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Large amplitude ion acoustic waves in ultrarelativistic degenerate plasma

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Abstract

By employing Sagdeev's pseudopotential technique large amplitude solitary waves are investigated in ultra-relativistic degenerate quantum plasma containing electrons and ions. The effect of relativistic degeneracy, quantum diffraction, ion temperature has important contribution in determining the nature of pseudopotential well. They also determine the formation and properties of ion acoustic waves in this two-component electron-ion dense quantum plasma.

Key words- quantum plasmas, quantum hydrodynamic model, relativistic degeneracy effect, ion-acoustic waves, Sagdeev's pseudopotential approach, solitary wave structures.

I. INTRODUCTION

The Plasma itself is a complex system and shows a no of linear & nonlinear effects [1, 2]. Ion acoustic wave (IAW) is one such important phenomenon. It can exist as a solitary wave in a steady state situation. Solitary waves of small amplitudes as well as double layers are investigated by using reductive perturbation technique. On the contrary large amplitudes solitary waves is generally investigated by using Sagdeev's pseudopotential method [3, 4].

Recently researches in quantum plasma have developed very fast because of its application in astrophysical as well as laboratory plasmas [5, 6]. Quantum plasma is characterized by low temperature and high density that causes the overlapping of thermal de Broglie wavelengths that give rise to quantum effects. Quantum plasma finds applications in semi conductor nano devices [7], quantum walls [8], CNTs [9], ultra cold plasmas [10], micro electronics [11], biophotonics [12] intense laser solid interaction [13] etc. In astrophysical environment super dense plasmas have been observed, namely in white dwarf, neutron star [14] etc. Several authors have studied different aspects of such ultracold dense plasmas with the pioneering works of Haas [15], Manfredi [16], Shukla [17], Eliasson [18], Brodin, Marklund [19, 20] & others [21 -24]. Quantum plasma has gained much popularity in recent years. By applying quantum hydrodynamic model (QHD) [15] the mathematical intricacies have become quite easier to explore. In the recent years solitary waves have been investigated in electron acoustic wave by Chandra *et al* [25, 26]. In a relativistically degenerate quantum plasma. Modulation instability and small amplitude solitary structure has also been investigated by many authors [27, 28]. Finite temperature effect [29, 30] & relativistic drifts [31, 32] has also been considered by some. Quantum drift waves have been studied by Shokri and Rakhadzem [33] using kinetic theory approach. Haque & Masood [34] have studied drifts solitons in quantum magneto plasma. Ourabah and Tribeche [35] have investigated the effect of exchange correlation in quantum ion acoustic waves. Kinetic viscosity in electron ion quantum plasma has been studied by Sahu & Roychoudhury [36].

Ion acoustic solitary waves (ISAW) have been studied by many authors [37-42, 43-45]. Nonlinear IAW in a one dimensional collisionless, unmagnetised quantum plasma has been investigated by Haas *et-al.* [46] by incorporating Bohm potential & quantum statistical pressure (using FD distribution) Misra & Bhowmik [38] studied the nonlinear IAWs in quantum plasma in spherical geometry by applying Kodomstev-Petviasville (KP) equation by using Zakharov-Kuznetsov equation in the quantum regime. IAWs have been investigated in quantum magneto plasma by Moslem *et-al.* [39]. The inclusion of dust in ion acoustic solitary wave have also been carried out by some authors [41].using Korteweg de-Vries (KdV) equation has been used by Masood *et al* [42]. Most of these works are done using reductive perturbation technique which a valid for small amplitude waves in order to investigate large amplitude solitary structure. It is necessary to analyze the exact solitary waves in which the total nonlinearity of the system is considered without any approximation. In plasma Sagdeev's pseudopotential is one such method which is widely used in various plasma models [47-49].Ion acoustic solitary waves in unmagnetised electron plasma has been studied by Masood & Mushtaq [43] using Sagdeev's pseudopotential approach. In their investigation they have neglected the ion temp which has finite effect in the formation and properties of ion acoustic solitary waves. The findings of Ali *et al* [44] have given much more insight to the properties of IAWs. He also neglected the effect of ion temperature.

