Screening Potentials and Wave Excitations in Dusty Plasmas

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ZEBA ISRAR

REG. NO. 08-GCU-PHD-PHY-07
SESSION 2007-2010

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In the name of Allah, the beneficent, the merciful

All that is the heavens and the earth glorifies Allah

Surah Al-Hadid

Dedicated to

My Parents

&

My Husband Tasaduq Ali

&

Sweetest Daughter Meerab Fatima

Screening Potentials and Wave Excitations in Dusty Plasmas

A thesis submitted to G. C. University, Lahore in partial fulfillment of the requirement for the award of degree

of

Doctor of Philosophy

in

Physics

by

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Declaration

I, **Zeba Israr**, Registration No. 08-GCU-PHD-PHY-07, PhD scholar in **Department of Physics, G. C. University**, Lahore, hereby declare that the material included in the thesis entitled **" Screening Potentials and Wave Excitations in Dusty Plasmas"** is my own work and has not been submitted in any form in any University/Research Institution in Pakistan or abroad for the award of an academic degree.

Date: ________________

____

Signature of the deponent

Research Completion Certificate

It is certified that the research work contained in this thesis entitled "**Screening Potentials and Wave Excitations in Dusty Plasmas**" has been carried out under our supervision by **Zeba Israr,** Reg. No: 08-GCU-PHD-PHY-07, during her postgraduate studies for **Doctor of Philosophy in Physics**.
Her overall supervision is gratefully acknowledged.

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Abstract

The primary orientation of this thesis is to explore some interesting features of static and dynamic potentials in magnetized quantum plasmas including the dust dynamics in the presence of wave field associated with different modes. These modes may be electrostatic in nature. These investigations find significance applications in small and large scale plasmas. This thesis contains some new extensions to dust-lower-hybrid modes in quantum dusty plasmas.

In chapter II, the effect of strong ambient static magnetic field on Shukla-Nambu-Salimullah (SNS) potential in a dusty quantum magnetoplasma has been investigated using quantum hydrodynamic (QHD) model. The potential is significantly modified by quantum statistical effects, density inhomogeneity and dust polarization drift effect. It is found that dust polarization drift effect pre-dominates the ion polarization drift effect in high magnetic field environments. The potential around a static test charge has been plotted for different parameters in high density quantum magnetoplasmas. We have seen that for increasing values of number density and inhomogeneity scale length, the modified SNS potential decreased due to the decrease in the Fermi Debye length.

Subsequently using the quantum hydrodynamic model for quantum magnetoplasmas, the Shukla–Nambu–Salimullah shielding potential and the far-field dynamical wake potential in a quantum dusty plasma with a nonuniform density and static magnetic field have been investigated in chapter III. The short-range screening potential and the long-range oscillatory wake potential are found to be significantly affected by the nonuniformities in the density and the static magnetic field. It is seen that SNS and oscillatory wake potentials increases with the increase of external magnetic field and for increasing values of number density and inhomogeneity scale length, the amplitude and effective length of wake potential decreased. The far-field oscillatory wake-field potential can explain attraction among the same polarity charges leading to the possible ordered structures or coagulation in the inhomogeneous quantum dusty magnetoplasma.

Finally in chapter IV, the dispersion relation of the dust-lower-hybrid wave has been derived using the quantum hydrodynamic model of plasmas in an ultracold Fermi dusty plasma in the presence of a uniform external magnetic field. The dust dynamics, electron Fermi temperature and the quantum correction give rise to significant effects on the dust-lower-hybrid wave of the magnetized quantum dusty plasmas. Numerically it is found that frequency of the quantum dust-lower-hybrid wave increases with increasing wavenumber and with the increase of magnetic field at the small angle of propagation. The summary and conclusions are in the end of the thesis.

Publications
This thesis based on the following papers

1. Modified screening potential in a high density inhomogeneous quantum dusty magnetoplasma.

   A. Hussain, **I. Zeba**, M. Salimullah, G. Murtaza, M. Jamil.
   Physics of Plasmas **17**, 054504 (2010)

2. Potentials in a nonuniform quantum dusty magnetoplasma.

   M. salimullah, **I. Zeba**, Ch. Uzma, M. Jamil.
   Physics of Plasmas **16**, 033703 (2009)

3. Dust-lower-hybrid waves in quantum plasmas.

   M. Salimullah, **I. Zeba**, Ch. Uzma, H. A. Shah, G. Murtaza.
   Physics Letter A **372**, 2291 (2008)

Other Publications

1. Solitary acoustic pulses in quantum semiconductor plasmas
W.M. Moslem, **I. Zeba**, P. K. Shukla.
Applied Physics Letters **101**, 032106 (2012)

2. Electron-hole two-stream instability in a quantum semiconductor plasma with exchange-correlation effects
I. Zeba, M. E. Yahia, P. K. Shukla, W. M. Moslem.
Physics Letter A **376**, 2309 (2012)

3. Diamagnetic drift instabilities in collisional nonuniform quantum dusty magnetoplasmas
M. Jamil, Ch. Uzma, K. Zubia, **I. Zeba**, H. M. Rafique, M. Salimullah.
Journal of Plasma Physics **78**, 589 (2012)

4. Ion solitary pulses in warm plasmas with ultrarelativistic degenerate electrons and positrons
I. Zeba, W. M. Moslem, P. K. Shukla.
The Astrophysical Journal **750**, 72 (2012)

5. Quantum modification of dust shear Alfven wave in Plasmas
M. Jamil,M. Shahid, **I. Zeba**, M. Salimullah, H. A. Shah, G. Murtaza.
Physics of Plasmas **19**, 023705 (2012)

6. The parametric decay of Alfven waves into shear Alfven waves and dust-lower-hybrid waves.
M. Jamil, H. A. Shah, M. Salimullah, K. Zubia, **I. Zeba**, Ch. Uzma.
Physics of Plasmas **17**, 073703 (2010)

7. Colloidal crystal formation in a semiconductor quantum plasma.
I. Zeba, Ch. Uzma, M. Jamil, M. Salimullah, P. K. Shukla.
Physics of Plasmas **17**, 032105 (2010)

8. Drift wave instability in a nonuniform quantum dusty magnetoplasma.
M. Salimullah, M. Jamil, **I. Zeba**, Ch. Uzma, H. A. Shah.
Physics of Plasmas **16**, 034503 (2009)

9. Stimulated Brillouin scattering of laser radiation in a piezoelectric semiconductor: quantum effect.
Ch. Uzma, **I. Zeba**, H. A. Shah, M. Salimullah.
Journal of Applied Physics **105**, 013307 (2009)

10. Electromagnetic dust-lower-hybrid and dust-magnetosonic waves and their Instabilities in a dusty magnetoplasma
M. Salimullah, M. M. Rehman, **I. Zeba**, H. A. Shah, G. Murtaza, P. K. Shukla.
Physics of Plasmas **13,** 122102 (2006)

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Chapter 1

Introduction

1.1 The Primer

The introductory chapter of my thesis has been divided into five sections using the logical sequence. After introduction, this chapter starts with the understanding of different type of plasma. These are dense quantum plasma, inhomogeneous plasma and dusty plasma and these have been the basis of my research work. In brief some properties and different approaches to treat the plasma are discussed here. In section 3, there is a description of some properties of quantum plasmas. Some of the modes propagating in complex plasmas have also been discussed. This is given in section 4. Section 5 contains explanations of some basic phenomena. These phenomena include physics of Debye screening potential, theory of wake potential and Coulomb crystals. Lastly, I give a layout of my thesis.

1.2 Plasma

Plasma is the dominate state of matter in the universe, estimated to comprise around 99% of all observable matter. It is often termed the fourth state of matter because its characteristics are quite different from the other three states. The word plasma was first used by Langmuir in 1928 to describe the ionized regions in gas discharges. Because of the abundance of plasma in the universe, the knowledge of plasma physics becomes essential to understand phenomena in Nature-especially in space. *A plasma can be described as a quasineutral gas of charged and neutral particles which exhibits collective behavior.* The plasma particles are governed by the long-ranged electrostatic and electromagnetic forces instead of collisions in a normal gas.

Plasma is an optical and dielectric medium which is rich with fluctuating electric and magnetic fields i.e. **E**, and **B**. Many challenging issues can be investigated, for example, the plasma may be non uniform with respect to number density, it may be dissipative or dispersive have different temperatures which may lead to complicated dispersion relations. The prominent property of the plasmas is that it hosts large number of wave motions. The possibility of existence of a particular wave depends upon typical plasma properties and parameters.

Normally the modes in plasmas are represented by the equation which relate the frequency and wave vector is known by dispersion relation. We have two approaches to solve for dispersion relation. Either we take ω as real and $\mathbf{k}$ as complex or ω is taken as complex and $\mathbf{k}$ is taken as real. The latter one has some mathematical ambiguities but sometime may be opted. The possible roots describe the natural modes existing in plasmas. The dispersion relation does lack of additive character. In other words we can not get dispersion relation of over all neutral plasmas consisting upon electrons, ions and dust by adding dispersion relations of individual species that are constituents of plasmas [1-3].

1.2.1 Debye Shielding

The phenomenon of Debye shielding is a fundamental property of a plasma. When a test charged particle is immersed in a plasma, it will be shielded out by either the ions or the electrons. A positively test charged particle will attract a cloud of electrons, while a negatively test charged particle will be enclosed in an ion cloud. This distribution of charges within the plasma gives rise to an electric potential $\Phi(\mathbf{r})$ that is called the Debye potential

$$\Phi = \Phi_0 \, exp(-r/\lambda_D) \, .$$

If the plasma is cold, the shielding will be perfect outside the cloud. For warmer plasmas, however, the small potentials at the edge of the clouds will not be able to prevent the electrons or ions from escaping. For the size of shielding cloud we introduce the Debye length which is a characteristic length for the shielding of the potential around a test charged particle. The Debye length λ_D is defined by the expression

$$\lambda_D = \sqrt{\frac{\epsilon_0 T_e}{n q_e^2}},$$

where ϵ_0 is the constant of permittivity, T_e is the electron temperature, n is the equilibrium plasma density at infinity and q_e is the electron charge. It is worth mentioning that the Debye length will increase when temperature increases, which can be explained by the fact that the thermal motion of the plasma particles will make the shielding weaker. Conversely, a dense plasma will make the Debye length shorter, as there are more particles to shield out the potential. A criterion for a plasma is that it is quasineutral. This is fulfilled when the dimensions of the physical system are much larger than the Debye length, since every local concentration of charge will be shielded in a distance much smaller than the size of the system.

Plasma must satisfy the following tree conditions

$$\lambda_D \ll L; \quad N_D >>> 1; \quad \omega\tau > 1,$$

where L is the dimensions of a plasma system, N_D is the number of particles in a Debye sphere and ω is the frequency of plasma oscillations and τ is the mean time between collisions with neutral atoms. Defining plasma as a collection of positive and negative charges that are not atomically bound to one another, we encounter two possibilities. Most commonly, the charges have abundant kinetic energy and fly easily past their neighbors, much like molecules in a gas. That's termed a weakly coupled plasma. For weakly coupled plasma electrostatic potential energy is less than the kinetic energy, so it have high temperature and low density plasma. Strongly coupled plasmas are characterized by dominant coulomb forces over their thermal agitation and it have large density and/or small temperature. The Γ (coupling coefficient) is the ratio of electrostatic to kinetic energy, is large for strongly coupled plasmas because of high density and small interparticle spacing.

1.2.2 Homogeneous and inhomogeneous Plasma

The plasmas with low temperature and with no external magnetic field has probable uniformity in all directions with respect to number densities. Such a plasma is enriched with simple waves due to uniform distribution of plasma particles and small variation of density. Under this condition, the current density and electric field strength of charged species is zero. The plasma of this nature rarely exists except for the case of small scale plasmas, e.g., bounded plasmas with small dimensions [4-7]. However, non-uniformity in fields either electric or magnetic as well as number densities is a natural occurrence. The gradient in density leads to electric field and hence some currents. Drift waves and instabilities are consequences of such situation [5,8].

1.2.3 Different approaches to treat the Plasmas

Analytically, we can tackle the plasmas by different possible ways [9].

Plasma as a Fluid: In a plasma one has to deal with an extensively large number of charged particles. As each of these particles follow a complicated trajectory, it becomes impossible to keep of them all and observe the plasma behavior. Hence there is need to find techniques to handle plasma to have a reasonably accurate results. One such approach is to assume plasma to be a conducting fluid. This model makes use of the well-established equations of Fluid mechanics with some general properties of ideal fluids applicable to plasma. This model, which is often referred to as the Magnetohydrodynamic (MHD) model, has been successful in explaining the majority particles is neglected and only the motion of fluid elements is taken into consideration. It is known as single fluid model. There is another fluid model that is called two fluid model in which each species like electrons, ions etc. can be treated as fluid elements separately.

Kinetic Theory of Plasma: The information that gets lost in a fluid model is that relating to the distribution of velocities of the particles within a fluid element, since the fluid variables are functions of position and time but not of velocity. Any physical properties of the plasma that depend on this microscopic detail can be discovered only by a description in six-dimensional $(\mathbf{r}, \mathbf{v})$ space. Thus, instead of starting with the density of particles $n(\mathbf{r}, t)$ at position $\mathbf{r}$ and time t, we begin with the so-called distribution function, $f(\mathbf{r}, \mathbf{v}, t)$, which is the density of particles in $(\mathbf{r}, \mathbf{v})$ space at time t. The evaluation of the distribution function is described by kinetic theory.

With the additional information on particle velocities within a volume element introduced by a phase space description, we now have microscopic detail that we did not have before. For that reason, kinetic and fluid theories are identified as microscopic and macroscopic, respectively.

1.2.4 The technique of Fourier transformation

In the universe, all the waveforms, no matter what we observe are actually just the sum of simple sinusoids of different frequencies. The Fourier transform is a mathematical tool that shows us how to deconstruct the waveform into its sinusoidal components. In other words, we can say that the Fourier transform decomposes a waveform into sinusoids. Mathematically, to solve the differential equations are little bit difficult. However by applying Fourier transformation we can simplify the differential equations. Differential operators are replaced by wave vector and angular frequency along with $i = \sqrt{-1}$ which lead from differential to a simple solvable algebraic expression. In this way, we actually shift coordinate space to Fourier space [10-12].

