Chapter-1

ACOUSTIC WAVES AND INSTABILITIES IN QUANTUM PLASMAS: A CONCISE OVERVIEW

Abstract: *This Chapter highlights the genesis of plasma physics and its physical uniqueness. A brief overview of plasmas along with their quantum and classical distinctions is presented in a broader perspective. The existence of large scale quantum plasmas in terms of the stellar evolutionary pathway leading to the formation of compact astrophysical objects is briefly described. We highlight the onset of acoustic waves and instabilities in such quantum plasmas. Their microphysical excitation mechanisms are concisely narrated. The significance of studying waves and instabilities in compact astrophysical objects is illustrated in the asteroseismic perspective. It outlines the main motivations and objectives of this compiled study exploratively.*

1.1 A BRIEF PLASMA OVERVIEW

It is well-known that plasma is a quasineutral ionized (unique) state of matter consisting of statistically large number of charged particles (in majority) and neutrals (in minority) [1, 2]. A unique property of this state lies in the superdominant existence of collective degrees of freedom in contrast with the conventional states of matter. A major distinction between the plasma and gaseous states of matter is that the long-range electromagnetic forces operate among the plasma constitutive particles against the short-range Vander Waal forces in the case of neutral gas constituents, and so forth.

Conventionally, the states of matter are ordered as solid, liquid, gas, and plasma. When a solid is heated at ambient pressure, the molecules of solid gain enough thermal energy to overcome the molecular forces of attraction, and change to liquid state after crossing a specific temperature, known as the melting point. Likewise, when sufficient thermal energy is supplied to a substance in liquid state, it gains kinetic energy sufficient to overcome the binding energy of the liquid state, and thereby changes to gaseous state, at the boiling point. Alternately, we also have direct transitions from solid to gaseous state, by the process of sublimation. These transitions from solid to liquid and gas, and vice-versa are termed as phase transitions. At sufficiently high temperatures, an increasing fraction of gaseous particles will gradually possess enough kinetic energy to overcome the binding energy of the outermost electronic orbitals, thereby resulting in the plasma state consisting of charged particles and neutrals. However, the transition from gaseous state to plasma is not considered a phase transition from the thermodynamic point of view. This can be physically attributed to the reason that the transitions from solid to liquid, liquid to gas, and vice-versa, occur at specific critical temperatures, that is, the melting point, boiling point, and so on. However, the transition from gaseous state to plasma occurs over gradually increasing temperature, that is, the degree of ionization changes with an increase in temperature. In other words, the former (non-plasmic) involves discontinuous processes; whereas, the latter (plasmic) is a continuous (gradual) change. The plasma state involves non-singularities in entropy or specific heat, unlike the rest as mentioned. Apart from the above, this fact is clearly implied by the ‘Saha ionization equation’, developed by the famous scientist, Meghnad Saha to calculate how the degree of ionization in plasma varies with temperature on the basis of the laws of quantum statistics [1]. Thus, the change of state from gas to plasma cannot be considered as a phase transition in thermodynamic sense [2].

It is extensively reported that 99% of the universe exists in the plasma state [1]. It is naturalistically found in stellar and planetary atmospheres and interiors, astrophysical nebulae, solar wind, and so on. However, not all collection of charged particles and neutrals or ionized gases can be classified as “plasma”. To qualify as plasma, the test media must satisfy certain necessary criteria [1, 2]. These criteria deal with several important characteristic definitions, like the Debye length, Debye sphere, plasma oscillation time-scale, and so on. The Debye length is the length over which the charged particles can experience the influence of the field of an individual charged particle. In other words, the deviation from charge neutrality can occur only up to a typical small length scale, namely the Debye length. This shielding effect arises as a consequence of the collective effects exhibited by the plasma constituent particles due to the long-range electromagnetic forces operating among them. Accordingly, the Debye sphere is a spherical plasma volume having a radius equal to the Debye length or Debye scaling distance, thereby characterizing the minimum scale length for plasma existence. That is, for the quasineutrality condition to exist, the typical plasma length scale must be much larger than the Debye length. This spatial super-criticality over the Debye scale length forms the first condition for the existence of quasineutral plasma.

