{3}} + \frac{M^2}{2\mu}\frac{1}{r^3} - \left(\frac{M^2}{2\mu} + \frac{A_i}{\mu} + d_1\right) r = 0 \tag{22}$$

Multiplying both side of the equation (22) by $2\frac{dr}{d\xi}$ and integrating with the boundary condition $n'' \to 0, n' \to 0$ and $n \to 0$ (here primes denote derivative with respect to ξ) we obtain the nonlinear differential equation in terms of density as :

$$\frac{1}{2}\left(\frac{dn}{d\xi}\right)^2 + u(n) = 0 \tag{23}$$

where the expression for the Sagdeev pseudo-potential corresponding to weakly relativistic degenerate case is defined as -

$$u(n) = \frac{1}{H^2}\left[\frac{12}{5}\left(\epsilon_2 - A_e - \frac{A_i}{\mu}\right) n^{\frac{8}{3}} - 3\epsilon_1 n^{\frac{7}{3}} - 4\left(\frac{M^2}{2\mu} + \frac{A_i}{\mu} + d_1\right) n^2 + 2\frac{M^2}{\mu}\right] \tag{24}$$

2.2 For Ultra Relativistic Degenerate Case

In this case pressure is given by

$$p_j = \frac{1}{8}\left(\frac{3}{\pi}\right)^{\frac{1}{3}} hc n_j^{\frac{4}{3}} \tag{25}$$

here

$$A_i = \frac{1}{2}\left(\frac{3}{\pi}\right)^{\frac{1}{3}} \frac{hc n_0^{\frac{1}{3}}}{m_i v_{th}} \quad \text{and} \quad A_e = \frac{1}{4}\left(\frac{3}{\pi}\right)^{\frac{1}{3}} \frac{hc n_0^{\frac{1}{3}}}{k_B T_e} \tag{26}$$

As in the previous case integrate equation (13), (14) & (15) and applying the boundary condition $n_e \to 1, n_i \to 1, v_i \to 0, \varphi \to 0$ as $\xi \to |\pm\infty|$ and neglecting small order terms, we obtained

$$v_i = M\left(1 - \frac{1}{n_i}\right) \quad (27)$$

$$\varphi - A_e n_e^{\frac{1}{3}} - \grave{o}_1 n_e^{\frac{1}{3}} + \grave{o}_2 n_e^{\frac{2}{3}} + \frac{H^2}{2}\frac{1}{\sqrt{n_e}}\frac{d^2\sqrt{n_e}}{d\xi^2} + d_2 = 0 \quad (28)$$

Where $d_2 = \grave{o}_1 + A_e - \grave{o}_2$ and

$$\varphi = \frac{1}{\mu}\left[Mv_i - \frac{v_i^2}{2} + A_i\left(1 - n_i^{\frac{1}{3}}\right)\right] \quad (29)$$

Using equation (27) in (29) then we have

$$\varphi = \frac{M^2}{2\mu}\left(1 - \frac{1}{n_i^2}\right) + \frac{A_i}{\mu}\left(1 - n_i^{\frac{1}{3}}\right) \quad (30)$$

Similarly, employing quasi-neutrality conditionsconditions $n_i \approx n_e \approx n$ and put $r^2 = n$, from equation (28) & (30) we get

$$\frac{H^2}{2}\frac{d^2 r}{d\xi^2} - \left(A_e + \frac{A_i}{\mu} + \grave{o}_1\right) r^{\frac{5}{3}} + \grave{o}_2 r^{\frac{7}{3}} - \frac{M^2}{2\mu}\frac{1}{r^3} + \left(\frac{M^2}{2\mu} + d_2 + \frac{A_i}{\mu}\right) r = 0 \quad (31)$$

Likewise multiplying both side of the equation (31) by $2\frac{dr}{d\xi}$ and integrating with the boundary condition $n'' \to 0, n' \to 0$ and $n \to 0$ and proceeding accordingly we obtain the nonlinear differential equation in terms of density for ultra relativistic case as :

$$\frac{1}{2}\left(\frac{dn}{d\xi}\right)^2 + u(n) = 0 \quad (32)$$

where the Sagdeev pseudo-potential for ultra relativistic degenerate case is define as -

$$u(n) = \frac{1}{H^2}\left[-\frac{3}{4}\left(A_e + \frac{A_i}{\mu} + \grave{o}_1\right) n^{\frac{7}{3}} + \frac{3}{5}\grave{o}_2 n^{\frac{8}{3}} + \left(\frac{M^2}{2\mu} + d_2 + \frac{A_i}{\mu}\right) n^2 + \frac{2}{4\mu}\right] \quad (33)$$