1.2.5 Conducting behavior of Plasma

The simplest plasmas consist of electrons and ions. The electrons are the lightest species and therefore are very mobile and their presence reflects the conducting behavior of plasmas. We can relate the current density and number density by an equation and hence, in turn with the electric field generated due to the motion of charged species. The vector equation can be described as $\mathbf{J} = q_e n_e \mathbf{u}$ [5,13]. The propagation of wave in the plasmas verifies the fact that the plasma is a dielectric medium, for which oscillations of the medium and fields is prerequisite. By default there is no external magnetic field inside the plasmas. However for multi fluid plasmas, such response is incorporated through susceptibility which shows the response of individual species or fluids for the fields. By taking sum over unity and susceptibility over all species present in plasmas, we can find the conducting response of plasmas as whole [6,7,10-12,14-25]. The mathematical expression in the presence of variety of effects like magnetic field, uniform or non uniform plasmas, turns it into a complex form which is represented by a dielectric tensor [6]. The response of medium to the externally applied field may be linear [5,10-12] if some sign of proportionality exists there. The constant of this proportionality is the medium response function which is constant. The nature of this function may be complex. The absorption of wave is due to the dissipative part and non zero refractive index is due to non dissipative part.

1.2.6 The dielectric response tensor

The inclusion of electric as well as magnetic fields, bring the algebraic complexity alongwith qualitative change of orbits. Tensor formalism known as a response tensor, develops the relationship between the disturbance and response in order to avoid from any kind of confusion. Hence, the dielectric tensor as a dimensionless expression contains the perturbations through susceptibilities which emphasizes the additive property of coefficients for all of the species of plasmas and then provides the dispersion relation of peculiar mode. Here the zero order quantities are taken as stationary with respect to time and space, while first order quantities are considered. The dielectric tensor is additive in its nature. The cold plasma is the simplest approach for the calculation of response tensor of unmagnetized plasmas, where each of the plasma species is solved by fluid equations that incorporate velocity, number density, charge and mass of corresponding species [1,2].

1.3 Dense Quantum Plasmas

The quantum effects should be taken into account when the plasma is dense enough, so that the de Broglie wavelength of the charged carries is frequently comparable to the average interparticle distance in the plasma system.

Many authors [26-35] have investigated the different quantum effects in the plasmas, such as the Bohm potential and the Fermi pressure [26-32], spin properties [33-40], as well as certain quantum electrodynamical effects [41-44].

In general, dense quantum plasma can be composed of electrons, positrons, ions, and charged nanoparticles. It is characterized by high-plasma particle number densities and low-temperatures, in contrast to classical plasma that has high-temperatures and low particle number density. Quantum plasmas are common in different environments, e.g. in superdense astrophysical bodies [37,45,46] (i.e. the interior of Jupiter and massive white dwarfs, magnetars, and neutron stars), in intense laser-solid density plasma experiments [47-50], and in ultrasmall electronic devices (e.g. in microelectronics, semiconductor devices [51], nanowires [52], carbon nanotubes [53], quantum diodes [54-58], ultracold plasmas [59,60], and microplasmas [61]). More than four decades ago, Pines studied the properties of the high-density and low-temperature quantum plasmas [62]. The latter is gaining momentum [26] in the context of studies of waves, instabilities and nonlinear structures.

1.3.1 Properties of Quantum plasmas

The complete description of the quantum plasma as a system of many interacting particles is a frantic task as is the case of classical plasmas, not only because it is impossible to solve the Schrödinger equation for the N-particles wavefunction of the system, but also because of the lack of such wavefunction for a macroscopic system [63]. Now this problem can be modified by considering the plasma as an ideal gas, i.e. that the two- and higher-order correlations between its particles can be ignored. If this is the case, then the plasma can be studied as a collection of quantum particles that act only via their mutual fields. In quantum plasmas, the Fermi-Dirac statistical distribution is usually applied rather than the extensively used classical Boltzmann-Maxwell distribution. The typical scales, viz. the time, the length, and the thermal speeds of the charged particles in quantum plasmas, are quite different from that of classical plasmas. A one-dimensional zero-temperature Fermi gas obeys the equation of state [38] of the form

$$P_\alpha = \frac{m_\alpha V_F^2 n_\alpha^3}{3n_{\alpha 0}^2}, \tag{1.1}$$

where m_α is the mass of the species α (α equals e for the electrons, p for the positrons), $V_F = (2E_F/m_\alpha)^{1/2}$ is the Fermi speed, E_F is the Fermi energy, and n_α is the particle number density with an equilibrium value $n_{\alpha 0}$.

Due to the high number density in quantum plasmas, the plasma frequency $\omega_{p\alpha} = (4\pi n_{\alpha 0} e^2/m_\alpha)^{1/2}$ and the Thomas-Fermi length (analogue of the Debye length in classical plasmas) $\lambda_{F\alpha} = V_F/\omega_{p\alpha} \equiv (2k_B T_F/m_\alpha)^{1/2}/\omega_{p\alpha}$ become significantly different from the usual plasmas. Here e is the magnitude of the electronic charge and k_B is the Boltzmann constant. The Fermi temperature T_F can be expressed in terms of equilibrium number density as

$$k_B T_F = \frac{1}{2} m_\alpha V_F^2 \equiv E_F = \left(\frac{\hbar^2}{2m_\alpha}\right)(3\pi^2 n_{\alpha 0})^{2/3}, \tag{1.2}$$

where $\hbar$ is the Planck constant divided be 2π. It is noted that when the temperature approaches T_F, the relevant distribution changes from the Maxwell-Boltzmann to the Fermi-Dirac. It is well-known that in quantum plasmas, the de Broglie wavelength (viz. $\lambda_B = \hbar/m_\alpha V_{Th}$) of the charge carriers is comparable to the interparticle distance in the plasma system. The thermal speed $V_{Th} = (2k_B T_{Th}/m_\alpha)^{1/2}$ is sufficiently smaller than the Fermi speed V_F. In such a situation, the plasma behaves like a Fermi gas, and the quantum mechanical effects are expected to play a role in the behavior of the plasma particles dynamics. The de Broglie wavelength roughly represents the spatial extension of Fermion wave function due to quantum uncertainty.

In quantum plasmas, a strong electron density correlations start playing a major role when the de Broglie wavelength is equal to or larger than the average interparticle distance $d = n_{e0}^{-1/3}$, that is

$$n_{e0}\lambda_{Be}^{3} \geq 1. \tag{1.3}$$

For an opposite condition $n_{e0}\lambda_{Be}^{3} < 1$, the plasma particles behave classically.

In fully degenerate quantum plasmas, there are two significant effects. The first one is caused by the quantum force involving the electron tunneling at quantum scales λ_{Be} through a potential barrier that contains the quantum mechanical effects and it is represented by $\varphi_B = -(\hbar^2/2m_e\sqrt{n_e})\nabla^2\sqrt{n_e}$. The second is due to the spin of the electrons and positrons in an external magnetic field [26,33]. The quantum force involving the Bohm potential produces dispersion at quantum scales, while the spin of the electrons gives rise to a force that depends on the charged particle magnetic moment $\mu_B = e\hbar/2m_ec$, where c is the speed of light in vacuum. Both effects have important consequences for collective processes in quantum plasmas.

1.3.2 Tackling Quantum Plasmas

The description of quantum plasma can be established on either Schrodinger's equation (in which the operators are time independent) or Heisenberg's representation (in which the time dependence is shifted from the wave function to operators). Most of the models for quantum plasma employed now [47], use the Schrodinger's representation; the state of quantum plasma accounted either by the wave functions of distinguish particles (supposed multistream model [27]), or by the Wigner function [64,65]. This approach can be solved by a set of the so-called hydrodynamics equations. Naturally, all models are made by simplifying assumptions, which one should appreciate when analyzing results obtained from them. Nevertheless, applicability limits of results obtained from a peculiar model are not always submitted explicitly (this particularly refer the widely used model of quantum hydrodynamics [66,67]), which can conduct to their wrong interpretation. With the rapid increase in the number of publications on quantum plasmas recently, the lack of detailed analysis of the made assumptions and the limitations connected for the most common quantum plasma models becomes obvious, therefore it is multipurpose to furnish such analysis. Studies of quantum plasma physics get down with pioneering theoretical works of Klimontovich and Silin [68] and Bohm and Pines [69-71] who analyzed the dispersive properties of the electron plasma oscillations (EPOs) in dense quantum plasma with degenerate electrons. Recently, there has been developing interest to look into new aspects of dense quantum plasmas by developing the quantum hydrodynamic (QHD) [26,72-74] and quantum kinetic equations by combining the quantum force relate with the Bohm potential [74]. The Wigner-Poisson (WP) model [75,76] has been applied to derive a set of QHD equations for dense electron plasma. The QHD equations are constitute the electron continuity, non-relativistic electron momentum and Poisson equations.

1.4 Complex Plasmas

Dust and plasmas are the two quite common components of the universe. Much of the solid matter in the universe is composed of dust. Dust can be found in different astrophysical environments in the form of dielectric (ices, silicates, etc.) and metallic (graphite, magnetite, amorphous carbons, etc.). On the other hand, a plasma is a quasi-neutral ionized gas consisting of electrons, ions, and neutral atoms or molecules which exhibits collective behavior. Thus, dust coexists with plasma and forms a Dusty Plasma [77,78]. A dusty plasma is a normal electron-ion plasma with an additional charged component of micron or sub micron-sized dust particulates. The additional component may have a distribution of sizes, shapes, and charge states, which can increase the complexity of the system, is responsible for the name Complex Plasma. Dust grains of various sizes, origin, and nature occur in many space environments [79-82]. They are extremely massive compared to the electrons and ions. The mass and size of the dust grains may have the range of $m_d \sim (10^{-2} - 10^{-15})$ g and 1 μm $-$ 1 cm, respectively. Dust grains are highly charged compared to the electrons and ions. Typically, they may have the charge of order $Q_{d0} = Z_{d0}e \sim (10^2 - 10^5)e$, where Z_{d0} the equilibrium charge of the dust grain and e is the magnitude of the electronic charge.

1.4.1 Properties of the Complex Plasmas

The qausi-neutrality condition at equilibrium can be modified in the presence of a negatively charged dust component as

$$Q_e n_{e0} + Q_d n_{d0} = Q_i n_{i0} \ , \tag{1.4}$$

It is obvious from Eq. (1.4) that the net resulting electric charge is zero if there are no perturbations in the dusty plasma. Here, n_{j0} is the equilibrium number density of the plasma species j (j equals e for electrons, i for ions, and d for dust grains), $Q_e = Z_e e$ is the electronic charge, $Q_i = Z_i e$ is the ionic charge, and $Q_d = -Z_{d0}e$ is the negatively charge dust grains. In dusty plasma, we assume that all the dust grains have a uniform size, spherical in shape, and have a negatively charge though there is a variation in mass, size, and charge. The plasma particles are assumed to be point charges [83] as long as the dust grain size a and the average inter-grain spacing $d = (3/4\pi n_{d0})^{1/3}$ are much smaller than the effective dusty Debye length (λ_D) and the particle gyro-radius ρ_j (if the ambient magnetic field is present). This model is appropriate for describing the interstellar clouds, cometary tails, planetary rings, as well as in noctilucent clouds. For $a \ll d \ll \lambda_D, \rho_j$, the charged dust particulates can be considered as massive point particles similar to multiply charged negative (or positive) ion in multi-species plasmas, while for $d < \lambda_D$, the effect of neighboring particles becomes significant. For $d \gg \lambda_D \gg a$, the dust grains are completely isolated from their neighbors and it is referred as dust in plasma [84]. For the negatively charged particulates in a dusty plasma, we consider $n_{e0} \ll n_{i0}$ and $T_e \geq T_i$ showing that $\lambda_{De} \gg \lambda_{Di} \simeq \lambda_D$. Whereas, the dust grains can be considered to be positively charged particulates under the condition $T_e n_{i0} \ll T_i n_{e0}$ giving $\lambda_D \simeq \lambda_{De} \ll \lambda_{Di}$, where $T_e(Ti)$ is the electron (ion) temperature and $\lambda_{De}(\lambda_{Di})$ is the electron (ion) Debye length. We note that the dust plasma frequency is much smaller than the ion plasma frequency, i.e. $\omega_{pd} \ll \omega_{pi}$, because the mass of the dust particles is much greater than the mass of ion.

1.4.2 Applications of Complex Plasmas

The electron-ion plasmas are often mingled with micron-sized dust grains to form dusty plasma. Such plasmas are present in various space environments, namely planetary rings, installer molecular clouds, earth's magnetosphere, cometary rings, auroral displays, zodiacal light. Dust is also present in the environment of low-temperature laboratory plasmas, like in tokamaks, semiconductor devices, and thin films. In the last few years, industrial plasma processing researchers have discovered that particles suspended in plasmas are a major cause of costly wafer contamination during semiconductor manufacturing. However, in many astrophysical and terrestrial plasmas, the dust grains are found to be elongated rather than point-like. Such dust grains are expected to be formed due to coagulation of smaller particles in partially or fully ionized plasmas by attractive forces. It is observed that inelastic, adhesive, and collective interactions between micron-sized charged dust particles give rise to kilometer-sized bodies, which are known as planetesimal. In literature, it is suggested the possibility for the charged dust particles to form Coulomb crystals if they are strongly coupled through the electrostatic force and have small thermal motion.

1.4.3 Modes in Complex Plasmas

During the last two decades, the physics of dusty plasmas has reached a matured level [77]. The inclusion of an additional dust component leads to new types of collective modes and associated instabilities. A number of collective modes such as the dust-acoustic waves (DAW), dust-ion-acoustic waves (DIAW), dust-lower-hybrid wave (DLHW), dust Coulomb waves (DCW), dust lattice waves (DLW) have been studied both in an unmagnetized and magnetized dusty plasmas.

Dust Acoustic Wave (DAW): The DAW in a multicomponent collionless dusty plasma whose constituents are the electrons, ions and negatively charged dust grains. The phase velocity of the DAW is much smaller than the electron and ion thermal speeds such that condition $v_{Td} << \omega/k << v_{Te}, v_{Ti}$ in which dust are mobile. These inertialess electrons and ions establish equilibrium in the DAW potential ϕ. The pressure gradient is balanced by the electric force, leading to Boltzmann electron and ion number density perturbations. The restoring force in the DAW comes from the pressures of the inertialess electrons and ions, while the dust mass provides the inertia to support the waves. The frequency of the DA waves is much smaller than the dust frequency. The electrostatic DAW is observed experimentally, which indicates that it has frequency $\approx$ 15Hz with a phase velocity - 9 cm/s [85].