In ultra dense matter the presence of relativistic degeneracy effects is given by Chandrasekhar in 1939 [50]. The expression given by him has been applied in quantum plasmas by Akbari-Moghanjoughi [51], El-Labany [52], Mamun and Shukla [53], Chandra *et al*. [25, 26]. Most of the work in ion acoustic waves including relativistic degeneracy effects were limited to small amplitude waves for which reductive perturbation technique is generally used. Large amplitude waves in such relativistic quantum plasma have so far to our knowledge has not been investigated. The motivation of the present paper is to study the large amplitude ion acoustic solitary structure ultra relativistic degenerate electron ion plasma by employing Sagdeev's pseudopotential method.

The paper is organized in the following way; in section two, the basic dynamic equations of the system using QHD model are introduced with proper justifications. It also derives the expression for pseudopotential U(n) in terms of n. The third section investigates the solitary properties of ion acoustic wave and its dependence of different parameters. Finally we discuss our results and came to a conclusion.

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II. BASIC EQUATIONS

Let us consider the homogeneous and unmagnetised electron-ion quantum plasma. In quantum plasma the effect of ion temperature on the IAW is studied by assuming the electrons to be inertialess & the ions are taken to be inertial. The phase velocity of the wave is taken to be $V_{Fi} << \omega / k << V_{Fe}$ (where V_{Fi} and V_{Fe} are the Fermi velocities of ions and electrons respectively). Ion pressure effects due to ion Fermi temperature can therefore be ignored. The basic dynamic equations ignoring the non-linear mechanisms of ion acoustic waves in quantum plasmas are given in the dimensional (unnormalised) form as;

$$\frac{\partial n_e}{\partial t} + \frac{\partial (n_e v_e)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial (n_i v_i)}{\partial x} = 0 \tag{2}$$

$$0 = \frac{e}{m_e}\frac{\partial \phi}{\partial x} - \frac{1}{m_e n_e}\frac{\partial p_e}{\partial x} + \frac{h}{2m_e^{2}}^{2}\frac{\partial}{\partial x}\left(\frac{\partial^2 \sqrt{n_e} \big/ \partial x^2}{\sqrt{n_e}}\right) \tag{3}$$

$$\frac{\partial v_i}{\partial t} + v_i\frac{\partial v_i}{\partial x} = -\frac{e}{m_i}\frac{\partial \phi}{\partial x} - \sigma_1 n_i \frac{\partial n_i}{\partial x} \tag{4}$$

$$\frac{\partial^2 \phi}{\partial x^2} = -4\pi e (n_i - n_e) \tag{5}$$

Here n_j, v_j, m_j, $-e$ are the density, velocity field, mass, and charge, respectively where j $=e$, i stands for electrons and ions. Meanwhile, ħ$=h/2\pi$ is the reduced Planck constant, ϕ is the electrostatic wave potential, p_e is the electron pressure, and $\sigma_1 = 3[T_{Ei}/T_{Fe}]$ is the ion-to-electron Fermi Temperature ratio, where T_{Fj} is the Fermi temperature of the j[th] species. At equilibrium, we have $n_{i0}=n_{e0}=n_0$. Following Chandrasekhar (1939) the electron degeneracy pressure in fully degenerate and relativistic configuration can be expressed in the following form:

$$P_e = \left(\frac{\pi m_e^4 c^5}{3h^3}\right)[\mathrm{R}_e(2R_e^2 - 3)\sqrt{(1+R_e^2)} + 3\sinh^{-1} R] \tag{6}$$

in which $R_j = p_{Fj}/m_e c = \left[3h^3 n_j / 8\pi m_e^3 c^3\right]^{\frac{1}{3}} = R_{j0} n_j^{\frac{1}{3}}$

[$R_{j0} = (n_{j0}/n_0)^{1/3}; n_0 = 8\pi m_e^3 c^3 / 3h^3 \approx 5.9\times 10^{29} cm^{-3}$], 'c' is the speed of light in vacuum. p_{Fj} is the electron Fermi relativistic momentum. It is to be noted that in the limits of very large values of relativity parameter R_e (the ultra relativistic case) we obtain:

$$P_e = \frac{1}{8}\left(\frac{3}{\pi}\right)^{\frac{1}{3}} hc n_e^{\frac{4}{3}} \text{ (For } R_e \to \infty) \tag{7}$$

Note that the degenerate electron pressure depends only on the electron number density but not on the electron temperature.