3. Result and Discussion

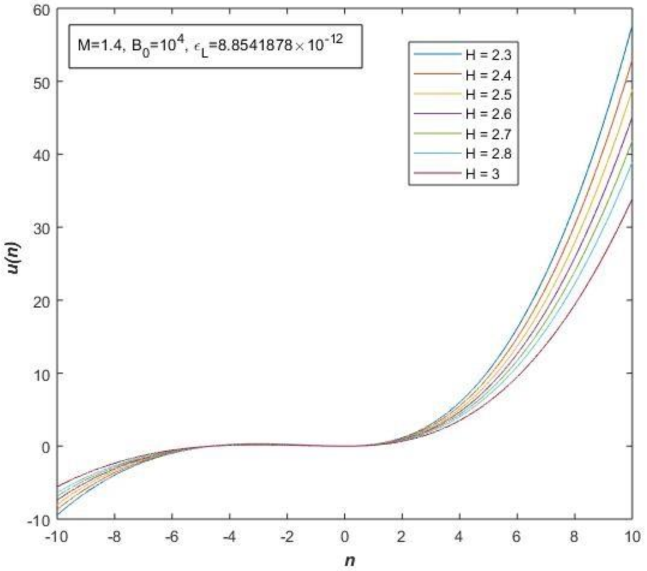

Figure 1. Variation of $u(n)$ for weakly relativistic case with quantum diffraction parameter H.

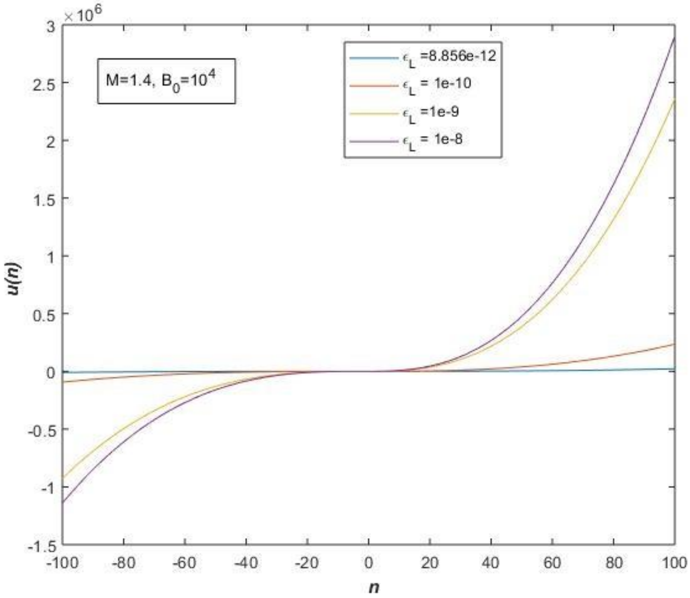

Figure 2. Variation of $u(n)$ for weakly relativistic case with dielectric parameter ϵ_L

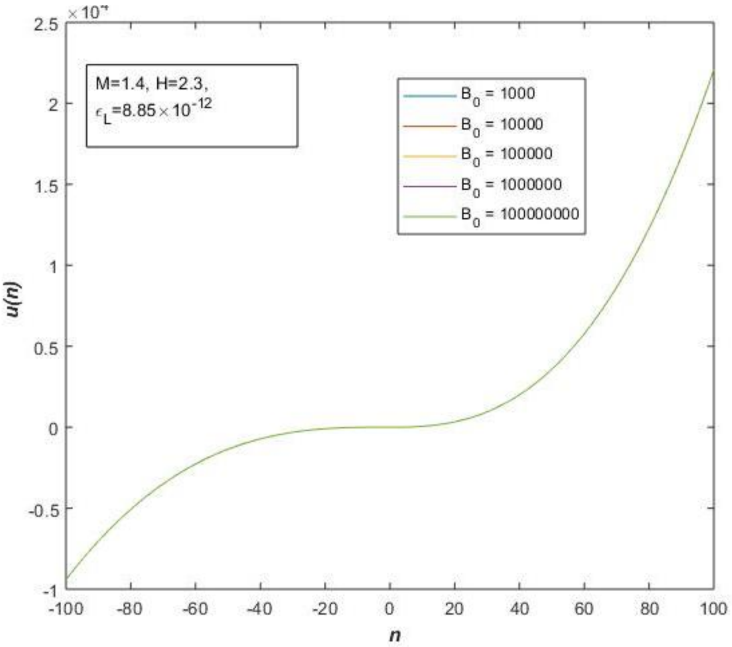

Figure 3. Variation of $u(n)$for weakly relativistic case with magnetic field B_0