Dust Ion-Acoustic Wave (DIAW): The phase velocity of the DIA waves is much smaller than the electron thermal speed such that $v_{Td}, v_{Ti} << \omega/k << v_{Te}$. The phase velocity of the DIA waves in a dusty plasma is larger than $C_s = \sqrt{T_e/m_i}$ because $n_{i0} > n_{e0}$ for negatively charged dust grains. The increase in the phase velocity is attributed to the electron density depletion in the background plasma, so that the electron Debye radius becomes larger. As a result, there appears a stronger space charge electric field which is responsible for the enhanced phase velocity of the DIA waves [86]. However, if the electrons are warm $T_e >> T_i$ an electrostatic wave in which ions do play a major role is found at lower frequencies. Since these are low-frequency oscillations, so ions are mobile, electrons are inertialess and dust dynamics are immobile providing neutralizing background, which can be seen through the quasi-neutrality condition. The electron pressure provides the restoring force, and the ion mass provides the inertial effect. These are also called ion-sound waves because all wavelengths propagate at the same speed, the ion-acoustic speed (T_e/m_i). This is in contrast to the plasma oscillations which have the same frequency for all wavelengths. For typical laboratory conditions, the frequency of the DIAW is few kHz. Both the DAW and DIAW have been observed experimentally [87-90].

Dust-Lower-Hybrid Wave (DLHW): A number of fundamental new modes, particularly the dust-lower-hybrid (DLH) wave, have been shown to exist in plasmas which occur invariably in the presence of magnetic fields. In electron-ion plasma, if the wave vector have small parallel component, the electron oscillate along the magnetic field, leading to the dispersion relation for the lower hybrid wave $\omega = \omega_{lh}[1 + (M/m)(k_{\parallel}^2/k_{\perp}^2)]^{1/2}$, where $\omega_{lh} = \omega_{pi}/[1 + (\omega_{pe}^2/\omega_{ce}^2)]^{1/2}$. In dusty plasma, including the dust dynamics and assuming $\omega_{pi}^2 \gg \omega_{ci}^2$ for a high-density plasma, the electrostatic dust-lower-hybrid wave frequency turns out to be $\omega^2 = \omega_{dlh}^2[1 + (k_{\parallel}^2/k^2)(\omega_{pe}^2/\omega_{pd}^2)]$ where $\omega_{dlh} = \omega_{pd}\omega_{ci}/\omega_{pi}$ is the DLH frequency.

1.5 Electrostatic Potential

Shielding of the electric fields generated by free charge in plasmas is a primary issue in plasma physics. When a free charge is placed into a plasma, charged particles respond to the electric field caused by the free charge, and this leads to the result that the electric field is determined by the dynamic response of the plasma to the electric field applied externally. For an unmagnetized plasma, the plasma equilibrium is simply the balance of the force due to the electric field and the force due to the plasma pressure gradient; this results to the well-known Debye shielding.

The search for model systems to study phase transitions of crystalline structures was initiated by Wigner in the 1930s with the theory of the Wigner Crystal [91]. Since that time experimental verification has been achieved for several specific systems. On the atomic scale these are ion crystals [92] and electron crystals [93] and on macroscopic scales colloidal crystals in aqueous solutions [94]. Each of these systems has advantages and disadvantages for the detailed study of the phase transition of interest, such as formation, growth and melting of crystalline structures. A macroscopic Coulomb crystal formed from a dusty plasma is termed as plasma crystal [95].

The wake-field potential caused by a test particle has received enormous amount of attention and is an active area of research in the perspective of its applications in many phenomena e.g., in the acceleration of particles [96,97], in the formation of the dust particles into regular crystalline structures in dusty plasmas [98-100], and in the coagulation of small dust particles in space and astrophysical plasmas. The idea of the wake potential was first introduced by Nambu and Akama [101] in the electron-ion plasma which was further extended for the dusty plasmas by Nambu et al. [102].

Nambu et al. [102] introduced the wakefield concept to a dusty plasma in which besides electron and ions one also has a large fraction of charged dust grains. The presence of the latter gives rise to DA [85] and DIA [86] waves. By incorporating the appropriate dielectric constant of DA and DIA waves, Nambu et al. [86,102] calculated the wake potential around a test charge. Besides the usual Debye screening potential, they found a new attractive potential. The latter can be responsible for the attraction of charged dust particulates, leading to microscopic coulomb crystallization and coagulation of dust grains in dusty plasmas.

When the speed of a dust test charge is comparable to the phase speed of the plasma wave, a wake-field potential is formed behind the test charge. This wake-field is an oscillatory in nature containing both the positive and negative potential regions. For higher speeds of test charge, the amplitude of the wake-field is pronounced. Furthermore, the attractive wake-field has been explained [103,104] with an external magnetic field and finite ion flows in the dusty plasmas. Numerous attempts [105-110] were made for calculating the Debye and wake potentials, as well as highlighting the Coulomb crystallization in the magnetoplasmas. Quite recently, Salimullah et al. [111] studied that the properties of the electrostatic Shukla- Nambu-Salimullah (SNS) potential in an inhomogeneous magnetoplasma with ion streaming and showed analytically the effects of inhomogeneity scalelength, the external static magnetic field, and the diamagnetic drift velocity of ion on the Debye and wake potential profiles. The effect of ion polarization drift causes this new type of potential. A new shielding length appears across the external magnetic field which is larger than the ordinary Debye shielding length.

The formation of Coulomb lattices is also seen when an appropriate electric field is applied in dusty plasmas. The physical mechanism behind the attractive force in a dusty plasma is similar to the Cooper pairing of the electrons in superconductors. The force of attraction between two electrons (or negatively charged particles) is attributed to the polarization of the medium caused by a test electron (negatively charged particulates) that attracts positive ions. The excess positive ions, in turn, attract a neighboring electron (negatively charged particulate). Thus, collective interactions involving phonons (DA waves) play an essential role both in the Cooper pair mechanism in superconductivity as well as in dusty plasmas. The electrostatic potential around the isolated test dust particle can be written as [112]

$$\Phi(\mathbf{x}, t) = \int \frac{q_t}{2\pi^2 k^2} \frac{\delta(\omega - \mathbf{k} \cdot \mathbf{v}_t)}{\epsilon(\omega, \mathbf{k})} \exp(i\mathbf{k} \cdot \mathbf{r}) \; d\mathbf{k} \; d\omega, \tag{1.5}$$

where q_t and $v_t(\ll v_{ti})$ are the charged and velocity of the test dust particle, respectively. The dielectric response function of the plasma in the presence of finite ion flow with the speed v_{io} is calculated under the condition $kv_{ti} \ll \mid \omega - k_z v_{io} \mid \ll kv_{te}$, where z-axis is directed along the ion flow. Here $v_{ti}(v_{te})$ is the ion (electron) thermal velocity. The dielectric response function is given by

$\epsilon(\omega, \mathbf{k}) = 1 + \chi_e + \chi_i + \chi_d$, where $\mathbf{k}$ is the wavevector, ω is the wave frequency, and χ_e, χ_i and χ_d are the susceptibilities of electron, ion and dust particulate, respectively. Substituting the vale of ϵ, one can obtain the electrostatic potential as $\phi = \phi_D + \phi_F + \phi_C$, where ϕ_D is the usual Debye screening potential, ϕ_F is the far-field potential and ϕ_C is the additional potential (wake potential) involving the collective effects caused by the oscillations in the ion flow. Besides the Debye screening potential, there appear far-field and non-Coulombian potentials. The latter could be attractive and may be responsible for bringing like particulates together so that microscopic Coulomb Crystallization can occur in dusty plasmas. Physically a charged dust grains polarizes the medium by attracting positive ions that are involved in the collective behaviors of the waves. Similar to the Cooper paring, the excess positive ions attract the neighboring dust grains. The force of attraction between the two negatively charged dust grains is strong when the test dust charge velocity is close to the Doppler shifted phase velocity of the particular waves. In such a situation, there appears an oscillatory wake potential behind a test particulate. Quasi-lattice structures could be formed because of the presence of near-field attractive forces between like polarity dust grains [113].

1.6 Review of thesis

Chapter 1 of the thesis is an introductory chapter. This provides relevant knowledge about plasma physics and basics of my work which are included in my thesis. In chapter 2, the effect of strong ambient static magnetic field on Shukla-Nambu-Salimullah (SNS) potential in a dusty quantum magnetoplasma has been investigated using quantum hydrodynamic (QHD) model. The potential is significantly modified by quantum statistical effects, density inhomogeneity and dust polarization drift effect. Effective length of the modified SNS potential is found to be a sensitive function of external static magnetic field, $\mathbf{E} \times \mathbf{B}_0$ drift and the scale-length of inhomogeneity. Here $\mathbf{E}$ is the electric polarization vector produced via density inhomogeneity and $\mathbf{B_0}$ is the ambient static magnetic field. It is found that dust polarization drift effect predominates the ion polarization drift effect in high magnetic field environments. It attracts our attention to the careful study of the underlying physics of dusty plasma environment of neutron stars and magnetars.

Chapter 3 deals with the detailed study of static shielding potential and oscillating far-field dynamical wake potential in quantum dusty plasma. Using the quantum hydrodynamic model for quantum magnetoplasmas, the Shukla-Nambu-Salimullah (SNS) shielding potential and the far-field dynamical wake potential in a quantum dusty plasma with a nonuniform density and ambient static magnetic field have been investigated in detail. The short range screening potential different from the symmetric Debye-Hückel potential and the long range oscillatory wake potential are found to be significantly affected by the nonuniformties in the density and the static magnetic field. The far-field oscillatory wake-field potential can explain attraction among the same polarity charges leading to the possible ordered structures or coagulation in the inhomogeneous quantum dusty magnetoplasma.

In chapter 4, the dispersion relation of the dust-lower-hybrid wave has been derived using the quantum hydrodynamic model of plasmas in an ultracold Fermi dusty plasma in the presence of a uniform external magnetic field. The dust dynamics, electron Fermi temperature effect, and the quantum corrections give rise to significant effects on the dust-lower-hybrid wave of the magnetized quantum dusty plasmas.

Discussion

References

Chapter 2

Modified screening potential in a high density inhomogeneous quantum dusty magnetoplasma

2.1 Introduction

The shielding of test charge is one of the most fundamental property of a plasma, either quasineutral or non-neutral and weakly or strongly coupled, in which a positive charge is placed in a plasma, this test charge is accumulated by oppositely charged particles [114]. Shielding was first introduced by Debye and Hückel [115] in 1923. Basically, the symmetric Debye-Hückel potential around a static test charge arises due to quasineutrality in the unmagnetized plasma. However, in magnetized plasma, a strongly anisotropic Shukla-Nambu-Salimullah (SNS) potential is presented. The SNS potential is elliptical in shape elongated across the external magnetic field [116]. The subsistence of the SNS electrostatic potential in magnetized plasmas was studied by several authors [105,108,109,117,118].

When plasma is very dense, the de Broglie wavelength associated to the charge particles is comparable to the inter-particle distance. In such circumstances, the plasma must behave as a Fermi gas and the quantum effects play imperative role to modify the behavior of the charged particles. For a quantum plasma, the Debye length is smaller than the dimension of the system. So, to study the Debye shielding, the quantum effects must be considerable when the de Broglie wavelength is comparable to the plasma Debye length. During the last two decades, plasma physics community has been trying to rediscover the new features of the quantum plasma using either the quantum fluid model [27,72,119] or the quantum kinetic model [120].

Astrophysical plasmas [121,122] and metallic plasmas [123] are the major areas that have been explored. Such systems have very high particle number density (as compared to classical plasma) and a quantum mechanical model is needed to describe the behavior of plasmas. Furthermore, the study of electrons and holes in semiconductors [124] is another flourishing area of quantum plasmas. Astrophysical and cosmological plasmas may have electrons, ions, positrons and dust as well [125,126]. The dust dynamics or even a stationary dust grains may generate new dust modes in these systems. Moreover, these compact objects have very strong magnetic field (of the order of $10^{10} - 10^{14}$ $Gauss$) that may influence the properties of plasmas [127] in their environment.

Some efforts have been carried out [128-132] to study the shielding processes in unmagnetized quantum plasmas. However, screening in magnetized quantum plasmas is an area which require more investigations. Recently, Salimullah et al. [133] have explored modified Debye screening potential in an electron-ion quantum plasma using laboratory parameters. The effect of inhomogeneity on the SNS potential [134] through the ion polarization drift in a quantum dusty plasma has also been studied. So far, no work has been done on the phenomenon of shielding potential in an inhomogeneous quantum dusty magnetoplasma environment incorporating the polarization drift effect of dust particles. In this chapter, we explore the effect of magnetic field on the shielding potential in an astrophysical environment where the density inhomogeneity and dust polarization drift effect are present. Let the electric field $E\hat{\mathbf{x}}$ produced due to the inhomogeneous ion/dust distribution be transversed to the ambient magnetic field $B_0\hat{\mathbf{z}}$ in the plasma. Thus, the inhomogeneity of plasma ions/dust in the $x-$direction gives rise to a diamagnetic drift frequency to the ions/dust in the $y-$direction. In addition, the presence of the uniform electric field $\mathbf{E}_0$, responsible for the uniform ion/dust drift and the magnetic field $\mathbf{B}_0$, causes the uniform ion/dust streaming in the $y-$direction and produces a Doppler shift of the electrostatic drift wave frequency in dusty plasma. However, the electrons satisfy the Boltzmann distribution. We shall use the quantum hydrodynamic (QHD) model. We assume that the Fermi temperature (T_F) of the system is more than the thermal temperature (T). In Sec. 2.2, the dielectric response function of the non-uniform quantum dusty magnetoplasma is derived using the QHD model. Sec. 2.3 will be devoted to the calculation of modified SNS potential. Numerical analysis and graphical discussion are given in Sec. 2.4.

2.2 Dielectric Response Function

We consider an infinitely extended inhomogeneous high density quantum plasma containing electrons, ions, and charged dust grains. A homogeneous ambient static magnetic field, $B_0\hat{\mathbf{z}}$, is taken into account. The quasineutrality condition for plasma species satisfy the relation, $n_{i0}(x) + (q_d/e)n_{d0}(x) = n_{e0}(x)$, where $n_{j0}(x)$ is the equilibrium number density of the jth species (j = electrons, ions or dust), q_d is the average charge on a dust grain, and e is the electronic charge. We are interested to analyze the screening potential of the system in the presence of modified electrostatic perturbations including the effects of the heavier species in the presence of strong ambient magnetic field.