For collective shielding effects, it is essential that the number of constitutive particles (electrons) inside the Debye sphere, which is termed as the *Debye number*, must be very large. This Debye number super-criticality, also known usually as the plasma approximation, lays down the second criterion for plasma existence. And thirdly, for the electromagnetic forces to dominate over collision forces in plasma, the plasma oscillation frequency must be greater than the collision frequency among the plasma constituents. Alternatively, it is evident that the time scale for the plasma observation must supercede the plasma oscillation time scale.

All the above three plasma existence criteria can be symbolically summarized for simplicity in the customary notations [1, 2] orderly as: (1) $\lambda_D << L$, (2) $N_D >> 1$, (3) $\omega\tau > 1$; where, $\lambda_D = \sqrt{\varepsilon_0 k_B T / n_e e^2}$ is the (electron) plasma Debye screening length (shielding scale), $N_D = (4/3)\,\pi\, n_e \lambda_D^3 = 1/3\Lambda \sim T_e^{3/2} n_e^{-1/2}$ stands for the number of plasma particles in the Debye sphere (Debye number), and n_e is the particle (electron) concentration [3, 4]. The plasma parameter is given as $\Lambda = 4\pi\, n_e \lambda_D^3$ [3]. Then, $\omega = \sqrt{n_e e^2 / \varepsilon_0\, m_e}$ is the frequency of the typical plasma oscillations (plasma frequency), and τ is the mean time between two successive collisions (relaxation time).

It is noteworthy that if the plasma density is enhanced keeping the temperature constant, then the magnitude of the Debye number decreases. If $N_D \sim 1$, the Debye shielding concept is not applicable because of the discontinuity of the electrical charge density on the Debye screening scale length. Accordingly, plasma classification can be made on the basis of the Debye number behaviours. In the supercritical Debye region ($N_D >> 1$, $\Lambda >> 1$), we term the plasmas as weakly coupled plasmas (classical) [3, 4]. The physical reason behind this nomenclature is that the ratio of electron thermal (kinetic) energy ($E_{Th} = k_B T_e$) and the Coulombic (potential) energy between electrons ($U_P = e^2 / 4\pi\varepsilon_0 d = e^2 n_e^{1/3} / 4\pi\varepsilon_0$) can be derived as $E_{Th} / U_P = 4\pi N_D^{2/3} = \Gamma^{-1}$. The plasma parameter, Λ, varies inversely as the Coulomb coupling parameter, Γ, which is discussed later in this Chapter. Thus, the supercritical Debye number ($N_D >> 1$) naturally means that the thermal energy (randomizing) supersedes the Coulombic energy (organizing) counterpart. In contrast, we term the subcritical Debye case ($N_D << 1, \Lambda << 1$) as the strongly coupled plasmas (quantum) [3, 4]. This is because of the fact that for higher number density, the degenerate electron Fermi energy supersedes the corresponding classical thermal energy. In such circumstances, the quantum effects become super dominant, thereby making classical thermal effects subdominant. This is exactly the case of quantum plasmas composed of degenerate electron gas, such as electron plasmas in metals, compact astrophysical objects, and so forth [3, 4]. It may be noted that strongly coupled classical plasmas in the form of complex (dusty) plasmas do exist in different laboratory and astrophysical circumstances as explained later.