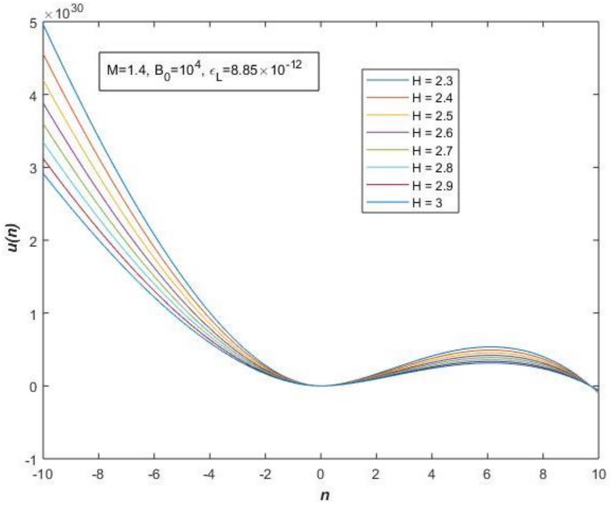

Figure 4. Variation of $u(n)$ for ultra relativistic case with quantum diffraction parameter H

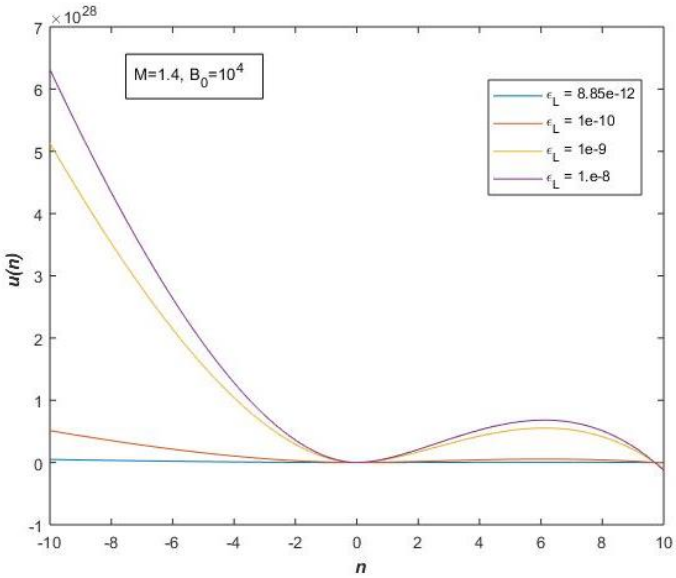

Figure 5. Variation of $u(n)$ for ultra relativistic case with dielectric parameter ϵ_L

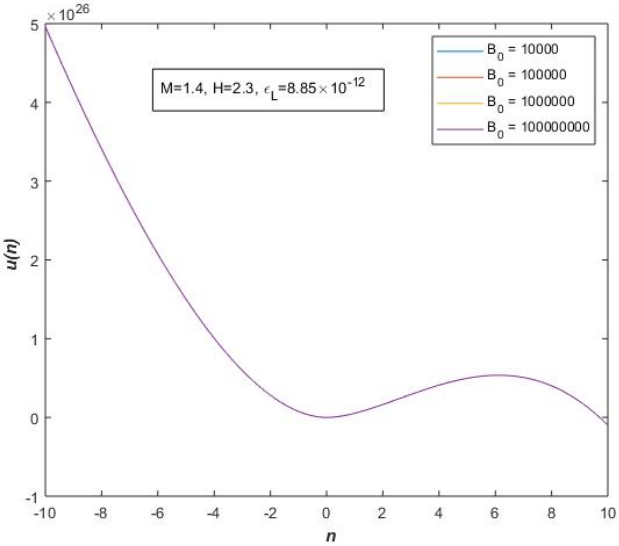

Figure 6. Variation of $u(n)$for ultra relativistic case with magnetic field B_0

In order to check the possibility of the formation stationary structures in the quantum domain with relativistic degeneracy pressure and exchange correlation terms in the free energy we will plot the pseudo-potential with variation for different parameters. The particle density in such astrophysical dense plasma is $n_0 = 10^{20}$, the magnetic field $B_0 = 10^4 \ Tesla$, the charge