The governing equations in the QHD model [28,133,134] for the electrons, ions and charged dust grains in the presence of the ambient magnetic field $\mathbf{B}_0$ are

$$m_j\, n_{j0}\, \frac{\partial}{\partial t}\mathbf{v}_j = -\, n_{j0}\, q_j \nabla\phi + n_{j0}\, \frac{q_j}{c}\, \mathbf{v}_j \times \mathbf{B}_0 - \nabla\, p_{Fj} + \frac{\hbar^2}{4m_j}\nabla(\nabla^2 n_{j1}), \qquad (2.1)$$

$$\frac{\partial n_j}{\partial t} + \nabla.\,(n_j\, \mathbf{v}_j) = 0, \qquad (2.2)$$

where n_j is the number density of species ($n_j = n_{j0} + n_{j1}$), $\phi(\mathbf{r}, t)$ is the electrostatic potential and q_j, $m_j, \hbar$ and c are the charge, mass, the Planck's constant divided by 2π, and the velocity of light in a vacuum, respectively. In Eq. (2.1), we assume that the plasma particles in a one-dimensional zero-temperature Fermi gas satisfying the pressure law [26,29,72], $p_j = m_j V_{Fj}^2 n_j^3/3n_{j0}^2$ where $V_{Fj} = (2k_B T_{Fj}/m_j)^{1/2}$ is the Fermi speed; k_B, and T_{Fj} are the Boltzmann constant and Fermi temperature.

Furthermore, the Poisson's equation satisfying the electrostatic potential ϕ of the electrostatic perturbation as

$$\nabla^2\phi = 4\pi e\left(n_{e1} - n_{i1} - \frac{q_d}{e}\, n_{d1}\right). \tag{2.3}$$

In the presence of the density inhomogeneities in the $x-$direction and the ambient static magnetic field, $\mathbf{B}_0 = \hat{\mathbf{z}}B_0$, we assume that the presence of drift waves propagating in the yz-plane, proportional to $\exp\left[-\,i\left(\omega t - k_y y - k_z z\right)\right]$, where $k_y^2 \gg k_z^2$. Here, ω and $\mathbf{k}$ are the angular frequency and wavenumber vector, respectively. Using Eqs. (2.1)-(2.3), we can obtain the dielectric susceptibility for the jth species [134,135] as

$$\chi_j = -\frac{\omega_{pj}^2\left[\frac{k_z^2}{\omega^2} + \frac{k_y^2}{\omega^2-\omega_{cj}^2}\left(1 - \frac{\omega_{cj}}{k_y L_j \omega}\right)\right]}{k^2 - k^2 V_{Fj}'^2\left[\frac{k_z^2}{\omega^2} + \frac{k_y^2}{\omega^2-\omega_{cj}^2}\left(1 - \frac{\omega_{cj}}{k_y L_j \omega}\right)\right]}, \tag{2.4}$$

where $\omega_{pj} = (4\pi n_{j0} q_j^2/m_j)^{1/2}$ and $\omega_{cj} = q_j B_0/m_j c$ are the plasma frequency and the cyclotron frequency of the jth species. In Eq. (2.4), $V_{Fj}' = V_{Fj}(1+\gamma_j)^{1/2}$ where $\gamma_j = \hbar^2 k^2/8 m_j T_{Fj}$, $L_j = n_{j0}/n_{j0}'$ is the scale length of inhomogeneity and $n_{j0}' = -\partial n_{j0}(x)/\partial x$.

The general dielectric response function for the magnetized inhomogeneous quantum dusty plasma is obtained by taking the following assumptions:

$$\omega \le \omega_{i,d}^* \ll \omega_{ci}\,, \omega_{cd} \quad , \quad k_y^2 \gg k_z^2,$$

$$kV_{Fe}' \gg \omega \;\gg\; kV_{F\,i,d}' \,. \tag{2.5}$$

Therefore

$$\epsilon(\omega,\mathbf{k}) = 1 + \chi_e(\omega,\mathbf{k}) + \chi_i(\omega,\mathbf{k}) + \chi_d(\omega,\mathbf{k}), \tag{2.6}$$

or

$$\epsilon(\omega,\mathbf{k}) = 1 + \frac{\omega_{pe}^2}{k_y^2 V_{Fe}'^2} + \frac{k_y^2}{k^2}\frac{\omega_{pi}^2}{\omega_{ci}^2} - \frac{k_z^2}{k^2}\frac{\omega_{pi}^2}{\omega'^2} - \frac{\omega_i^*}{\omega'} + \frac{k_y^2}{k^2}\frac{\omega_{pd}^2}{\omega_{cd}^2} - \frac{k_z^2}{k^2}\frac{\omega_{pd}^2}{\omega'^2} - \frac{\omega_d^*}{\omega'}, \tag{2.7}$$

where $\omega_i^* = \omega_{pi}^2/k_y L_i \omega_{ci}$ is the ion-drift frequency, $\omega_d^* = \omega_{pd}^2/k_y L_d \omega_{cd}$ is the dust-drift frequency and $\omega' = \omega - k_y u_0$ stands for the Doppler shifted frequency both for ion and dust dynamics. The density inhomogeneity along the $x-$direction generates an electric field $E\hat{\mathbf{x}}$ which in turn produces $\mathbf{E} \times \mathbf{B}_0$ drift u_0 in the $y-$direction. This drift speed $u_0 = c\,E/B_0$ is same for ion and dust species because it does not depend upon mass and charge. Here, the quantum mechanical effect for ions and dust grains is neglected due to their heavier masses, but is retained through the dynamics of electrons. Note that both ions and dust are taken as cold, inhomogeneous, and magnetized. Usually dust species is taken as cold and unmagnetized, but in the presence of strong magnetic field it can be taken as magnetized. Equation (2.7) can be written as

$$\epsilon(\omega, \mathbf{k}) = \frac{1}{k^2}\left[k_\parallel^2 + k_\perp^2(1 + f_i + f_d) + k_{Fe}'^2\left(1 + \frac{u_0 M_{Fs}^{-2}}{L_i \omega_{ci}} + \frac{u_0 M_{Fd}^{-2}}{L_d \omega_{cd}}\right)\right], \tag{2.8}$$

where L_i and L_d are the scale length of inhomogeneities for ion and dust particles, $f_i = \omega_{pi}^2/\omega_{ci}^2$, $f_d = \omega_{pd}^2/\omega_{cd}^2$, $M_{Fs,d} = u_0/C_{Fs,d}$, $k'_{Fe} = 1/\lambda'_{Fe}$, and $\lambda'_{Fe} = V'_{Fe}/\omega_{pe}$. Note that C_{Fs} and C_{Fd} are the ion-acoustic and dust-acoustic velocities at electron Fermi temperature, respectively. In obtaining Equation (2.8), we have considered low frequency waves assuming $\omega' \simeq -k_y u_0$ and $k_y^2 \gg k_z^2$.

2.3 Modified Screening Potential

Now, the standard formula of electrostatic potential [101,136] around a test charge in the presence of electrostatic mode $(\omega, \mathbf{k})$ is given in the Eq. (1.5).

Substituting Eq. (2.8) into Eq. (1.5), and using the cylindrical coordinates [133,134], we may obtain the potential due to the test charge as

$$\Phi(\rho, \xi) = \frac{q_t}{\pi}\int \frac{J_0(k_\perp \rho)\ e^{ik_\parallel \xi}\ k_\perp\, dk_\perp\, dk_\parallel}{k_\parallel^2 + k_\perp^2(1 + f_i + f_d) + k_{Fe}'^2\left(1 + \frac{u_0 M_{Fs}^{-2}}{L_i \omega_{ci}} + \frac{u_0 M_{Fd}^{-2}}{L_d \omega_{cd}}\right)}. \tag{2.9}$$

In obtaining Equation (2.9), we have evaluated ω - and θ - integrations. Now taking $V_{Fe}^2 \gg (\hbar^2 k^4/4m_e^2)$ for long wavelengths and after performing the $k_\parallel-$ and

$k_\perp-$integrations [133,134], we get

$$\Phi(\rho,\xi) = \frac{q_t}{\sqrt{1+f_i+f_d}} \; \frac{exp\,[-\sqrt{\rho^2+\xi^2(1+f_i+f_d)}\;\;/\;L_s']}{\sqrt{\rho^2+\xi^2(1+f_i+f_d)}}, \tag{2.10}$$

where

$$L_s' = \lambda_{Fe}\,\sqrt{1+f_i+f_d}/\sqrt{1+C_{Fs}^2/u_0L_i\omega_{ci}+C_{Fd}^2/u_0L_d\omega_{cd}}. \tag{2.11}$$

Using the quasi-neutrality condition, the length L_s' can be re-written as

$$L_s' = \lambda_{Fe}\,\sqrt{1+f_i+f_d}/\sqrt{1-\frac{1}{u_0}\frac{\omega_{pe}^2}{\omega_{ce}}\frac{\lambda_{Fe}^2}{|L_e|}}. \tag{2.12}$$

If the inhomogeneity of the dust species is neglected and consider the dust as unmagnetized, thus our findings resemble with the result of Ref. [134]. However, in Ref. [134], the gradient of the magnetic field is presented, while it is absent here. We have taken this simpler choice because a static magnetic field is usually considered to confine the astrophysical and laboratory plasmas. But the purpose of this chapter is to explore the SNS potential in a very high magnetic field environment. Therefore by taking the assumption $f_i \ll f_d$, we can write Eq. (2.10) as

$$\Phi(\rho,\xi) = \frac{q_t}{\sqrt{1+f_d}} \; \frac{exp\,[-\sqrt{\rho^2+\xi^2(1+f_d)}\;\;/\;L_s'']}{\sqrt{\rho^2+\xi^2(1+f_d)}}, \tag{2.13}$$

with

$$L_s'' = \lambda_{Fe}\,\sqrt{1+f_d}/\sqrt{1-\frac{1}{u_0}\frac{\omega_{pe}^2}{\omega_{ce}}\frac{\lambda_{Fe}^2}{|L_e|}}\,. \tag{2.14}$$

The quantum effect in Eq. (2.13) is represented by the Fermi statistical effect. From Eqs. (2.13) and (2.14), we notice that the modified Debye shielding is a sensitive function of the scale length of inhomogeneity $|L_e|$, drift speed u_0, dimensionless parameter f_d, and ambient magnetic field B_0. The amplitude of the potential is reduced by the factor $\sqrt{1+f_d}$, however the effective length $L_s'' = \lambda_{Fe}\sqrt{1+f_d}$ is increased by this factor when the particle moves in the $z-$direction. For a homogeneous strongly magnetized quantum plasma ($L_e \to \infty$), Eq. (2.13) can be written as

$$\Phi(\rho,\xi) = \frac{q_t}{\sqrt{1+f_d}}\ \frac{exp\,[-\sqrt{\rho^2+\xi^2(1+f_d)}\ /\ L_s'']}{\sqrt{\rho^2+\xi^2(1+f_d)}}, \tag{2.15}$$

where $L_s'' = \lambda_{Fe}\sqrt{1+f_d}$. Note that the usual SNS potential is modified by the contribution of the dust polarization drift effect. So, in the dusty plasma environment of astrophysical objects, which have very high magnetic field, the ion polarization drift effect is much less than the dust polarization drift effect ($f_i \ll f_d$). The same effect is achieved under the condition $\omega_{pe}^2\lambda_{Fe}^2 \ll u_0\omega_{ce}L_e$. For $\omega_{pe}^2\lambda_{Fe}^2 \gg u_0\omega_{ce}L_e$, with positive density gradient, the Debye shielding is lost and the plasma does not behave as plasma. However, if we take negative density gradient for $\omega_{pe}^2\lambda_{Fe}^2 \gg u_0\omega_{ce}L_e$, then the shielding can exist and the effective length L_s'' in Eq. (2.14) reduces to

$$L_s'' \simeq \lambda_{Fe}\,\sqrt{1+f_d}/\sqrt{\frac{1}{u_0}\frac{\omega_{pe}^2}{\omega_{ce}}\frac{\lambda_{Fe}^2}{L_e}} \simeq \lambda_{Fe}\,\sqrt{1+f_d}\sqrt{\frac{M_{Fs}L_e\omega_{ci}}{C_F s}}. \tag{2.16}$$

Here, we notice that L_s'' increases by the factor "$M_{Fs}L_e\omega_{ci}$". It is important to mention here that the scale length of the inhomogeneity can be either positive or negative depending upon the density gradient.

2.4 Numerical and graphical representations

To better understand the behavior of the potential of a test charge particle in a quantum dusty plasma, we have numerically solved Eq. (2.13). We choose some parameters for high density quantum plasmas like white dwarf, neutron stars [125,137]: $n_{e0} \approx n_{i0} = 10^{27}$ cm^{-3}, $T_{Fe} \approx 10^7$K, $B_0 = 10^8$G and plotted the potential for $f_i = \omega_{pi}^2/\omega_{ci}^2$ and $f_d = \omega_{pd}^2/\omega_{cd}^2$. The results of our calculations are depicted in the form of curves in Figs. 1-3. Figs. 1-3 show the normalized SNS potential as a function of ρ' and ξ' in the presence of the static magnetic field. Here, the quantum effect arises through the Fermi temperature only. Fig. 1 shows the normalized potential as a function of ξ' with $\rho' = 0$ for $M = 0.005, f_i \approx 10$ and $f_d \approx 10^3$.

Fig. 1 clearly shows that normalized SNS potential decreases in dusty plasma as compared to SNS potential in electron-ion plasma. It is also observed here, that potential is rapidly decaying with the contribution of dust polarization drift effect $f_d = \omega_{pd}^2/\omega_{cd}^2$. Because the ion polarization drift effect is much less than the dust polarization drift effect ($f_i \ll f_d$), this is due to the ion gyrofrequency which is much larger than the dust gyrofrequency, $\omega_{ci} \gg \omega_{cd}$ and polarization drift effect depends directly on the mass. To compare the SNS screening potential with other potentials, for example, almost spherically symmetric Debye-Hückle potential, SNS screening potential is asymmetric in the direction perpendicular to $\hat{\mathbf{z}}B_0$. It is also mentioned here SNS potential decreases as compared to Debye-Hückle potential due to the presence of ion polarization drift effect $f_i = \omega_{pi}^2/\omega_{ci}^2$. When effects of shielding are negligible and charge q must give rise to the usual Coulomb potential $\phi(\mathbf{r}) \approx 1/\mathbf{r}$.