Now, let us assume $p_e = \frac{1}{8}\left(\frac{3}{\pi}\right)^{\frac{1}{3}} hc n_e^{\frac{4}{3}} = F n^{\frac{4}{3}}$ (8)

where $F = \frac{1}{8}\left(\frac{3}{\pi}\right)^{\frac{1}{3}} hc$

So; $\frac{\partial p_e}{\partial x} = \frac{\partial}{\partial x}\left(Fn_e^{\frac{4}{3}}\right) = \frac{4}{3}Fn_e^{\frac{1}{3}}\frac{\partial n_e}{\partial x}$

$$\frac{1}{n_e}\frac{\partial p_e}{\partial x} = \frac{4}{3}Fn_e^{\frac{-2}{3}}\frac{\partial n_e}{\partial x} \qquad (9)$$

Now putting (8) in the equation (3) and using the following normalization:

$x \to \frac{x\omega_i}{c_s},\ t \to t\omega_i,\ \phi \to \frac{e\phi}{2k_B T_{Fe}}, n_j \to \frac{n_j}{n_0},\ u_j \to \frac{u_j}{c_s}$ the set of normalized (dimensionless) equations are given as:

$$\frac{\partial n_e}{\partial t} + \frac{\partial(n_e v_e)}{\partial x} = 0 \qquad (10)$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial(n_i v_i)}{\partial x} = 0 \qquad (11)$$

$$0 = \frac{\partial \phi}{\partial x} - \frac{4}{3}Fn_e^{\frac{-2}{3}}\frac{\partial n_e}{\partial x} + \frac{H^2}{2}\frac{\partial}{\partial x}\left(\frac{\partial^2\sqrt{n_e}/\partial x^2}{\sqrt{n_e}}\right) \qquad (12)$$

$$\frac{\partial v_i}{\partial t} + v_i\frac{\partial v_i}{\partial x} = -\frac{\partial \phi}{\partial x} - \sigma_1 n_i\frac{\partial n_i}{\partial x} \qquad (13)$$

$$\frac{\partial^2 \phi}{\partial x^2} = (n_i - n_e) \qquad (14)$$

in which $\omega_e = \sqrt{4\pi n_{e0}e^2/m_e}$ is the plasma frequency, $c_s = \sqrt{2k_B T_{Fe}/m_e}$ is the quantum ion-acoustic speed. H is the non-dimensional quantum diffraction parameter defined as $H = \hbar\omega_{ec}/2k_B T_{Feh}$, where T_{Fe} is the Fermi temperatures for electrons.

In order to get localized stationary solution, let us assume that all dependent variables are functions of single independent variable:

$$\xi = x - Mt \qquad (15)$$

where M is the Mach number defined by v/c_s, v is the velocity of the nonlinear waveform moving with the frame.

By integrating (12) once and applying boundary conditions $n_e \to 1$ & $\phi \to 0$ at $\xi = |\pm\infty|$; we obtain:

$$\phi = -4F + 4Fn_e^{\frac{1}{3}} - \frac{H^2}{2}\frac{1}{\sqrt{n_e}}\frac{\partial^2\sqrt{n_e}}{\partial x^2} \qquad (16)$$

From the ion continuity equation (11) and ion momentum equation (13) with proper boundary conditions $\phi \to 0,\ v_i \to 0,\ n_i \to 1\ as\ \xi \to |\pm\infty|$ we obtain:

$$v_i = M(1 - \frac{1}{n_i}) \qquad (17)$$

$$v_i^2 - 2Mv_i + \sigma_1 n_i^2 - \sigma_1 = -2\phi \qquad (18)$$

Substituting equation (17) in (18) we get,

$$\phi = \frac{M^2}{2}[1 - \frac{1}{n_i^2}] + \frac{\sigma_1}{2}(1 - n_i^2) \qquad (19)$$

Now by employing quasi-neutrality conditions

$$n_i \approx n_e = n \qquad (20)$$

and also substituting $Z = \sqrt{n}$, from equations (16-19) we obtain

$$\frac{H^2}{2}\frac{\partial^2 Z}{\partial \xi^2} = -4FZ + 4FZ^{\frac{2}{3}} - \frac{M^2}{2}[Z - \frac{1}{Z^3}] - \frac{\sigma_1}{2}[Z - Z^5] \qquad (21)$$