& mass electron and ionic as well as universal constant like m_e, m_i, h, c are taken accordingly. The term ϵ_L is taken as $\epsilon_L = 8.8541878 \times 10^{-12} F/m$, using the value of Mach number $M = 1.4$ we plot various cases corresponding to Sagdeev pseudo-potential for various parameter.

First we plot the pseudo-potential for the weakly relativistic degenerate case. While varying the quantum diffraction parameter H we observe that for any variation of H, there is no dip in the plot for pseudo-potential; which implies that there is no possibility for the formation of solitary structure or double layer or shocks this is shown in figure-1. In the next figure (figure-2) we vary the linear dielectric function ϵ_L included the exchange correlation energy . Over a range of ϵ_L from 10^{-12} to 10^{-9} , there is no visible change in the plot for $u(n)$. It is thus clear that the variation in the linear dielectric factor also fails to provide a potential well. It is seen from figure-3 where we vary the magnetic field the potential curve become independent of such variations. However, here in the weakly relativistic degenerate case we do not obtain any conditions for the formation of solitary structure shocks or double layers [43-51].

We next study the parametric dependence of Pseudo-potential for ultra relativistic case. It has been shown in figure-4 that there is small potential dip in the pseudo potential versus number density plot. It is further shown that with increased value of quantum diffraction parameter the potential well becomes shallow. Or in other words a relatively smaller value of H parameter in essence apparently give rise to a possibility of solitary structures. But the potential well corresponds to positive values of $u(n)$. This means that no stable structures which necessitates negative value of pseudo-potential would be formed.

Next in figure-5 we find that with increase in the value of linear dielectric function over some orders of magnitude it is more apparent to obtain the solitary structures, when compared to the effect of quantum diffraction, the variation of dielectric function is more prominent. For no values of ϵ_L there is possibility in obtaining the required condition for stationary structures.

As expected from the previous weakly relativistic case there is no effect of magnetic field on the pseudo-potential.

The result discussed above is crucial in further study of wave characteristics along with correlation energy function in the quantum domain including ultra relativistic degeneracy pressure [52-54]. Thus it can be said that there is no possibility of the formation of shocks, double layer or solitary structure in such regime. Any further theoretical study in this direction will apparently give nonphysical solutions. The above findings may be important to those who will try to incorporate exchange correlation term in many plasma situations. Though the result appear to be null in influencing the conditions for formation of stationary structure, yet it is significant in directing the future researchers to properly include the exchange term in situations where it is more meaningful and appropriate.

References

[1] D. Bohm, B. J. Hiley, (2006) The Undivided Universe: An Ontological Interpretation of Quantum Theory. Routledge, https://doi.org/10.4324/9780203980385

[2] D. Bohm, D. Pines, A collective description of electron interactions: III. coulomb interactions in a degenerate electron gas, Physical Review, 92, (1953) 609-625. https://doi.org/10.1103/PhysRev.92.609

[3] D. Bohm, A suggested interpretation of the quantum theory in terms of "hidden" variables. I, Physical Review, 85(1952) 166-179. https://doi.org/10.1103/PhysRev.85.166

[4] D. Bohm, A suggested interpretation of the quantum theory in terms of "hidden" variables. II, Physical Review, 85(1952) 180-193. https://doi.org/10.1103/PhysRev.85.180

[5] D. Bohm, B. Hiley, On the intuitive understanding of nonlocality as implied by a quantum theory, Foundations of Physics, 5, (1975) 93-109. https://doi.org/10.1007/BF01100319

[6] E. Madelung. Quantentheorie in hydrodynamischer form. Zeitschrift für Physik A Hadrons and Nuclei, 40(3), (1927) 322-326. https://doi.org/10.1007/BF01400372

[7] MA. Leontovich, (1966) Reviews of plasma physics, Springer New York, NY. https://doi.org/10.1007/978-1-4615-7799-7