Fig. 2 shows the normalized SNS potential in quantum dusty magnetoplasma at the different values of the number density n_{e0}. It is observed here, potential decreases with the increase of number density e.g. $n_{e0} = 10^{27}\text{cm}^{-3}$, $n_{e0} = 10^{28}\text{cm}^{-3}$ and $n_{e0} = 10^{29}\text{cm}^{-3}$ in quantum dusty magnetoplasma. For higher densities of plasma particles shielding length of the potential is decreased and potential falls much faster in quantum plasmas.

Fig. 3 shows the normalized SNS potential with the effect of inhomogeneity scale length L_e. If we consider the inhomogeneity in our chosen plasma system, potential increases. When we plot the potential at different values of inhomogeneity scale length $L_e = 4\text{cm}$, $L_e = 6\text{cm}$ and $L_e = 8\text{cm}$, the SNS potential decreases with the increase of L_e. These values of inhomogeneity scale length are estimated in comparison of the Fermi Debye length of the plasma and the other parameters n_{e0}, B_0 and M when the effect of inhomogeneity is considered to exist the SNS potential [c.f. Eq. 2.14]. The inhomogeneity scale length should be greater than the Fermi Debye length. If inhomogeneity scale length approaches to infinity ($L_e \to \infty$) then plasma system will be homogeneous and we will get usual SNS potential.

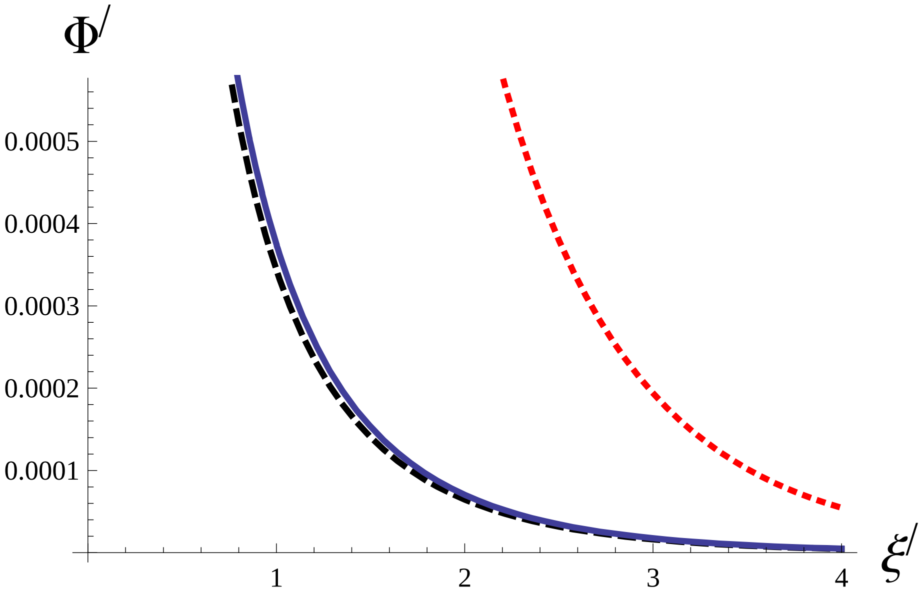


Figure 1:

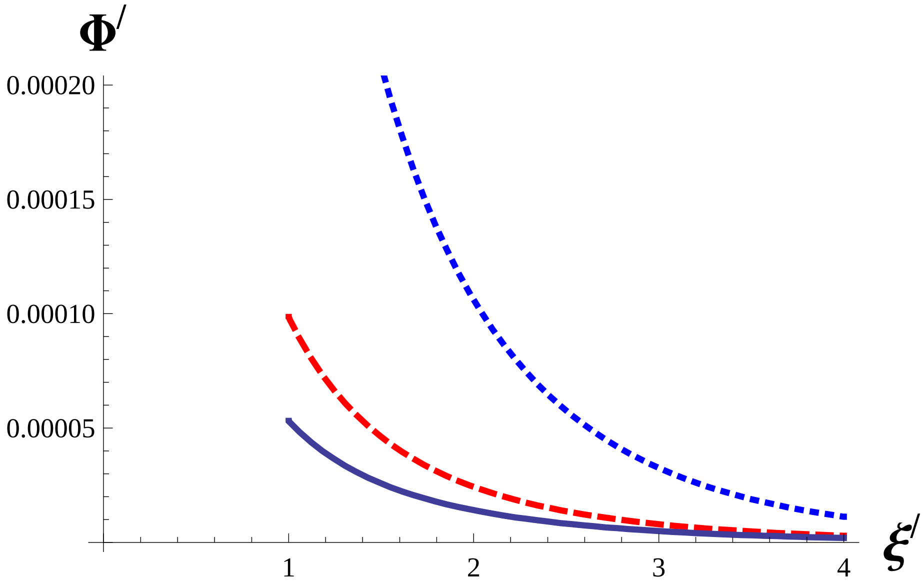


Figure 2:

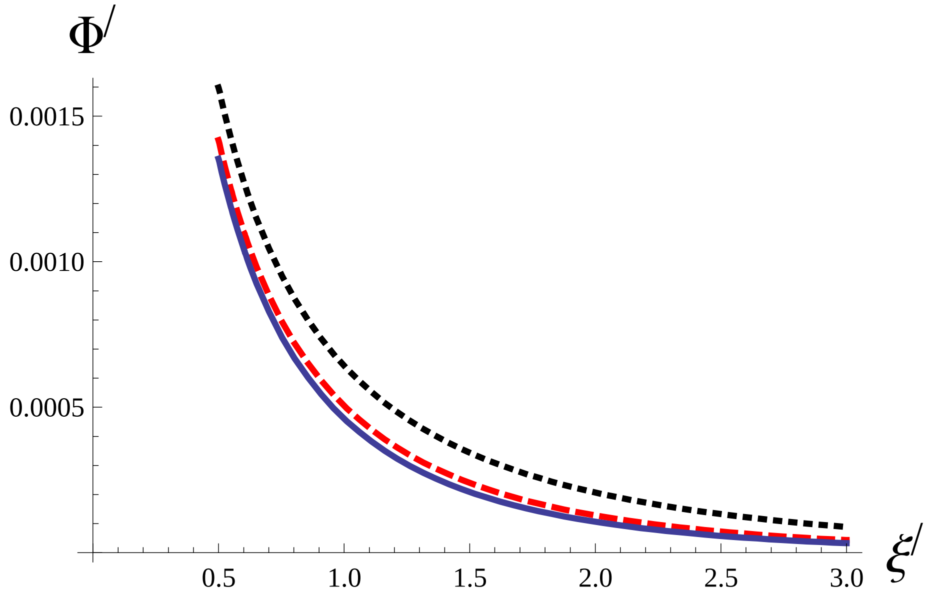


Figure 3:

Figure Captions

Fig. 1: The variation of the normalized SNS potential $\Phi'(\rho', \xi')$ for $f_i = \omega_{pi}^2/\omega_{ci}^2$ and $f_d = \omega_{pd}^2/\omega_{cd}^2$. Dotted line corresponds to $f_i = 10$, dashed line for both $f_i = 10$ and $f_d = 10^3$ and solid line for $f_d = 10^3$. Other parameters are $n_{e0} \approx n_{i0} = 10^{27}$ cm^{-3}, $T_{Fe} \approx 10^7$K, $B_0 = 10^8$G.

Fig. 2: The variation of the normalized SNS potential $\Phi'(\rho', \xi')$ for different values of the number density, n_{e0} with the presence of f_d. Dotted line corresponds to $n_{e0} = 10^{27}$cm^{-3}, dashed line for $n_{e0} = 10^{28}$cm^{-3} and $n_{e0} = 10^{29}$cm^{-3} for solid line and other parameters as in Fig. 1.

Fig. 3: The variation of the normalized SNS potential $\Phi'(\rho', \xi')$ with different values of inhomogeneity scale length L_e. Dotted line corresponds to $L_e = 4$ cm, dashed line for $L_e = 6$ cm and $L_e = 8$ cm for solid line and other parameters are same as in Fig. 1.

Chapter 3

Potentials in a nonuniform quantum dusty magnetoplasma

3.1 Introduction

The fundamental property of a plasma is the Debye-Hückel potential [115] which is the reduced potential of a static test charged particle in the plasma. Later, the potential distribution of a slowly moving test charge was pursued by others [138-140]. The concept of an oscillatory wake-field potential in an electron-ion plasma was first introduced by Nambu and Akama [101]. They explained the attraction among the same charged electrons in terms of the wake potential generated due to the resonant interaction of the electrons and the ion-acoustic wave. This idea was extended to dusty plasmas by Nambu et al. [102] to explain the dust-crystal formation in the laboratory [141]. In all these studies, the plasma was assumed to be homogeneous and quantum mechanical effects were neglected at higher density. Recently, the Debye-Hückel and wake potentials have been studied in homogeneous and unmagnetized quantum plasmas [129-131]. However, in most of the laboratory situations of plasma experiments and space and astrophysical systems, plasmas involved will be nonuniform in nature. Also, the ambient magnetic field in space systems or the applied magnetic field in the laboratory plasmas may be inhomogeneous with uniform gradient.

Moreover, in recent years, there has been a growing enthusiasm in quantum plasmas because of their importance in microelectronics and electronic devices with nano-electronic components [29,51], dense astrophysical systems [45,121,122], and in laser-produced plasmas [44,142-144]. When a plasma is cooled to an extremely low temperature, the de Broglie wavelengths of the plasma particles could be at least comparable to the scale lengths, such as Debye length or Larmor radius, etc. in the system. In such systems, the ultracold dense plasma would behave as a Fermi gas and quantum mechanical effects might play a vital role in the behavior of the charge carriers of these plasmas under extreme conditions. Recently, Shukla and Eliasson [131] have studied the screening and wake potentials of a test charge in a homogeneous and unmagnetized quantum plasma. They considered the quantum effect through the Bohm potential only, which is valid for a relatively low-density quantum plasma and a short wavelength perturbation. For high-density quantum plasmas and relatively longer wavelength, the Fermi degenerate pressure will dominate over the Bohm potential term in the equation of motion.

We can visualize that the density and static ambient magnetic field in a quantum dusty magnetoplasma can be nonuniform with finite scale lengths. The density inhomogeneity causes the presence of very low-frequency drift waves due to diamagnetic drifts and the magnetic field inhomogeneity causes a uniform stream of ions.

In this chapter, we study the potential distributions around a slowly moving or static test charge in a dense quantum dusty plasma in the presence of a nonuniform density and nonuniform magnetic field with uniform gradients in the same direction (**x**-axis). In Sec. 3.2, we derive the dielectric response function of the nonuniform quantum dusty magnetoplasma using the quantum hydrodynamic model of plasmas (QHD). Then, using the test particle model, we obtain the modified Shukla-Nambu-Salimullah (SNS) and the wake potential in Sec. 3.3. Numerical results and graphical representations are given in Sec. 3.4.

3.2 Quantum Dielectric Response Function

We consider an infinitely extended inhomogeneous high-density dusty magnetoplasma containing electrons, ions and charged dust grains in the presence of an inhomogeneous static ambient magnetic field $\mathbf{B}_0(x) \parallel \hat{\mathbf{z}}$. At equilibrium, we assume that the charge quasineutrality condition is satisfied, that is $n_{i0}+(q_d/e)n_{d0} = n_{e0}$, where $n_{j0}(x)$ is the equilibrium number density of the jth species ($j =$ electrons, ions or dust), q_d is the average charge on a dust grain, and e is the electronic charge.

The governing equations in the quantum hydrodynamic model [28,72,145-147] for the electrons, ions and charged dust grains ($j = e, i, d$) in the presence of the ambient magnetic field $\mathbf{B}_0$ are given in Eqs. (2.1)-(2.3) and in the presence of the density inhomogeneities in the x-direction and the ambient magnetic field, $\mathbf{B}_0 = \hat{\mathbf{z}}\, B_0(x)$, we assume the presence of drift waves propagating in the YZ-plane, proportional to $\exp\left[-\,i\,(\omega t - k_y y - k_z z)\right]$ where $k_y^2 \gg k_z^2$. Here, ω and $\mathbf{k}$ are the angular frequency and wavenumber vector, respectively. Using Eqs. (2.1-2.3) and after some straight-forward calculations, we obtain the dielectric susceptibility for the jth species where $j = e, i, d$ as

$$\chi_j = -\frac{\omega_{pj}^2\left[\frac{k_z^2}{\omega^2} + \frac{k_y^2}{\omega^2 - \omega_{cj}^2}\left(1 - \frac{\omega_{cj}}{k_y L_j \omega}\right)\right]}{k^2 - k^2 V_{Fj}'^2\left[\frac{k_z^2}{\omega^2} + \frac{k_y^2}{\omega^2 - \omega_{cj}^2}\left(1 - \frac{\omega_{cj}}{k_y L_j \omega}\right)\right]}, \tag{3.1}$$

where $\omega_{pj} = (4\pi n_{j0} q_j^2/m_j)^{1/2}$ and $\omega_{cj} = q_j B_0/m_j c$ are the plasma frequency and the cyclotron frequency of the jth species. In Eq. (3.1), $V_{Fj}' = V_{Fj}(1+\gamma_j)^{1/2}$ where $\gamma_j = \hbar^2 k^2/8 m_j T_{Fj}$ and the scale length of inhomogeneity $L_j = n_{j0}/n_{j0}'$ where $n_{j0}' = -\partial n_{j0}(x)/\partial x$. $\omega' = \omega - k_y V_0$ is the Doppler shifted frequency for ions. We use Eq. (3.1) to find the general dielectric response function of the nonuniform quantum dusty magnetized plasma under various possible conditions from

$$\epsilon(\omega, \mathbf{k}) = 1 + \chi_e(\omega, \mathbf{k}) + \chi_i(\omega, \mathbf{k}) + \chi_d(\omega, \mathbf{k}). \tag{3.2}$$

3.3 Modified SNS and Wake Potentials

To study the screening and dynamical potentials in a nonuniform quantum dusty plasma in the presence of a static ambient magnetic field with a gradient, we assume

$$\omega \leq \omega_i^* \ll \omega_{ci}, \qquad k_y^2 \gg k_z^2,$$

$$k_z V'_{Fe} \gg \omega \gg k_z V'_{Fi}, \tag{3.3}$$

where $\omega_i^* = \omega_{pi}^2/k_y L_i \omega_{ci}$ is the ion-drift frequency. Then, using assumptions, Eqs. (3.3), the dielectric response function is obtained from Eqs. (3.1) and (3.2)

$$\epsilon(\omega, \mathbf{k}) \simeq 1 + \frac{\omega_{pe}^2}{k_y^2 V_{Fe}'^2} + f_i - \frac{\omega_i^*}{\omega} - \frac{\omega_{pd}^2}{\omega^2}, \tag{3.4}$$

where, $f_i = \omega_{pi}^2/\omega_{ci}^2$. Here, the quantum mechanical effect is taken through the motion of electrons, which is neglected for ions and dust grains because of their heavier masses.