Multiplying both sides of equation (21) by $dz/d\xi$ and integrating with the boundary condition $n'' \to 0$ and $n' \to 0$ and $n \to 0$, (where primes represent derivatives with respect to ξ) we obtain the nonlinear differential equation in terms of density as:

$$\frac{1}{2}\left(\frac{dn}{d\xi}\right) + u(n) = 0 \qquad (22)$$

Where, the Sagdeev's pseudopotential is defined as equation:

$$U(n) = \frac{8n}{H^2}\left[\begin{array}{c}\left(4F + M^2 + \sigma_1\right)\left(\frac{n-1}{4}\right) \\ -3F\left(\frac{n^{\frac{4}{3}} - 1}{2}\right) + \frac{M^2}{4}\left(\frac{1}{n} - 1\right) \\ -\frac{\sigma_1}{12}\left(n^3 - 1\right)\end{array}\right] \qquad (23)$$

Equation (23) is called the energy integral of an oscillatory particle of mass unity moving with a velocity $n' = dn/d\xi$ at position n in a potential well U(n). It has similar expression as found by Chatterjee *et al.* [54]. If the ion temperature is neglected the equation (23) agrees with equation (19) as reported by Mahmood & Mustaque [43].

The dependence of the pseudopotential on different plasma parameters (viz. F, H and σ) is shown in Figures 1-6.

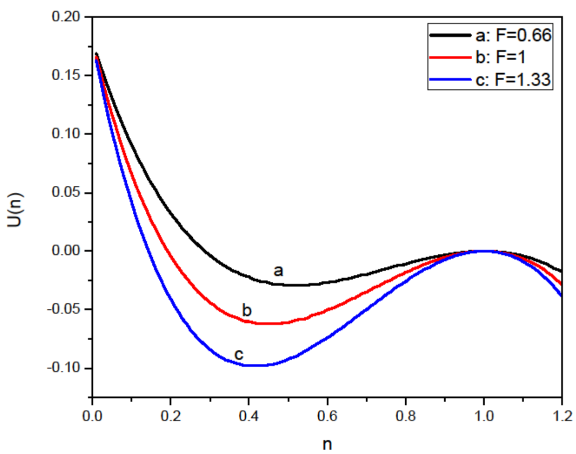

Fig. 1: U (n) is plotted vs. *n* for different values of Relativistic degeneracy parameter F in an ultra relativistic plasma, The black curve denotes F=2/3, the red curve denotes F=1, the blue curve denotes F=4/3. Other parameters are M=0.6, H=6 & σ=0.1.

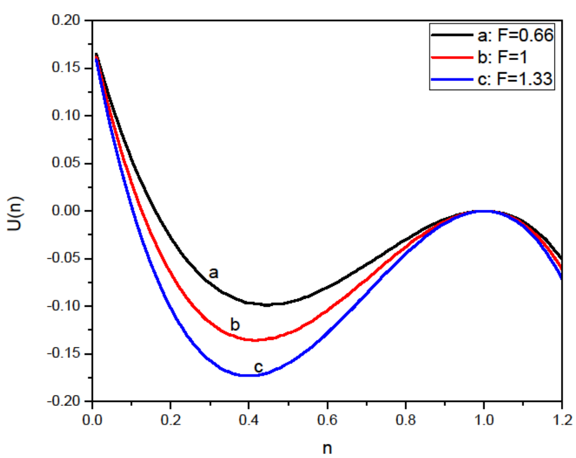

Fig. 2: U (n) is plotted vs. *n* for different values of Relativistic degeneracy parameter F in ultra-relativistic plasma, the black curve denotes F=2/3, the red curve denotes F=1, the blue curve denotes F=4/3. Other parameters are M=0.6, H=6 & σ=1.2.

In Figure 1 it is found that with cold ions (σ =0.1), the potential well becomes more deep with increase in relativistic degeneracy parameter F. However if the ions are warmer than the electrons the potential well becomes deeper with similar value of the relativistic parameter F as shown in Figure 2.

The dependence of quantum diffraction parameter H on the properties of the pseudopotential well is shown in Figures 3 and 4.