[8] T. Sjostrom, J. Daligault. Gradient corrections to the exchange-correlation free energy. Physical Review B, 90(2014), 155109. https://doi.org/10.1103/PhysRevB.90.155109

[9] M. Corradini, R. Del Sole, G. Onida, and M. Palummo. Analytical expressions for the local-field factor g(q) and the exchange-correlation kernel K_xc (r) of the homogeneous electron gas, Physical Review B, 57(1998) 14569-14571. https://doi.org/10.1103/PhysRevB.57.14569

[10] S. Groth, T. Dornheim, T. Sjostrom, F.D. Malone, W. M. C. Foulkes, M. Bonitz, Ab initio exchange-correlation free energy of the uniform electron gas at warm dense matter conditions, Physical Review Letters, 119(2017) 135001. https://doi.org/10.1103/PhysRevLett.119.135001

[11] L. Brey, Jed Dempsey, N.F. Johnson, B.I. Halperin, Infrared optical absorption in imperfect parabolic quantum wells, Physical Review B, 42(1990) 1240. https://doi.org/10.1103/PhysRevB.42.1240

[12] G. Chabrier, F Douchin, A.Y. Potekhin, Dense astrophysical plasmas, Journal of Physics: Condensed Matter, 14(40), (2002) 9133. https://doi.org/10.1088/0953-8984/14/40/307

[13] S. Ichimaru, Strongly coupled plasmas: high-density classical plasmas and degenerate electron liquids, Reviews of Modern Physics, 54(4), (1982) 1017. https://doi.org/10.1103/RevModPhys.54.1017

[14] S. Singla, S. Chandra, N.S. Saini, Simulation study of dust magnetosonic excitations in a magnetized dusty plasma, Chinese Journal of Physics, 85 (2023) 524-533. https://doi.org/10.1016/j.cjph.2023.06.014

[15] A. Roychowdhury, S. Banerjee, S. Chandra, Stationary formation of dust-ion acoustic waves in degenerate dusty plasma at critical regime, African Review of Physics, 15(2021) 102.

[16] S. Ballav, S. Kundu, A. Das, S. Chandra, Non-linear behaviour of dust acoustic wave mode in a dynamic dusty plasma containing negative dust particles and positrons, African Review of Physics, 15(2021) 54.

[17] S. Chandrasekhar, (1957) An Introduction to the Study of Stellar Structure, Dover Publications, United Kingdom.

[18] J. Goswami, S. Chandra, J. Sarkar, B. Ghosh, Amplitude modulated electron acoustic waves with bipolar ions and kappa distributed positrons and warm electrons, Pramana-Journal of Physics, 95, (2021) 54. https://doi.org/10.1007/s12043-021-02085-1

[19] C. Das, S. Chandra, B. Ghosh, Effects of exchange symmetry and quantum diffraction on amplitude modulated electrostatic waves in quantum magnetoplasma, Pramana-Journal of Physics, 95 (2020) 78. https://doi.org/10.1007/s12043-021-02108-x

[20] H. Sahoo, C. Das, S. Chandra, B. Ghosh, and K. K. Mondal, Quantum and relativistic effects on the kdv and envelope solitons in ion-plasma waves, IEEE Transactions on Plasma Science, 50(6), (2022) 1610-1623. https://doi.org/10.1109/TPS.2021.3120077

[21] A. Das, P. Ghosh, S. Chandra, V. Raj, Electron acoustic peregrine breathers in a quantum plasma with 1-d temperature anisotropy, IEEE Transactions on Plasma Science, 50(6), (2022)1598-1609. https://doi.org/10.1109/TPS.2021.3113727

[22] S. Chandra, C. Das, J. Sarkar, Evolution of nonlinear stationary formations in a quantum plasma at finite temperature, Zeitschrift fur¨ Naturforschung A, 2021. https://doi.org/10.1515/zna-2020-0328

[23] S. Shilpi, C. Das, S. Chandra, Study of quantum-electron acoustic solitary structures in fermi plasma with two temperature electrons, Springer Proceedings in Complexity, (2022). https://doi.org/10.1007/978-3-030-99792-2_6

[24] C. Das, S. Chandra, S. Kapoor, and P. Chatterjee, Semi-lagrangian method to study nonlinear electrostatic waves in quantum plasma, IEEE Transactions on Plasma Science, 50(6), (2022) 1579-1584. https://doi.org/10.1109/TPS.2022.3158965

[25] C. Das, S. Chandra, B. Ghosh, Amplitude modulation and soliton formation of an intense laser beam interacting with dense quantum plasma: Symbolic simulation analysis, Contributions to Plasma Physics, 6(8), (2020). https://doi.org/10.1002/ctpp.202000028

[26] A. Maiti, S. Chowdhury, P. Singha, S. Ray, R. Dasgupta, S. Chandra, Study of small amplitude ion-acoustic bunched solitary waves in a plasma with streaming ions and thermal electrons, African Review of Physics, 15, (2021) 97.