On account of the density inhomogeneities, the electrons and ions acquire diamagnetic drift frequencies. However, because of the inhomogeneity of the ambient static magnetic field in the dusty plasma with a gradient in the x-direction, ions can have an additional drift velocity [148]

$$\mathbf{V_0} = -\frac{c\, \partial B_0(x)/\partial x}{4\pi q_{d0} n_{d0}}\ \hat{\mathbf{y}}. \tag{3.5}$$

In the presence of the density nonuniformity and the continuous ion streaming because of the magnetic field nonuniformity, the dielectric function can be written as

$$\epsilon(\omega, \mathbf{k}) = 1 + \frac{\omega_{pe}^2}{k_y^2 V_{Fe}'^{\,2}} + f_i - \frac{\omega_i^*}{\omega - k_y V_0} - \frac{\omega_{pd}^2}{\omega^2}\ . \tag{3.6}$$

Since the above dielectric function involves an extremely low-frequency and low-phase velocity mode involving the dust dynamics, we can assume $V_0 > \omega/k_y$ and Eq. (3.6) reduces to

$$\epsilon(\omega, \mathbf{k}) \simeq F - \frac{\omega_{pd}^2}{\omega^2}, \tag{3.7}$$

where

$$F = 1 + \frac{1}{k^2 \lambda_{Fe}'^2} + \frac{k_\perp^2}{k^2}\, f_i - \frac{\omega_{pi}^2}{k^2 V_0 |L_i| \omega_{ci}}, \tag{3.8}$$

and $|L_i| = |n_{i0}(x)/(\partial n_{i0}(x)/\partial x)|$.

Taking $1/k^2\lambda_{Fe}'^2 \ll f_i - \omega_i^*/(\omega - k_y V_0)$, the dust-lower-hybrid drift wave dispersion relation is given by

$$\omega^2 = \omega_{dlh}^2 / \left(1 - \frac{\omega_{ci}}{k^2 V_0 |L_i|}\right). \tag{3.9}$$

The inverse of the dielectric response function associated with the dust-lower-hybrid drift wave is

$$\frac{1}{\epsilon(\omega, \mathbf{k})} = \frac{1}{F}\left(1 + \frac{\omega_k^2}{\omega^2 - \omega_k^2}\right), \tag{3.10}$$

where

$$\omega_k^2 = \omega_{pd}^2 / F. \tag{3.11}$$

The electrostatic potential around a test charge particulate [101,136] in the presence of the electrostatic mode $(\omega, \mathbf{k})$ in a magnetized dusty plasma whose response function is given by $\epsilon(\omega, \mathbf{k})$, Eq. (3.6), is given by Eq. (1.5).

Substituting Eq. (3.10) into the standard formula of electrostatic potential Eq. (1.5), we obtain the total potential as $\Phi = \Phi_c + \Phi_w$ where the Coulombian potential is given by substituting first part of Eq. (3.10)

$$\Phi_c(\mathbf{x}) = \frac{q_t}{\pi} \int \frac{J_0(k_\perp \rho) \exp(i k_\parallel z) k_\perp \, dk_\perp \, dk_\parallel}{k_\parallel^2 + (1 + f_i) k_\perp^2 + \frac{\omega_{pe}^2}{V_{Fe}^2 + \hbar^2 k_\perp^2 / 4\, m_e^2} - \frac{\omega_{pi}^2}{V_0 |L_i|\, \omega_{ci}}}, \tag{3.12}$$

where J_0 is the zero-order Bessel function of the first kind with argument $k_\perp \rho$. We note that the quantum effect in Eq. (3.12) arises through the Fermi degenerate pressure as well as the Bohm potential effect. For a sufficiently high-density quantum plasma, the Bohm potential effect can be small at relatively small $k_\perp$, i.e. longer wavelength waves ($\lambda_{Fe}^2 \gg \hbar^2 k_\perp^2 / 4 m_e^2 \omega_{pe}^2$). Then, the Eq. (3.12) reduces to

$$\Phi_c(\rho, z) = \frac{q_t}{\pi} \int \frac{J_0(k_\perp \rho) \exp(i k_\parallel z) k_\perp \, dk_\perp \, dk_\parallel}{k_\parallel^2 + (1 + f_i) k_\perp^2 + k_{Fe}^2 (1 - V_0 M^{-2} / |L_i|\, \omega_{ci})}, \tag{3.13}$$

where $k_{Fe} = 1/\lambda_{Fe} = \omega_{pe}/V_{Fe}$, $M = V_0/C_{Fs}$ and $C_{Fs} = \omega_{pi} \lambda_{Fe}$

Following Ref. [111,116], the Coulombian part of the electrostatic potential is given by

$$\Phi_c(\rho, z) = \frac{q_t}{\sqrt{1 + f_i}} \frac{\exp[-\sqrt{\rho^2 + z^2(1 + f_i)}/L_s]}{\sqrt{\rho^2 + z^2(1 + f_i)}}, \tag{3.14}$$

where

$$L_s = \frac{\lambda_{Fe}\sqrt{1+f_i}}{\sqrt{1 - C_{Fs}^2/V_0|L_i|\,\omega_{ci}}}\,. \tag{3.15}$$

For $C_{Fs}^2 \ll V_0|L_i|\,\omega_{ci}$, the modified shielding potential reduces to the usual SNS potential [111,116] which is elongated in the direction perpendicular to the magnetic field. The plasma inhomogeneity effect, the ion streaming due to the ambient magnetic field inhomogeneity and the ambient magnetic field have the significant effects on the shielding potential. For $C_{Fs}^2 \gg V_0|L_i|\,\omega_{ci}$, L_s becomes imaginary and the shielding is lost. Hence, there is a drastic modification of the shielding potential when $C_{Fs}^2 \leq V_0|L_i|\,\omega_{ci}$.

Substituting the second part of Eq. (3.10) in Eq. (1.5), we obtain the dynamical potential as

$$\Phi_w(\mathbf{x},t) = \frac{q_t}{\pi}\int \frac{\delta(\omega - \mathbf{k}.\mathbf{v}_t) J_0(k_\perp\rho)\exp(i\,k_\parallel z)\,k_\perp\omega_{pd}^2\,dk_\perp\,dk_\parallel}{(\omega^2 - k_\perp^2\omega_{pd}^2)\,F}\,. \tag{3.16}$$

For a slowly moving test charge ($\mathbf{k}\cdot\mathbf{v}_t \approx 0$), time-independent wake potential reduces to

$$\Phi_w(\rho,z) = -\frac{q_t}{\pi}\int \frac{J_0(k_\perp\,\rho)\ \exp(ik_\parallel z)\,k_\perp\,dk_\perp\,dk_\parallel}{k_\parallel^2 + (1+f_i)k_\perp^2 + \frac{\omega_{pe}^2}{V_{Fe}^2+\hbar^2k_\perp^2/4\,m_e^2} - \frac{\omega_{pi}^2}{V_0|L_i|\,\omega_{ci}}}\,. \tag{3.17}$$

Taking $V_{Fe}^2 \gg \hbar^2\,k_\perp^2/4\,m_e^2$ and following the standard technique [106]

$$\Phi_w(\rho=0,z) = \left(\frac{q_t}{(1+f_i)z}\right).\ \sin\left(\frac{z}{L_w}\right)\,, \tag{3.18}$$

where the effective length of the wake potential is given by

$$\begin{aligned} L_w &= \frac{1}{\sqrt{\frac{\omega_{pi}^2}{V_0|L_i|\,\omega_{ci}} - \frac{1}{\lambda_{Fe}^2}}}\,, \\ &= \frac{\lambda_{Fe}}{\sqrt{V_0\,M^{-2}/|L_i|\,\omega_{ci} - 1}}\,, \\ L_w &= \frac{\lambda_{Fe}}{\sqrt{\rho_{Fs}/M|L_i| - 1}}\,, \end{aligned} \tag{3.19}$$

where $\rho_{Fs} = C_{Fs}/\omega_{ci}$.

The wake potential exists for $V_0 M^{-2} > |L_i|\omega_{ci}$, that is for $C_{Fs} > \sqrt{V_0|L_i|\,\omega_{ci}}$. In the other limit $C_{Fs} < \sqrt{V_0|L_i|\,\omega_{ci}}$, the wake potential does not become effective. Under this condition, the total potential reduces to the SNS potential. However, the wake potential shows a drastic modification when $C_{Fs} \simeq \sqrt{V_0|L_i|\,\omega_{ci}}$.

On inspection of Eqs. (3.14) and (3.18), we notice that for $C_{Fs}^2 \ll V_0|L_i|\,\omega_{ci}$, one retrieves the SNS potential of a homogeneous plasma ($|L_i| \cong \infty$). However, for $C_{Fs}^2 \gg V_0|L_i|\,\omega_{ci}$, the dynamical oscillating wake potential becomes operative for distances greater than the modified shielding length.

3.4 Numerical results and graphical representations

To have some numerical appreciation of the potential around a slowly moving or static test charge in a dense nonuniform quantum dusty magnetoplasma, we have plotted the the modified Shukla-Nambu-Salimullah (SNS) Eq. (3.14) and the wake potential Eq. (3.18) for the following set of parameters for high density quantum plasmas like white dwarf, neutron stars [125,137]: $n_{e0} \approx n_{i0} = 10^{27}$ cm^{-3}, $T_{Fe} \approx 10^7$K, $B_0 = 10^8$G and plotted the potential for $f_i = \omega_{pi}^2/\omega_{ci}^2$. The results of our calculations are depicted in the form of curves in the Figs. 1-4. Fig. 1 shows the normalized SNS potential as a function of ξ' with $\rho' = 0$ and Figs. 2-4 show the normalized wake potential as a function of ξ' with $\rho' = 0$ in the presence of nonuniform density and nonuniform magnetic field. Here, the quantum effect arises through the Fermi temperature only.

Figure 1 shows the effect of magnetic field on the normalized SNS potential Φ' via different values of $f_i = \omega_{pi}^2/\omega_{ci}^2$ and $M \leq 1$. It follows that normalized SNS potential decreases with the increasing value of $f_i = 10$, $f_i = 50$, and $f_i = 100$. For relatively smaller value of magnetic field, f_i is large then potential decreases in the parallel direction to the external magnetic field.

Figure 2 shows the effect of magnetic field on the normalized wake potential Φ' via different values of $f_i = \omega_{pi}^2/\omega_{ci}^2$. From the dotted, dashed and solid curves, we notice that the amplitude of the oscillatory wake potential decreases with increasing value of f_i.

Figures 3 illustrates the variation of the normalized wake potential, Φ' as a function of the number density, n_{e0}. It is evident from Fig. 2 that the amplitude of the oscillatory wake potential decreases with the increase of number density e.g. $n_{e0} = 10^{27}\text{cm}^{-3}$, $n_{e0} = 5 \times 10^{27}\text{cm}^{-3}$ and $n_{e0} = 10^{28}\text{cm}^{-3}$ in quantum dusty magnetoplasma. For higher densities of plasma particles effective length of the oscillatory wake potential is decreased in quantum plasmas. This oscillatory wake potential has maxima or minima in plasma BEYOND the Debye potential. These positive or negative places will attract Dust particles or clusters of particles giving rise to a quasi lattice in the plasma, called the plasma crystals. So, the effective length is the lattice spacing of the plasma crystals. Therefore, this long-range potential is responsible for the formation of new ordered structures of particles in plasmas.

Figure 4 shows the behavior of Φ' with the effect of inhomogeneity scale length L_i. When we plot the potential at different values of inhomogeneity scale length, the amplitude of the oscillating wake potential decreases with the increase of L_i. If inhomogeneity scale length approaches to infinity ($L_i \to \infty$) then plasma system will be homogeneous.