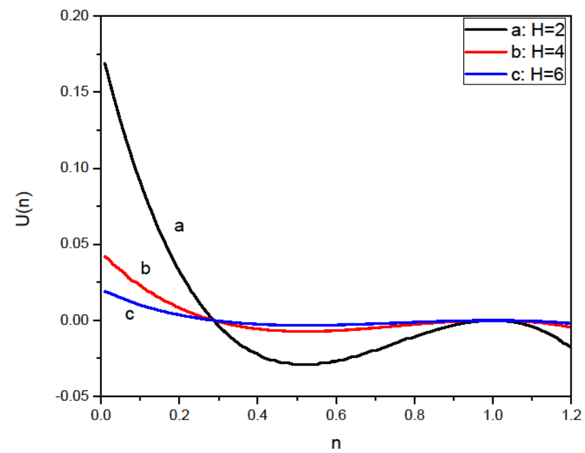

Fig. 3: U (n) is plotted vs. n for different values of Quantum diffraction parameter H in ultra relativistic plasma, the black curve denotes H=2, the red curve denotes H=4, the black curve denotes H=6. Other parameters are M=0.6, F=2/3 & σ=0.1.

In Figure 3 it is found that there exists two regions in the potential curve plot; for values of n from 0 to a finite one (around $0.24=n_m$).The potential curve decreases with H. In the next region that is (from n_m to 1) the lower most point of the potential well decreases in depth with increase in H. Figure 4 shows the same plot for warmer ions with similar features but with the only characteristics that it becomes more deeper in this case.

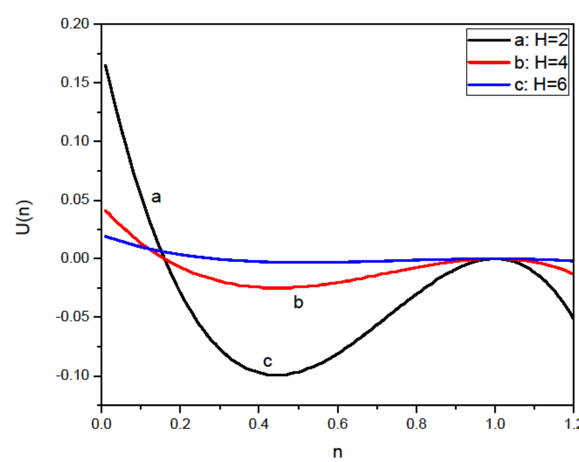

Fig. 4: U (n) is plotted vs. *n* for different values of Quantum diffraction parameter H in ultra-relativistic plasma, the black curve denotes H=2, the red curve denotes H=4, the black curve denotes H=6. Other parameters are M=0.6, F=2/3 & σ=1.2.

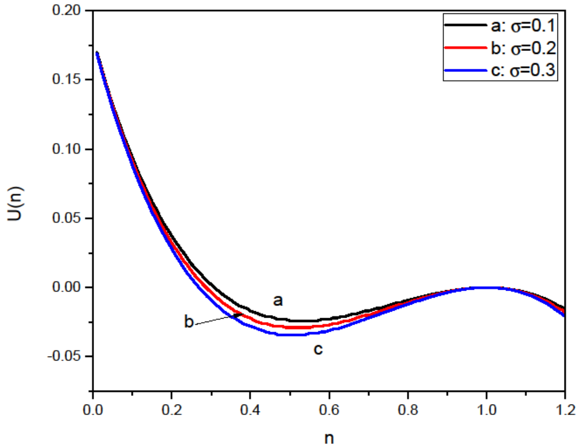

Fig. 5: U (n) is plotted vs. *n* for different values of ion temperature ratio σ in ultra-relativistic plasma, the black curve denotes σ =0.1, the red curve denotes σ =0.2, the black curve denotes σ =0.3. Other parameters are M=0.6, F=2/3 & H=2.

Figures 5 and 6 shows the pseudopotential well profile for different values of σ both for cold and warm ions. It is found that with increase in the parameter σ (which is directly proportional to ion Fermi temperature) for cold ions the depth of the potential slightly increases, (Figure 5). For warmer ions the depth of U(n) increases in σ (Figure 6). Thus it is found that the relativistic degeneracy parameters (F) & ion temperature ratio (σ) has similar effects throughout. But quantum diffraction parameter H shows dual characteristics in two different regimes in density space.