1.1.1 Genesis of plasma physics

Blood is composed of red blood cells, white blood cells, and platelets, suspended in a clear liquid called ‘plasma’. The word plasma has been first coined by the medical scientist Johannes Purkinje from the Greek word ‘plasma aimatos’, which refers to a jelly-like substance [5]. Later, Nobel laureate Irving Langmuir used the term while working with electric discharges. The term ‘plasma oscillation’ has then been used by Langmuir and Lewi Tonks to describe periodic electronic oscillations in specific regions of electric discharges. Sheath formation had been first noticed by them [6, 7]. David Bohm and David Pines then noticed a significant difference in behaviour of metals from that of ionized gases. They noticed electrons in metals showed collective behaviour. Later, certain solar problems have been discovered which could be explained by means of mutual interaction between the magnetic fields and charged particles. The concept of magnetohydrodynamics has then been put forward by Nobel winning physicist Hannes Alfven in 1940s. He predicted its applicability in astrophysical plasma. Large-scale magnetic fusion energy study based on plasma physics had been concurrently going on in the USA, Britain, and the former Soviet Union at the beginning of the 1950s [8]. In due course of time, plasma research has gradually spread in other interdisciplinary directions with wider applicability. The different scopes of plasma physics are briefly outlined in the next section.

1.1.2 Plasma physics in various fields

As far as seen, plasma physics has a wide-range applicability in various fields, ranging from the nanoscales to the astrocosmical scales of space and time. It has been first used extensively in the study of gas discharges in early 1920s. It has been fueled basically by the need to develop vacuum tubes to carry large amount of current. The phenomenon of plasma sheath formation near the vicinity of a boundary wall has been discovered by Lewi and Tonks during their study of gas discharges [1, 5-7]. Active plasma research has also been going on to devise a way of controlling the thermonuclear fusion reaction. Plasma is found in the Earth's magnetosphere, ionosphere, Van Allen radiation belt, and so on. Hence, solar wind effects on magnetosphere, weakly ionized plasma in the ionosphere, and so on are interesting branches of study in plasma physics. Solar surface and interior, Jovian planets, compact astrophysical objects and their circumvent atmospheres also have plasma. Hence, plasma physics has also been used to study different structure formation in large molecular clouds, collective waves, instabilities, and so on. Plasma physics also has extensive application in semiconductors, gas lasers, and so on [1]. The applicability of plasma physics is further enhanced to meet the power requirement of modern times. In the early twentieth century, the International Thermonuclear Experimental Reactor (ITER) agreement was signed by the seven members, namely, China, European Union, India, Japan, South Korea, Russia, and the United States [9-11]. According to this international agreement, the member nations would bear the cost of project construction and operation. The aim has been to build the world's largest thermonuclear fusion output power via tokamak technology. Active research work has still been going on with a view for a large-scale production of fusion power (~2.5 GW) at a steady-state condition within a stable window of plasma performance parameters operational for a typical tokamak device [11, 12].