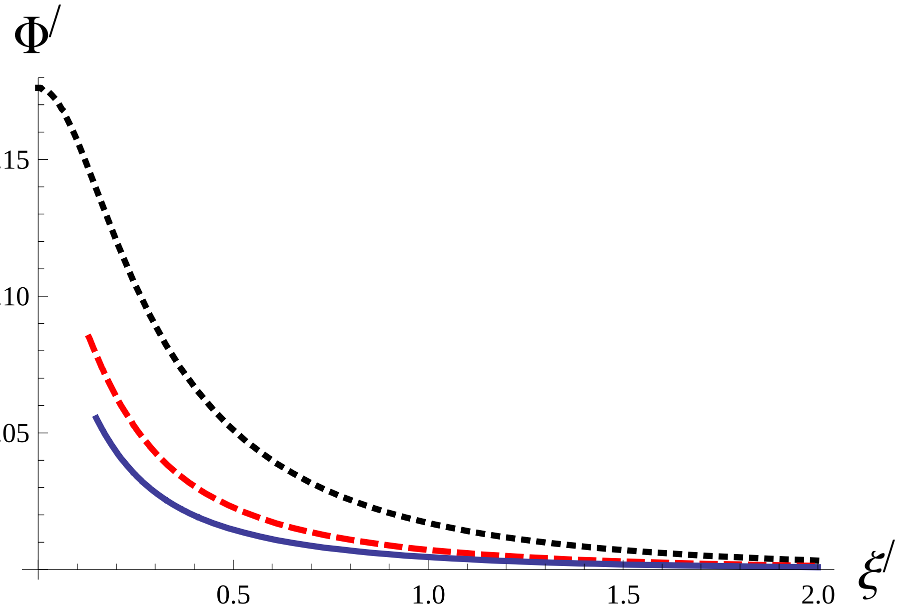


Figure 4:

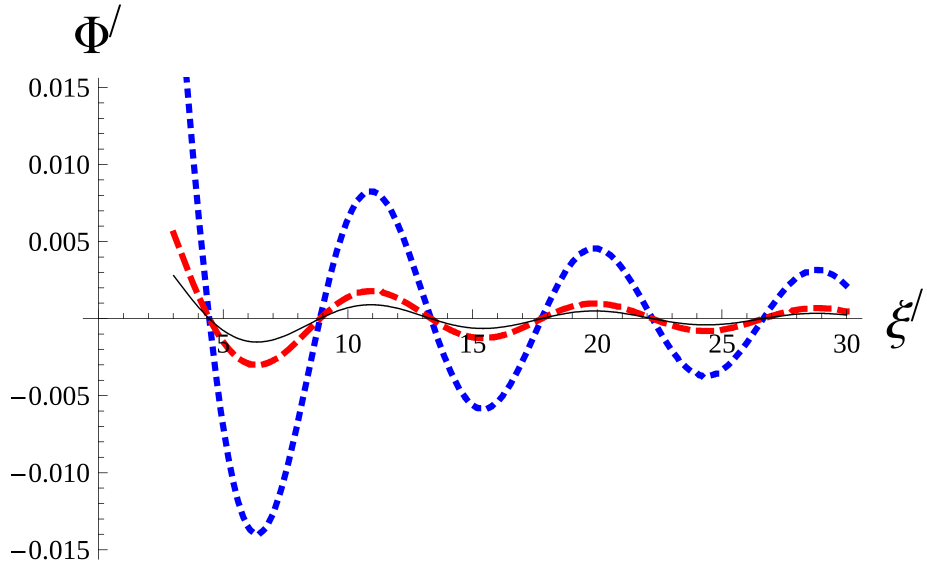


Figure 5:

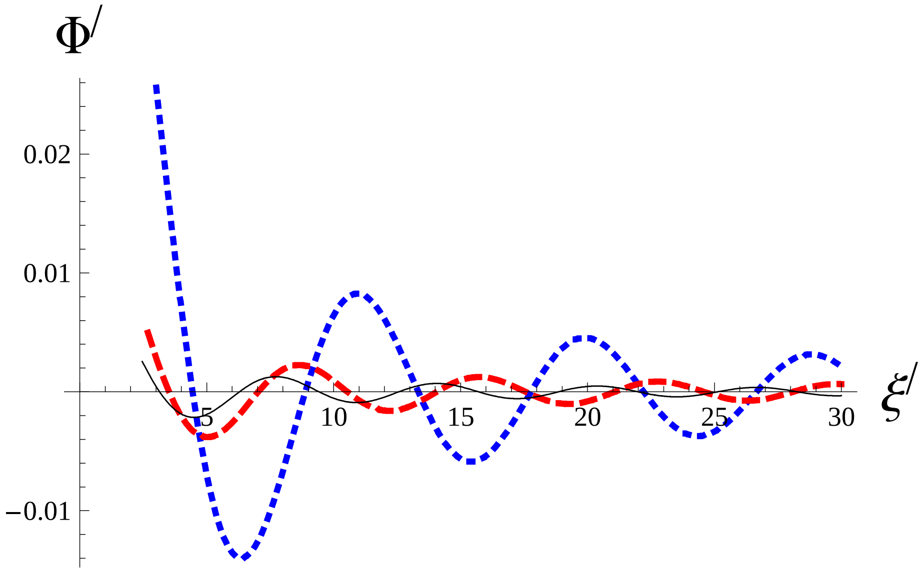


Figure 6:

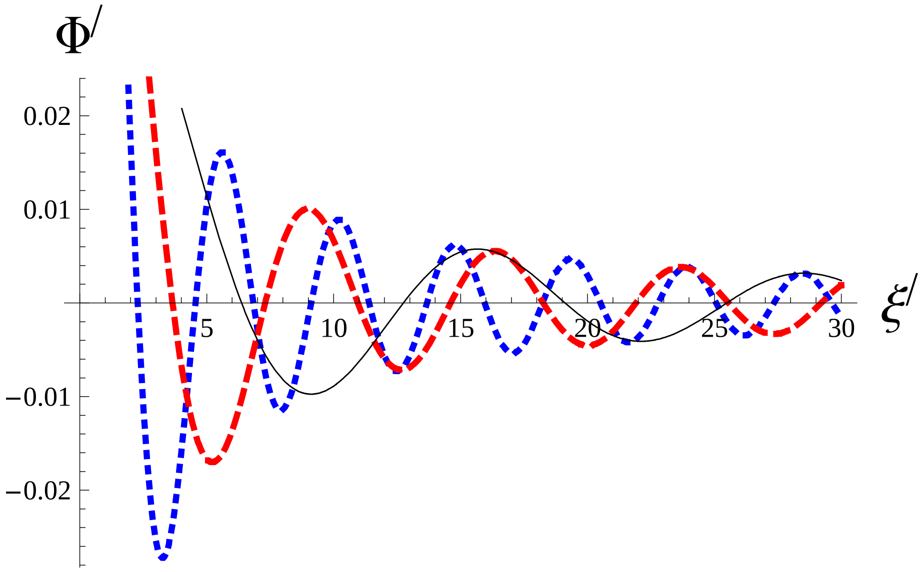


Figure 7:

Figure Captions

Fig. 1: The variation of the normalized SNS potential $\Phi'(\rho', \xi')$ for different values of $f_i = \omega_{pi}^2/\omega_{ci}^2$. Dotted line corresponds to $f_i = 10$, dashed line for $f_i = 50$ and $f_i = 100$ for the solid line. Other parameters are $n_{e0} \approx n_{i0} = 10^{27}$ cm^{-3}, $T_{Fe} \approx 10^7$K, $B_0 = 10^8$G.

Fig. 2: The variation of the normalized wake potential $\Phi'(\rho', \xi')$ for different values of $f_i = \omega_{pi}^2/\omega_{ci}^2$. Dotted line corresponds to $f_i = 10$, dashed line for $f_i = 50$ and $f_i = 100$ for the solid line. Here, other parameters are same as in Fig. 1.

Fig. 3: The variation of the normalized wake potential $\Phi'(\rho', \xi')$ for different values of the number density, n_{e0}. Dotted line corresponds to $n_{e0} = 10^{27}$cm^{-3}, dashed line for $n_{e0} = 5 \times 10^{27}$cm^{-3} and $n_{e0} = 10^{28}$cm^{-3} for solid line and other parameters as in Fig. 1.

Fig. 4: The variation of the normalized wake potential $\Phi'(\rho', \xi')$ with different values of inhomogeneity scale length L_i. Dotted line corresponds to $L_i = 1.5$ cm, dashed line for $L_i = 2.5$ cm and $L_i = 3.5$ cm for solid line and other parameters are same as in Fig. 1.

Chapter 4

Dust-lower-hybrid waves in quantum plasmas

4.1 Introduction

There has been a considerable interest on the quantum mechanical effects in some specific areas of plasma physics, viz. microelectronics [29,51], dense astrophysical systems [45,121,122], and in laser-produced plasmas [142]. When a plasma is cooled to an extremely low temperature, the de Broglie wavelengths of the plasma particles could be comparable to the dimensions of the systems. In such plasmas, the ultracold dense plasma would behave as a Fermi gas and quantum mechanical effects might play a vital role in the behavior of the charge carriers of these plasmas under these extreme conditions. In microelectronics and very large integrated circuit fabrications, the systems may develop contaminants due to etching, implantations, etc. which might lead to new properties. The laser-produced plasmas and plasmas in high density astrophysical objects may also be contaminated by a number of reasons. Thus, these ultracold plasma systems may behave as dusty plasmas [31,125,128,149] where quantum mechanical effects could lead to new properties of these systems.

A number of fundamental new modes, particularly the dust-lower-hybrid (DLH) wave, have been shown to exist in plasmas which occur invariably in the presence of magnetic fields. In electron-ion plasma, if the wave vector have small parallel component, the electron oscillate along the magnetic field, leading to the dispersion relation for the lower hybrid wave $\omega = \omega_{lh}[1 + (M/m)(k_{\|}^2/k_{\perp}^2)]^{1/2}$, where $\omega_{lh} = \omega_{pi}/[1 + (\omega_{pe}^2/\omega_{ce}^2)]^{1/2}$. In dusty plasma, including the dust dynamics and assuming $\omega_{pi}^2 \gg \omega_{ci}^2$ for a high-density plasma, the electrostatic dust-lower-hybrid wave frequency turns out to be $\omega^2 = \omega_{dlh}^2[1 + (k_{\|}^2/k^2)(\omega_{pe}^2/\omega_{pd}^2)]$ where $\omega_{dlh} = \omega_{pd}\omega_{ci}/\omega_{pi}$ is the DLH frequency. Waves and instabilities play a vital role in these ultracold and superdense plasma systems, particularly in diagnostics of charged grain impurities in microelectronics. Recently, using the magnetohydrodynamic model for the magnetized quantum plasmas developed by Haas [28] and others, Shukla et al. [150] have studied the nonlinear interactions in quantum magnetoplasmas including the usual high-frequency ($\omega \simeq \sqrt{\omega_{ce}\,\omega_{ci}}$) electrostatic lower-hybrid wave where electrons are assumed magnetized and ions unmagnetized. We present here the quantum effects on the low-frequency dust-lower-hybrid waves below the ion-cyclotron frequency, where dust dynamics plays the vital role. Shukla and Ali [149] have also studied the modification of dust-acoustic waves in unmagnetized dusty quantum plasmas. Haas et al. [29] studied the linear ion-acoustic wave in an unmagnetized quantum plasma at these super conditions. The counterpart of dust-acoustic wave in a magnetized dusty plasma involving the dust dynamics is the existence of the dust-lower-hybrid (DLH) mode which was pointed out in the literature [151-153]. In this chapter, we investigate the modification of the DLH wave in a quantum plasma in the presence of a uniform external magnetic field. In Sec. 4.2, we derive the dispersion relation of the modified quantum dust-lower-hybrid wave in dusty magnetoplasma using the quantum hydrodynamic model of plasmas (QHD). Then numerical analysis and graphical representations is given in Sec. 4.3.

4.2 Modified quantum dust-lower-hybrid wave

We consider a collisionless supercooled and dense dusty plasma consisting of electrons, ions, and relatively highly charged and massive dust particles in the presence of a uniform external magnetic field, ($\mathbf{B}_0 \parallel \hat{z}$). We assume that the electrons possess significant quantum mechanical effects. However, we neglect the quantum effects on ions and dust dynamics because of the high mass which gives rise to an insignificant de Broglie wavelength.

The governing equations Eq. (2.1) and Eq. (2.2), for quantum hydrodynamic model in the presence of external magnetic field $\mathbf{B}_0$ are used to calculate the dynamics of electrons, ions and dust particulates in dusty plasma. Following the standard techniques [151-153,154], the dielectric susceptibility of the plasma can be obtained by solving Eqs. (2.1) and (2.2) to obtain

$$\chi_j = \frac{k_\perp^2}{k^2}\frac{\omega_{pj}^2 F_j'}{\omega_{cj}^2 - \omega^2\, F_j'^{\,2}} - \frac{k_\parallel^2}{k^2}\frac{\omega_{pj}^2}{\omega^2}\,\frac{1}{F_j'}, \tag{4.1}$$

where the quantum correction factor is given by

$$F_j' = 1 - \frac{k^2\, V_{Fj}'^{\,2}}{\omega^2} = 1 - \frac{k^2\, V_{Fj}^2}{\omega^2} - \frac{\hbar^2\, k^4}{4m_j^2\omega^2}. \tag{4.2}$$

Let us consider a supercooled Fermi dusty plasma where electrons are considered hot at the Fermi temperature with Bohm potential effect, ions are cold, magnetized and non quantum. Then

$$\chi_e = \frac{1}{k^2\lambda_{Fe}'^{\,2}}, \tag{4.3}$$

$$\chi_i = \frac{k_\perp^2}{k^2}\,\frac{\omega_{pi}^2}{\omega_{ci}^2} - \frac{k_\parallel^2}{k^2}\,\frac{\omega_{pi}^2}{\omega^2}, \tag{4.4}$$

where $\lambda_{Fe}' = V_{Fe}'/\omega_{pe}$ is the Debye length of electrons at the Fermi temperature, T_{Fe}. Here, we have assumed the low-frequency electrostatic wave of the dusty magnetoplasma with $\omega^2 \ll \omega_{ci}^2$ and $\omega^2 \ll k^2 V_{Fe}'^{\,2}$.

The susceptibility for the unmagnetized and cold dust particles is obtained as

$$\chi_d = -\,\frac{\omega_{pd}^2}{\omega^2}, \tag{4.5}$$

where the dust plasma frequency, $\omega_{pd} = (4\pi q_d^2 n_{d0}/m_d)^{1/2}$ and the symbol d refers to dust grains.

Substituting the density perturbations, $n_s = -\,\chi_s k^2\phi/4\,\pi\, q_s$ with $s = e, i, d$ in the Poisson's equation, one can easily obtain the dispersion relation for the dust-lower-hybrid mode from [151-153]

$$\epsilon(\omega, \mathbf{k}) = 1 + \chi_e + \chi_i + \chi_d = 0, \tag{4.6}$$

Taking $k_\perp^2 \gg k_\parallel^2$ to take into account the maximum effect of the external magnetic field and $\omega_{pi}^2 \gg \omega_{ci}^2$ for a high-density plasma, we write the dielectric function of the quantum dusty plasma under consideration with quantum correction as

$$\epsilon(\omega, \mathbf{k}) = 1 + \frac{1}{k^2 \lambda_{Fe}'^2} + \frac{k_\perp^2}{k^2}\frac{\omega_{pi}^2}{\omega_{ci}^2} - \frac{k_\parallel^2}{k^2}\frac{\omega_{pi}^2}{\omega^2} - \frac{\omega_{pd}^2}{\omega^2}, \tag{4.7}$$

For $\omega_{pi}^2/\omega_{ci}^2 \gg 1/k^2\lambda_{Fe}'^2 \gg 1$, we finally obtain the dispersion relation of the dust-lower-hybrid wave with quantum correction as

$$\omega^2 = \omega_{dlh}^2 \left(1 + \frac{k_\parallel^2}{k^2}\frac{\omega_{pi}^2}{\omega_{pd}^2}\right)\left(1 - \frac{1}{k_\perp^2 \rho_{Fs}'^2}\right), \tag{4.8}$$

where $\omega_{dlh} = \omega_{pd}\omega_{ci}/\omega_{pi}$ is the DLH frequency, and

$$\rho_{Fs}'^2 = \frac{C_{Fs}'^2}{\omega_{ci}^2},$$

$$C_{Fs}'^2 = \omega_{pi}^2 \lambda_{Fe}'^2,$$

$$\lambda_{Fe}'^2 = \frac{V_{Fe}^2\,(1+\gamma_e)}{\omega_{pe}^2},$$

$$\gamma_e = \frac{\hbar^2 k^2}{8 m_e\, k_B\, T_{Fe}}.$$

Here, ρ_{Fs} is the ion Larmor radius at the electron Fermi temperature with quantum correction $\gamma_e = \frac{\hbar^2 k^2}{8m_e\, k_B\, T_{Fe}}$. Equation (4.8) is the main result of this paper. The DLH wave is seen to be significantly modified by quantum effect. The dispersion relation for the DLH wave in the magnetized Fermi dusty plasma is given by Eq. (4.8) where the electrons at the Fermi temperature drive the wave.