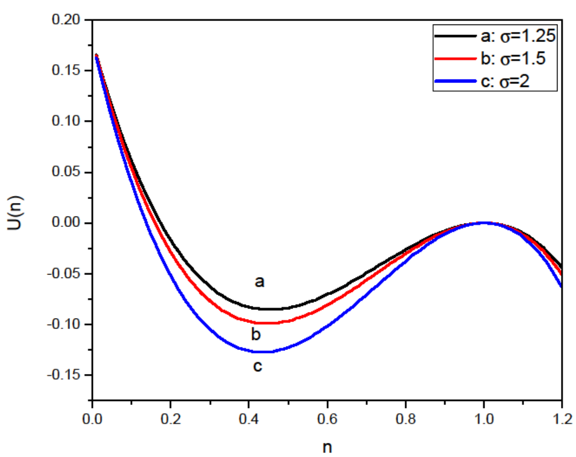

Fig. 6: U (n) is plotted vs. *n* for different values of ion temperature ratio σ in ultra relativistic plasma, the black curve denotes σ =1.25, the red curve denotes σ =1.5, the black curve denotes σ =2. Other parameters are M=0.6, F=2/3 & H=2.

III. SOLITARY WAVE SOLUTIONS

The motion of a particle whose Sagdeev's pseudopotential well *U*(*n*) which is a function of n is described by Eq. (23). The characteristics of the pseudopotential *U*(*n*) will then decide the conditions for the existence of solitary wave solution. If it is found that between any two roots (in this case, 0 and n_m) of the pseudopotential, *U*(*n*) is negative, then an oscillatory wave is found. On the reverse, if in the interval one root is a single root and another is a double root, then a solitary wave can be predicted [2]. If both the roots are double root, then a double layer exists. The initial conditions are chosen such that the double root appears at *n*=1. Therefore it takes an infinitely long time to get away from it and *n* reaches a zero at n_m, then again taking infinitely long time to return to *n*=0. Hence, the conditions for the existence of soliton solution are the following:

a) $U(n)=0$ at *n*=1 and $n=n_m$,

b) $\dfrac{dU(n)}{dn}=0$ at n=1 but $\dfrac{dU(n)}{dn}\neq 0$ at $n=n_m$ and,

c) $\dfrac{d^2U(n)}{dn^2}<0$ at n=1

If n_m is less than one then rarefractive solitary wave structures are formed. On the other hand if it is greater than unity, then compressive structures are obtained. It is to be noted that complex U(n) is not physically allowed as it would imply complex density which is not physical. From equation (23), it is seen that the shape of the solitary structures can be determined from the following:

$$\xi=\pm\int_{n_m}^{n}\frac{dn}{\sqrt{-2U(n)}} \tag{24}$$

The solitary profile obtained from integrating the reciprocal of the square root of the negative value of the pseudopotential between the two roots (visually n_m and unity in this case). The effect of relativistic degeneracy parameter (Figure 7), quantum diffraction parameter (Figure 8) & ion temperature (Figure 9) on the formation and properties of ion acoustic solitons are investigated are investigated.

Figures 7-9 shows the dependence of the solitary profiles containing colder ions & comparatively warmer electrons (in terms of Fermi temperature) on the relativistic degeneracy parameter F, quantum diffraction parameter H and ion-to-electron Fermi temperature ratio σ on the solitary structures of ion acoustic waves. The solitary profile show features typical in this case where there is a small protruding tip at ξ =0.

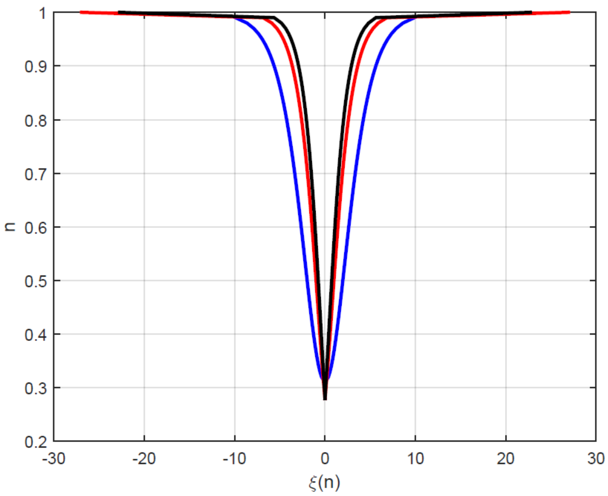

Fig. 7: n is plotted vs. ξ in ultra relativistic plasma with variation of Relativistic Degeneracy parameter F. The blue curve denotes F=2/3, the red curve denotes F=1, the black curve denotes F=4/3; other parameters are M=0.6, H=2 & σ=0.1.