1.1.3 Classical and quantum plasmas

Traditionally, plasma physics usually deals with systems of high temperature and low density. This refers to the classical domain of plasma physics or classical plasma physics. Fusion and space plasmas are examples of classical plasma physics [13]. An important criterion that is used to characterize traditional plasma is the Coulomb coupling parameter [14]. In simple terms, the coulomb coupling parameter may be defined as the ratio of the mean potential energy to that of the mean kinetic energy per particle. Mathematically, it is usually characterized by Γ. If $\Gamma < 1$, the system is referred to as weakly coupled plasma system. Most of the classical plasmas, like gas discharge plasma in a laboratory, plasma in solar corona, and so on are usually weakly coupled [15]. The system becomes strongly coupled when $\Gamma > 1$ [14]. In laboratory, strongly coupled plasma has been experimentally produced in laser-driven fusion experiments [16], non-ideal plasma in shock tubes [17], and so on. Strongly coupled classical plasma is also found in Jovian interiors [18]. However, there is yet another branch of physics, which deals with low temperature and high density, where quantum effects become relevant. This branch of plasma physics is referred to as the quantum plasma physics. In other words, quantum plasma refers to that particular domain where the combined influence of the wave-particle duality and quantum statistics play a major role in guiding the dynamics of the particles [19]. Quantum plasma is ubiquitous in metallic nanostructures, quantum dots, laser-plasma interaction, compact astrophysical objects like white dwarfs, neutron stars, etc. In this case, the kinetic energy (thermal) part gets replaced by the degenerate Fermi pressure in the Coulomb coupling parameter [15]. Quantum effects become relevant when the de-Broglie wavelength $\left(\lambda_B = \hbar / m v_T\right)$ is similar to or larger than the average inter-particle distance $\left(\sim n^{-1/3}\right)$. In the expression of the de-Broglie wavelength, $\hbar = h/2\pi$ is the reduced Planck constant and v_T is the thermal velocity. Mathematically, this can be written as $n\lambda_B^3 \geq 1$. Thus, it is noteworthy to mention that the quantum effects will be reached much more easily for the electrons as compared to the ions, owing to the smaller mass of electrons $\left(m_e << m_i\right)$ [13]. Under the corresponding circumstances, the particles would most generally be dominated by the Fermi-Dirac statistics, rather than the Maxwell-Boltzmann statistics as in case of classical plasma. In physical terms, the quantum effects can be manifested in plasma in a two-fold way. The first being the influence of the wave character of the quantum particles. This gives rise to tunneling effect, and overlapping of wave functions of the particles [20]. This, in turn, is responsible for the quantum diffraction effects. The second way in which quantum behaviour in plasma can be seen is the indistinguishable nature of the quantum particles, giving rise to the degeneracy effect. The degeneracy parameter is an important criteria to distinguish quantum systems from classical ones [19]. The degeneracy parameter is given as $\chi = T_F / T$, where T_F is the Fermi temperature, and T is the thermodynamic temperature. For a system to be treated quantum-mechanically, $\chi > 1$. Thus, high density, low temperature plasmas are usually treated quantum-mechanically, whereas, plasmas with low-density and high temperature are treated classically [19].

When we talk of compact astrophysical objects, we refer to white dwarfs, neutron stars, and black holes [21]. These are the end products of stellar evolution.

Stellar evolutionary process begins in the nebula, which is essentially a large cloud composed of gas and dust. The most dominant gas in the nebula is hydrogen. Gravity starts acting on the dense regions of the gas cloud, making them denser. As a result, increasing density makes gravity stronger. This kind of instability, that arises by the action of gravity, is termed as gravitational instability [22-25]. This leads to the collapse of the gas cloud, leading to formation of several small cloudlets. The cloudlets formed as a result of gravitational collapse have very high temperatures. Eventually, the temperature is sufficient enough to start the process of nuclear reactions. Nuclear fusion provides energy to the star. At this stage, the stars are said to be at the main-sequence stage [26]. The life-cycle of a star actually depends on its mass. Higher the mass of the star, the sooner will the star consume its fuel [27]. During the process of nuclear reaction, the hydrogen is converted to helium. When the hydrogen in the core runs out, the star no longer generates heat by the process of nuclear fusion. Thus, it becomes unstable as radiation pressure no longer balances gravity. Thus, the core becomes unstable and contracts. The outer layer, composed mainly of hydrogen, begins to expand and cool. At this stage, the star is said to be in the red giant phase. In the red giant core, helium fuses to carbon. Now, the life cycle that a star follows from herein is strictly mass-dependent. For the low-mass stars, after the helium fuses to carbon, the core collapses again. The outer layers expand to form the planetary nebula, while the core forms the white dwarf. White dwarf is a stellar core remnant composed mainly of electron-degenerate matter. The inward pull of gravity is balanced by the electron degeneracy pressure, till a critical mass limit, known as the Chandrasekhar mass. It has mass that is comparable to the mass of the Sun, and a volume comparable to that of the earth. A massive star, however, undergoes supernova explosion. If the remnant of the explosion is $(1.4-3)\ M_{\Theta}$, it will lead to formation of a neutron star. If the mass of the remnant is more than $3M_{\Theta}$, the core is swallowed by its own gravity, leading to formation of a black hole [27, 28]. Thus, white dwarfs, neutron stars, and black holes are the densest form of matter in astrophysical plasma [21, 27, 28].