4.3 Numerical analysis and discussion

We now proceed with the presentation of our numerical results of nearly perpendicular quantum dust-lower-hybrid wave Eq. (4.8) ω as a function of various parameters of interest in a quantum dusty magnetoplasmas. Our plasma model is inspired by high density quantum plasmas. Thus, we apply our results to astrophysical quantum plasmas like environment of white dwarf [125,137]: $n_{e0} \approx n_{i0} = 10^{27}$ cm^{-3}, $T_{Fe} \approx 10^7$K, $B_0 = 10^7$G and $\theta = \pi/10$. Here, the quantum effect arises through the Fermi temperature and Bohm potential.

Figure 1 shows the variation of ω as a function of wavenumber k. It follows that frequency of the quantum dust-lower-hybrid wave increases with the increase of k.

Figure 2 illustrates the variation of ω as a function of propagation angle θ. It is evident from Fig. 2 that frequency of the quantum dust-lower-hybrid wave increases at small angle of propagation. Here we consider nearly perpendicular propagation of the quantum dust-lower-hybrid wave.

Finally we examine the variation of ω as a function of external magnetic field B_0 as depicted in Fig. 3. It is seen that frequency of the quantum dust-lower-hybrid wave increases with the increase of the magnetic field.

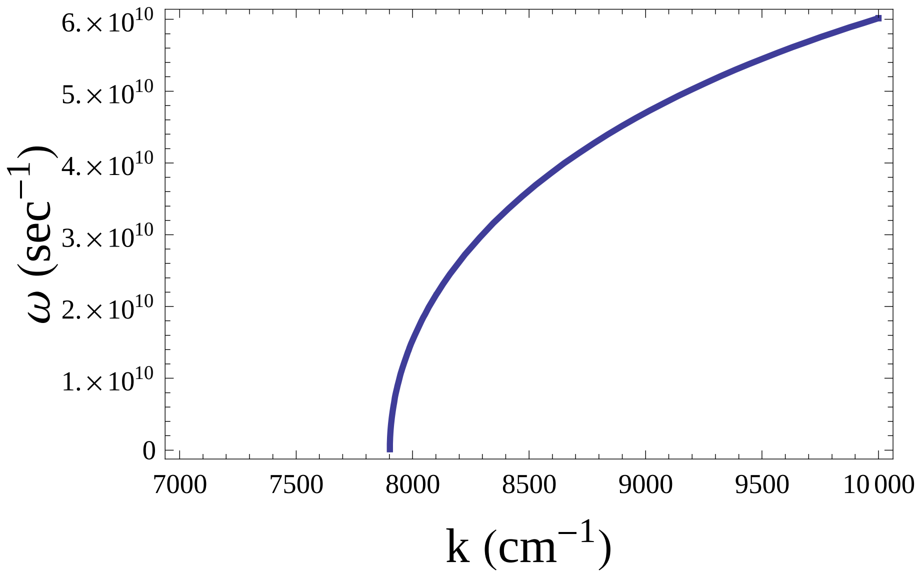
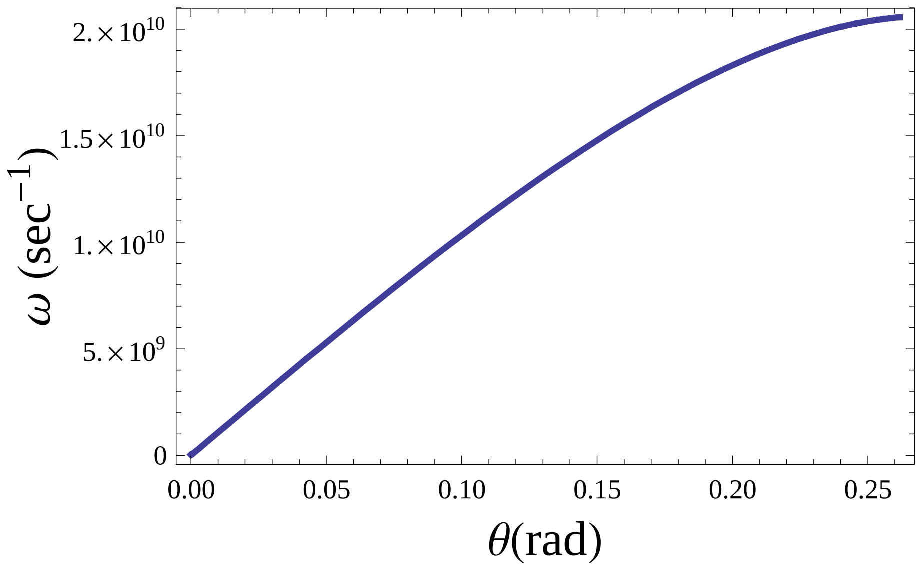
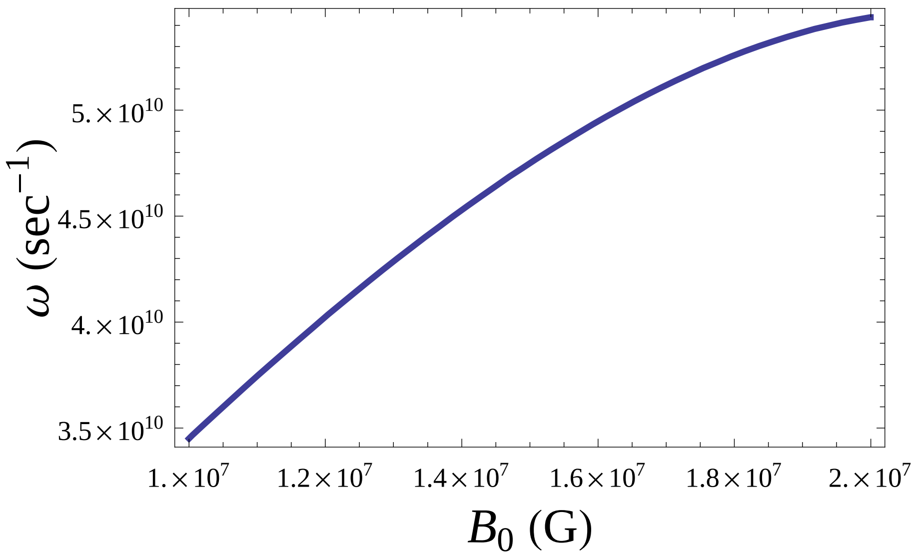

6.×10^10
5.×10^10
4.×10^10
3.×10^10
2.×10^10
1.×10^10
0
ω (sec^−1)
7000
7500
8000
8500
9000
9500
10 000
k (cm^−1)

Figure 8:



ω (sec^{-1})
$2.\times10^{10}$
1.5×10^{10}
$1.\times10^{10}$
$5.\times10^{9}$
0
0.00
0.05
0.10
0.15
0.20
0.25
θ(rad)

Figure 9:



5. × 10^10
4.5 × 10^10
4. × 10^10
3.5 × 10^10
ω (sec^−1)
1. × 10^7
1.2 × 10^7
1.4 × 10^7
1.6 × 10^7
1.8 × 10^7
2. × 10^7
B0 (G)

Figure 10:

Figure Captions

Fig. 1: The variation of ω as a function of the wavenumber k for the following parameters in a high density astrophysical quantum plasmas like white dwarf: $n_{e0} \approx n_{i0} = 10^{27}$ cm^{-3}, $T_{Fe} \approx 10^{7}$K, $B_0 \approx 10^{8}$G, $k = (3 \times 10^{3} - 10^{4})\,\mathrm{cm}^{-1}$ and $\theta = \pi/10$.

Fig. 2: The variation of ω as a function of the propagating angle θ for $k = 8 \times 10^{3}\mathrm{cm}^{-1}$ and the other parameters are same as in Fig. 1.

Fig. 3: The variation of ω as a function of the magnetic field B_0 for $k = 8 \times 10^{3}\mathrm{cm}^{-1}$ and other parameters are same as in Fig. 1.

Chapter 5

Summary of the Thesis

5.1 Summary and Conclusion

This chapter summarizes the results of the whole work in this thesis and conclusions drawn from them.

Modern technological advancement demands miniaturization of electronic devices. In such (nano-scale) devices quantum effects play a significant role. The study of quantum effects in plasmas therefore becomes important and indeed helps to understand a number of phenomena. Quantum mechanical effects in plasmas enable us to overcome some very important issues like resonance tunneling in semiconductor diodes. Further, the dense astrophysical objects like neutron stars and white dwarfs, can also be studies as a quantum plasma. In the introductory chapter of this thesis, the quantum plasma, its properties and its potential applications have briefly described.

The shielding of a test charge particle is an intrinsic property of the plasma, a test charge may be plasma species inside or injected from the outside. This is expressed as Debye potential or Debye-Hückel potential. This electrostatic potential of the test charge does not fall like in vacuum, as $1/r$, but rather obeys a Yukawa-like potential $exp(-r/\lambda_D)/r$, which decays much more quickly and on a distance of the order of Debye length. In quantum plasmas, this Debye length decreases to many orders as compare to classical plasma. But, if a test charge propagates through a plasma (as a boat in a river or a bullet in the air), then an additional wake-field potential is formed behind the test charge. This wake-field is an oscillatory in nature containing both the positive and negative potential regions. In quantum Plasmas, these positive and negative potential regions give the modification in the effective length of the wake potential that is the lattice spacing of the plasma crystals.

This thesis presents new features of the electrostatic potential containing the shielding and wake potentials by using linear dielectric theory in a quantum dusty magnetoplasmas. Chapter 2 described the Shukla-Nambu-Salimullah SNS potential in a nonuniform quantum magnetoplasma using test particle approach. The QHD equations have been employed in the presence of static ambient magnetic field to study a system composed of electrons, ions, and dust. The general expression for the dielectric response function has been derived. The inhomogeneity of the number density and the quantum effect are taken into account to study dense magnetoplasma environments in the presence of dust grains. The major issue addressed here is the contribution of dust polarization drift effect in a high magnetic field environment, like white dwarf, atmosphere of neutron stars. We applied our theoretical results to high density quantum plasma. From numerical analysis, it is found that the dust polarization drift effect significantly modifies the usual SNS potential. It turns out that the presence of dust polarization drift overpowers the ion polarization drift in very high magnetic field regions. So, in a very dense environment having dust and strong magnetic field, the dust polarization drift effect must be taken into account. Furthermore, we have seen that for increasing values of number density and inhomogeneity scale length, the modified SNS potential decreased due to the decrease in the Fermi Debye length. Our results may help to study the energy loss phenomenon due to particle-particle and wave-particle interactions in the dense strongly magnetized plasma systems. The present investigation may also help to study the insight features of dusty magnetoplasma environments of astrophysical objects and space plasmas as well. In chapter 3, we consider the shielding and dynamical wake potentials around a static or a slowly moving test charge in a nonuniform quantum dusty magnetoplasma. Both the short-range SNS and long-range wake potential around the slowly moving test charge significantly depend on the density and static magnetic field inhomogeneities. The quantum hydrodynamic model has been used to find the particle dynamics under appropriate conditions. The quantum plasma is assumed having inhomogeneities in the density and static magnetic field in the same direction transverse to the direction of the magnetic field. The nonuniform static magnetic field gives rise to a uniform ion streaming. The density inhomogeneity causes modification of the plasma dielectric response function. We find that the uniform ion streaming due to the gradient in the static magnetic field, the scale-length of density inhomogeneity of ions, the magnitude of the static magnetic field, and the quantum effect on electrons due to degenerate pressure, cause a significant modification of the shielding and the oscillatory wake potentials. From numerical and graphical representation, it is seen that SNS and oscillatory wake potentials increases with the increase of external magnetic field. Furthermore, we have found that wake potential is modified by higher values of number density of plasma particles and scale length of inhomogeneity. For increasing values of number density and inhomogeneity scale length, the amplitude and the effective length of wake potential decreased. The wake potential has a long-range behavior in both forward and backward directions which oscillates in a periodic manner. This long-range potential should be responsible for the formation of new ordered structures of dust particles in plasmas that are confined in an external magnetic field. The wake-field potential may give rise to attraction among the like-polarity charges providing the possibility of Wigner crystal formation at nano-scale in dense inhomogeneous quantum dusty magnetoplasmas. Chapter 4 illustrates the dispersion relation for the dust-lower-hybrid waves in an ultracold and uniformly magnetized Fermi dusty plasma by employing the quantum hydrodynamic model of a plasma with quantum and thermal corrections. It is found that the dispersion relation of the dust-lower-hybrid wave is significantly affected by the quantum correction. Numerically it is seen that frequency of the quantum dust-lower-hybrid wave increases with increasing wavenumber. Finally, we have examined the effects of external magnetic field and angle of propagation on the nearly perpendicular propagating dust-lower-hybrid wave. It is found that frequency of quantum dust-lower-hybrid wave increases with the increase of magnetic field and with the small angle of propagation. This is a fundamental mode of a quantum dusty plasma in the presence of a uniform external magnetic field. These modes will find applications in diagnosing the charged dust impurities in microelectronics and wave-particles interactions in the dusty quantum magnetoplasmas.

Finally, Chapter 5 is the concluding chapter of the thesis has been written on the basis of chapter 1 to chapter 4. The major findings and the ideas of further development have also been given in this chapter.

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