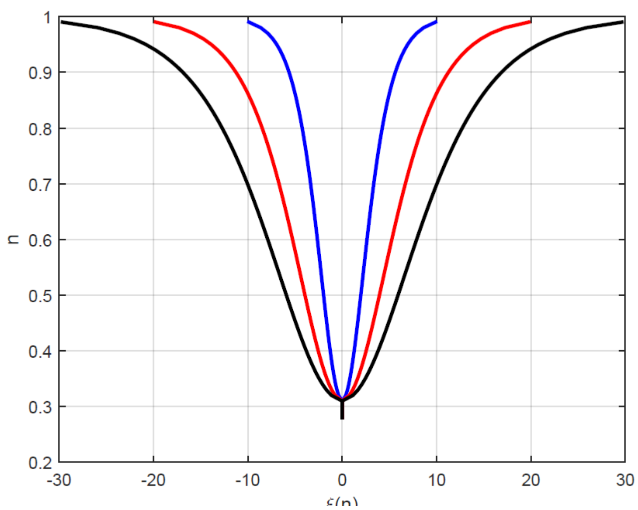

Fig. 8: n is plotted vs. ξ in ultra relativistic plasma with variation of quantum diffraction parameter H. The blue curve denotes H=2, the red curve denotes H=4, the black curve denotes H=6. Other parameters are M=0.6, F=2/3 & σ=0.1.

Figure 7 shows the rarefractive solitary structures for variation in relativistic degeneracy parameter F. It is found that as F increases the solitary structures become narrower keeping the amplitude constant. Figure 8 shows the same for variations in quantum diffraction parameter H. In this case it is found that with enhancement of quantum diffraction effect the solitary profile becomes much wider in contrast to that of Figure 7.

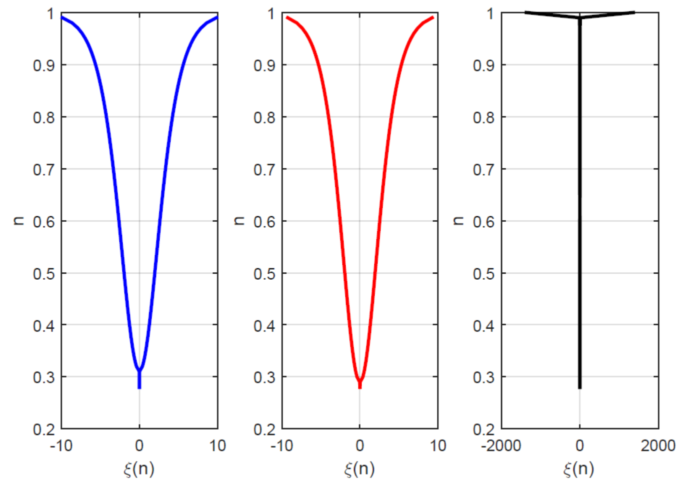

Figure 9: n is plotted vs. ξ in ultra relativistic plasma with variation of ion temperature ratio σ. The blue curve denotes σ =0.1, the red curve denotes σ =0.2, the black curve denotes σ =0.3; other parameters are M=0.6, F=2/3 & H=2.

Figure 9 depicts the dependency of solitary profile on ion Fermi temperature (σ). It is found that the relative amplitude increases with increasing σ but the waves decreases. With warmer ions the features will be similar as can be predicted by observing the pseudopotential well profiles U(n) [Figures 2, 4, 6].

IV. CONCLUSION & REMARKS

In these paper large amplitude ion acoustic solitary structures has been investigated in a two component electron ion quantum plasma containing ultra relativistically degenerate electron & non relativistic ions. The dependency of Sagdeev's pseudopotential on relativistic degeneracy parameter, quantum diffraction parameter & ion Fermi temperature are investigated & from this information the feasibility for obtaining ion acoustic solitary structures are investigated. It is found that all three of the parameters (F, H & σ) have significant effect in determining the properties of ion acoustic waves. The results found here may be helpful in explaining different kinds of wave phenomenon observed in space plasma and astrophysical environments.

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