1.2 ACOUSTIC WAVES AND INSTABILITIES IN PLASMAS

In general, acoustic waves are the propagatory longitudinal oscillations that propagate by means of compressions and rarefactions. Compressions are the high density regions, whereas, rarefactions are the low-density regions in acoustic waves. An electromagnetic wave refers to coordinated oscillations of electric and magnetic field that propagate in the speed of light. They are transverse waves, meaning that the direction of propagation of the wave, electric and magnetic fields are mutually perpendicular to each other. However, in astrophysical plasmas, the general concepts of electromagnetic waves and acoustic waves do not hold true [29]. In other words, the demarcation between the electromagnetic and acoustic waves becomes blurry in astrophysical plasmas. In astrophysical plasmas, the charged particles move when they are influenced by the electric and magnetic fields of the electromagnetic waves. And general particle motion in plasmas is of acoustic nature [29]. So, electromagnetic waves in plasmas are partly acoustic. On the other hand, motion of charged particles leads to creation of electric and magnetic fields in plasmas. Thus, acoustic waves in plasmas are partly electromagnetic in origin. Thus, waves in astrophysical plasma have a rich and complex nature [29].

Ideal plasma in an unperturbed state is in thermal equilibrium. Thus, it does not have any free energy available with it. However, in practicality, plasma can never be in unperturbed state. Perturbations or disruptions in astrophysical plasma can arise due to the effect on particle motion by different perturbative agents like cosmic rays, gravitational field, and so on. This gives rise to free energy in the system. The free energy which is available can cause self-excitation of the waves. The equilibrium of the plasma system is then an unstable one. Instability is an active process of minimization of the free energy available with the system leading the system to equilibrium state. The free energy that gives rise to instabilities are responsible for the creation of diversified waves, and oscillations in the plasma system [1, 2]. Waves in astrophysical plasma have a rich and complicated structure, which makes it an interesting branch of study. Moreover, for linear systems, wave is the only phenomenon we need to study in order to understand the dynamics of the system. However, even though most of the systems are non-linear, linear approximations are often very useful. Thus, waves are fundamental to our understanding [29].

As already stated, quantum plasma is ubiquitous in white dwarfs. Recent studies have highlighted that depending on the mass of the progenitor, white dwarfs have different compositions. The same is given in the following table.

Table 1.1: White dwarf composition and progenitor mass

S. No.	White dwarf (core) composition	Progenitor (stellar) mass	Remnant core (white dwarf) mass
1	Helium (He) white dwarf	$0.08 \leq M/M_{\Theta} \leq 1$ [30]	Yet to be known
2	Carbon-Oxygen (CO) white dwarf	$1 \leq M/M_{\Theta} \leq 8.0$ [31]	$0.55 \leq M/M_{\Theta} \leq 1.1$ [33]
3	Oxygen-Neon (ONe) white dwarf	$8.0 \leq M/M_{\Theta} \leq 11.0$ [32]	$1.1 \leq M/M_{\Theta} \leq 1.37$ [33]

Thus, we see that white dwarfs are composed of particles of different masses. Whenever there are particles of different masses, there will be collective correlative effects arising due to the mutual interaction between them. This will, in turn, give rise to different waves, oscillations, and instabilities. The works of this thesis mainly focus on the structure formation by the onset of gravitational instability, followed by different acoustic waves and instabilities excitable in compact astrophysical objects, more specifically the white dwarfs.

1.3 MOTIVATION

The study area of gravitational instability towards structure formation, diverse modal behaviours, and consequent compact astrophysical objects has been gaining a growing interest of researchers for years. In particular, in the latter case, an in-depth understanding of the waves and instabilities require a thorough knowledge of the microphysical interaction of the constitutive particles and the effect of different perturbative agents that might impact their motion either microphysically or from a global macrophysical perspective. A few similar agents are the gravitational field, rotation, magnetic field, geometrical curvature, distance from the degenerate core, viscoelasticity, and so on. The existing theory of compact astrophysical objects has shortcomings when confronted with asteroseismic probes of interior physical properties. Different quantum correlative factors and geometry of the system might also influence the stability of the compact astrophysical objects. Also, there is a lack of comprehensive plasma models that can explain certain behavioural patterns that have been observationally detected. Also, a lot of scope of improvement lies in the already existing plasma models. As a result, the various inadequacies hidden in the existing models, improper methodology for a comprehensive and well-planned investigation of the waves and instabilities in compact astrophysical objects from a non-classical point of view, lack of a bridge between the theoretical results and observational evidences are the main motivational forces driving the compiled thesis.