[27] T. Ghosh, S. Pramanick, S. Sarkar, A. Dey, S. Chandra, Chaotic scenario in three-component fermi plasma, The African Review of Physics, 15, (2021) 45.

[28] C. Das, S. Chandra, B. Ghosh, Nonlinear interaction of intense laser beam with dense plasma, Plasma Physics and Controlled Fusion, 63(1), (2020). https://doi.org/10.1088/1361-6587/abc732

[29] S. Dey, D. Maity, A. Ghosh, P. Samanta, A. De, S. Chandra, Chaotic excitations of rogue waves in stable parametric region for highly-energetic pair plasmas, The African Review of Physics, 15, (2021) 33.

[30] M. Ghosh, K. Sharry, D. Dutta, S. Chandra, Propagation of rogue waves and cnoidal waves formations through low frequency plasma oscillations, The African Review of Physics, 15, (2021) 63.

[31] A.K. Singh, S. Chandra, Second harmonic generation in high density plasma, The African Review of Physics, 12, (2017) 84-89.

[32] P. Samanta, A. De, S. Dey, D. Maity, A. Ghosh, S. Chandra, Nonlinear excitations in dust-ion acoustic waves and the formation of rogue waves in stable parametric region in a 3-component degenerate plasma, The African Review of Physics, 15, (2021) 10.

[33] S. Chandra, J. Sarkar, C. Das, B. Ghosh, Self-interacting stationary formations in plasmas under externally controlled fields, Plasma Physics Reports, 47, (2021) 306-317. https://doi.org/10.1134/S1063780X21030041

[34] A. Mukhopadhyay, D. Bagui, S. Chandra, Electrostatic shock fronts in two-component plasma and its evolution into rogue wave type solitary structures, The African Review of Physics, 15 (2021), 25.

[35] A. Ghosh, J. Goswami, S. Chandra, C. Das, Y. Arya, and H. Chhibber, Resonant interactions and chaotic excitation in nonlinear surface waves in dense plasma, IEEE Transactions on Plasma Science, 50(6), (2022) 1524-1535. https://doi.org/10.1109/TPS.2021.3109297

[36] S. Ballav, A. Das, S. Pramanick, S. Chandra, Plasma shock wave in gamma-ray bursts: Nonlinear phenomena and radiative process, IEEE Transactions on Plasma Science, 50(6), (2022) 1488-1494. https://doi.org/10.1109/TPS.2021.3112178

[37] J. Sarkar, S. Chandra, A. Dey, C. Das, A. Marick, P. Chatterjee, Forced kdv and envelope soliton in magnetoplasma with kappa distributed ions, IEEE Transactions on Plasma Science, 50(6), (2022) 1565-1578,. https://doi.org/10.1109/TPS.2022.3140318

[38] S. Sarkar, A. Sett, S. Pramanick, T. Ghosh, C. Das, and S. Chandra, Homotopy study of spherical ion-acoustic waves in relativistic degenerate galactic plasma, IEEE Transactions on Plasma Science, 50(6), (2022) 1477-1487. https://doi.org/10.1109/TPS.2022.3146441

[39] Sharry, D. Dutta, M. Ghosh, and S. Chandra, Magnetosonic shocks and solitons in fermi plasma with quasiperiodic perturbation, IEEE Transactions on Plasma Science, 50(6), (2022) 1585-1597. https://doi.org/10.1109/TPS.2022.3148183

[40] A. Majumdar, A. Sen, B. Panda, R. GHOSH, S. Mallick, S. Chandra, Study of shock fronts and solitary profile in a weakly relativistic plasma and its evolution into an amplitude modulated envelop soliton, The African Review of Physics, 15(18), (2021).