1.4 OBJECTIVES

We want to investigate the gravitational instability dynamics leading to structure formation in the presence of various important and unavoidable factors, such as viscoelasticity, geometric curvature, etc. We also aim to develop a comprehensive linear model to explore the excitation of acoustic waves and instabilities in compact astroobjects and their environments. We theoretically account for some of the important observational evidences that have been experimentally reported in this direction. A great need for proper theoretical formalisms is realized to pre-exist to fill up the gap in between the available theoretical and experimental scenarios in the asteroseismic fabric of compact astrophysical fluid dynamics.

Accordingly, an extensive literature survey and critical analysis trigger the motivational force behind this proposed thesis compiled with the main objectives given as:

(1) Jeans instability in astrophysical viscoelastic fluids with geometrical curvature effects
(2) Nucleus-acoustic waves in gyrogravitating electrospherically confined degenerate quantum plasmas
(3) Behaviours of ion-acoustic waves in relativistic gyromagnetoactive quantum plasmas
(4) Nucleus-acoustic waves in degenerate ONe and CO white dwarf cores and nearly degenerate envelopes
(5) Acoustic stability of astrophysical gyromagnetoactive viscous cylindrical plasmas

1.5 METHODOLOGY

Different approaches and plasma modeling techniques can be used to study the waves and instabilities in compact astrophysical objects. Our focal aim in the compiled thesis is to study the linear wave and instability dynamics in compact astrophysical objects and their circumvent atmospheres. To fulfill our aim, our directional approach towards analyzing the considered problems at hand we use the generalized hydrodynamic and quantum hydrodynamic approach. The basic governing equations are the equation of continuity, force balancing momentum equation, and appropriate equations of states for each of the considered species. The model closure is systematically obtained by means of gravitational and electrostatic Poisson equations. These equations are modified accordingly by including realistic parameters according to the model configurations and solved analytically or numerically to get the results, mostly in graphical format. In stability analysis, each parameter is expanded about the equilibrium position. The fluctuation part may contain one or more than one term depending upon the order up to which one wishes to analyze the stability of the system. The perturbed terms are then Fourier analyzed. Substituting these in the set of perturbed equations, we arrive at a set of algebraic equations. These algebraic equations are then solved by the method of substitution and simplification to finally come to a dispersion relation in terms of ω and k. Analysis of the wave gives information about the various factors responsible for the growth/ decay of the wave. The phase and group velocity of the wave can also be calculated by means of the obtained dispersion relation, which gives information about the propagatory dynamics of the wave.

1.6 CONCLUDING REMARKS

A brief overview of plasma physics along with the necessary criteria to qualify as plasma is highlighted. An account on the coining of the term “plasma”, and its subsequent incorporation in physical sciences during the study of discharge tubes by Langmuir and Tonks is also given. The widespread applicability of plasma physics is also pointed out. We trace the evolution of the compact astrophysical objects and focus on the importance of waves and instabilities in the same. The methodologies applied to conduct the semi-analytic investigatory studies in the compiled thesis are briefly pointed out. In the subsequent chapters linked organically via gravito-electrostatics, we primarily focus on the collective modal dynamics of gravitational instability, acoustic instability, and their hybrid propagatory forms in different circumstances. The excitation physical process of such collective modes in diversified compact astrophysical objects is summarily indicated with a special pin-pointed illustration to white dwarfs, brown dwarfs, and so on.

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