[41] S. Thakur, C. Das, S. Chandra, Stationary structures in a four component dense magnetoplasma with lateral perturbations, IEEE Transactions on Plasma Science, vol. 50(6), (2022) 1545-1556. https://doi.org/10.1109/TPS.2021.3133082

[42] S. Chandra, J. Goswami, J. Sarkar, C. Das, B. Ghosh, D. Nandi, Formation of electron acoustic shock wave in inner magnetospheric plasma, Indian Journal of Physics, 2021. https://doi.org/10.1007/s12648-021-02276-x

[43] A. Dey, S. Chandra, C. Das, S. Mandal, T. Das, Rogue wave generation through non-linear self interaction of electrostatic waves in dense plasma, IEEE Transactions on Plasma Science, vol. 50, no. 6, pp. 1557-1564, 2022.

[44] S. Chandra, R. Banerjee, J. Sarkar, S. Zaman, C. Das, S. Samanta, F. Deeba, B. Dasgupta, Multistability studies on electron-acoustic wave in a magnetized plasma with supra-thermal ions, Journal of Astrophysics and Astronomy, vol. 43, no. 71, 2022. https://doi.org/10.1007/s12036-022-09835-6

[45] S. Chandra, S. Kapoor, D. Nandi, C. Das, and D. Bhattacharjee, Bifurcation analysis of eaws in degenerate astrophysical plasma: Chaos and multistability, IEEE Transactions on Plasma Science, vol. 50, no. 6, pp. 1495-1507, 2022. https://doi.org/10.1109/TPS.2022.3166694

[46] G. Manna, S. Dey, J. Goswami, S. Chandra, J. Sarkar, A. Gupta, Formation of nonlinear stationary structures in ionospheric plasma, IEEE Transactions on Plasma Science, vol. 50(6), (2022) 1464-1476,. https://doi.org/10.1109/TPS.2022.3166685

[47] S. Dey, S. Ghosh, D. Maity, A. De, S. Chandra, Two-stream plasma instability as a potential mechanism for particle escape from the venusian ionosphere, Pramana-Journal of Physics, 2022. https://doi.org/10.1007/s12043-022-02462-4

[48] M. Chatterjee, M. Dasgupta, P. DAS, M. Halder, S. Chandra, "Study of dynamical properties in shock & solitary structures and its evolutionary stages in a degenerate plasma," The African Review of Physics, 15, (2021) 75.

[49] S. Ghosh, S. Saha, T. Chakraborty, K. Sadhukhan, R. Bhanja, S. Chandra, "Linear and non-linear properties of electron acoustic waves in a viscous plasma," The African Review of Physics, 15, (2021) 90.

[50] S. Singla, S. Chandra, N. Saini, Simulation study of dust magnetosonic excitations in a magnetized dusty plasma, Chinese Journal of Physics, (2023) 10-1016. https://doi.org/10.1016/j.cjph.2023.06.014

[51] S. Chandra, C. Das, J. Sarkar, C. Chowdhari, Degeneracy affected stability in ionospheric plasma waves, Pramana-Journal of Physics, 98 (2), (2023) https://doi.org/10.1007/s12043-023-02687-x

[52] S. Chandra, P.S. Maji, I. Maiti, K. Samanta, S. Mukherjee, S.Kapoor, J. Goswami, S. Nasipuri, A. Bala, S. Nasrin, Double Layers and Solitary Structures Observed in Ion Acoustic Mode Around Critical Regime and Its Possible Precursory Mechanism, IEEE Transactions on Plasma Science, (2024) 1-14. https://doi.org/10.1109/TPS.2024.3388272

[53] S.Chandra, C. Das, D. Batani, A.A. Aliverdiev, R. Myrzakulov, A. Majumdar, S.Mallick, R. Ghosal, B. Panda, A. Sen, Evolutionary Stages of Envelope Soliton During Laser-Plasma Interaction, IEEE Transactions on Plasma Science, (2024), https://doi.org/10.1109/TPS.2024.3388317

[54] C. Das, S. Chandra, A. Saha, P. Chatterjee, Field Modulations of Ion Acoustic Waves in Plasma With Vasyliunas-Schamel Distributed Electrons, IEEE Transactions on Plasma Science, (2024). https://doi.org/10.1109/TPS.2024.3388319

Acknowledgements

The authors also acknowledge the Institute of Natural Sciences and Applied Technology, Kolkata for providing research facilities.

Conflict of interest: The Authors have no conflicts of interest to declare that they are relevant to the content of this article.