Chapter 1

Introduction

This introductory chapter provides an in-depth exploration of dusty plasmas, their characteristics, and occurrences in both laboratory and astrophysical settings. Furthermore, the chapter explores the dynamic behavior of dust particles within plasmas and examines a variety of waves propagating through these intriguing media. Additionally, it introduces the concept of strongly coupled dusty plasmas, highlighting their distinct properties and their occurrence in both natural and laboratory settings. Finally, this chapter provides an introduction to the interaction potential of complex plasma systems, establishing the foundation for subsequent chapters that will delve deeper into these aspects.

1.1 A brief introduction to plasma:

Plasma is a unique state of matter that is distinct from the solid, liquid, and gas phases [11]. It is often referred to as the fourth state of matter. Plasma is an ionized gas that consists of a collection of charged particles, including free electrons and positive ions, along with neutral atoms or molecules. Plasma is believed to make up approximately 99% of the observable universe [11]. While this statistic might not be exact, it is a plausible estimate considering the stars, their surroundings, gaseous nebulae, and most of the space between stars containing plasma. Just beyond Earth's atmosphere, the Van Allen radiation belts and the solar wind are other examples of plasma. Yet, on Earth, our direct interactions with plasma are quite rare. They can be seen in phenomena like lightning, the Northern Lights, neon signs, and the ionized gases in rocket exhausts [12]. Interestingly, it seems that our daily experiences place us in the unique 1% of the universe where plasmas aren't commonly found.

Beyond its relevance in astrophysics, plasma's unique properties have been harnessed for various industrial purposes [13; 14; 15; 16; 17; 18]. One of the notable applications of plasma is in the domain of semiconductor manufacturing, where it plays a pivotal role in the creation of integrated circuits. What sets plasma apart from other forms of matter is its inherent collective behavior. This collective nature leads to phenomena such as Debye shielding, the emergence and movement of distinct wave patterns, and the transportation of different plasma entities. Plasma has brought a transformative change in the realm of renewable energy production. It serves as a crucial fuel component in the pursuit of controlled nuclear fusion here on Earth. To efficiently convert nuclear energy into usable forms, a condition of high-temperature plasma is essential. In this context, it's worth noting that the ITER (International Thermonuclear Experimental Reactor) project is a significant international collaboration aimed at demonstrating the feasibility of nuclear fusion as a large-scale and carbon-free source of energy based on the same principle that powers our Sun and stars [19; 20; 21; 22; 23].

Understanding and studying plasmas is important for a range of scientific and technological applications, such as fusion energy research, space physics, plasma processing for semiconductor manufacturing, plasma medicine, etc. These are just a few examples of the wide range of scientific and technological applications that rely on understanding and harnessing the unique properties of plasmas. Continued research in plasma physics and engineering holds significant potential for advancements in energy, space exploration, materials science, medicine, and technologies.

1.2 A review of dusty plasma:

Dusty plasma is a type of plasma that includes charged dust particles along with the usual electron-ion components [24]. Dust grains are generally metallic, conducting, or made of ice particles [24]. The shape and size of these particles can widely vary, particularly in natural settings, though they are typically more uniform when artificially created in a laboratory environment. Depending on the surrounding plasma environment, dust particles are either negatively or positively charged [24]. This extra component of macro-particles increases the complexity of the system even further. Due to this increased complexity, the term "complex plasma" is often used as a synonym for dusty plasma [24]. Complex plasmas present interesting challenges for theoretical modeling and experimental study, and understanding their behavior can provide valuable insights into a wide range of physical phenomena. Fig. 1.1 depicts how the existence of a dust component is a distinguishing feature of plasmas occurring in different spatial, temporal, and density ranges. This is observed in both controlled laboratory settings and natural occurrences within astronomical surroundings.

1.2.1 Basic characteristics of dusty plasma:

Macroscopic neutrality:

The dust particles primarily acquire their charge by collecting electrons and ions from the background plasma [24]. Due to the charging of these particles, they affect the plasma parameters and modify the existing collective processes in the plasma. Despite the charging of dust particles, the overall electric charge of the dusty plasma system remains zero in equilibrium with no external forces present. Therefore, the condition of charge neutrality is maintained in equilibrium. This

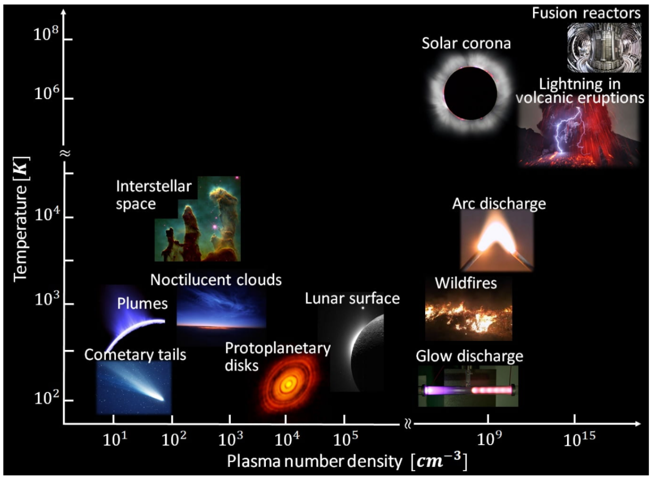

Figure 1.1: The diagram illustrates the parameter space associated with dusty plasma. Photo credit: https://sites.baylor.edu

condition can be expressed by the following equation,

$$Q_d n_{d0} + e n_{e0} = e n_{i0} \tag{1.1}$$

where n_{e0}, n_{i0}, and n_{d0}, are the equilibrium densities of plasma electrons, ions, and charged dust particles, respectively. Q_d represents the charge of a dust grain.

Debye shielding:

One of the fundamental characteristics of plasma is its ability to shield the electric field of an individual charged particle. This characteristic provides a measure of the distance, known as the Debye length (λ_D) or Debye radius, over which the influence of the electric field of an individual charged particle is felt by other charged particles inside the plasma. The expression for Debye length is given by

$$\lambda_D = \frac{\lambda_{De}\lambda_{Di}}{\sqrt{\lambda_{De}^2 + \lambda_{Di}^2}} \tag{1.2}$$

Where λ_{De} and λ_{Di} are the Debye length associated with electrons and ions respectively, which are expressed as,

$$\lambda_{De} = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_{e0} e^2}} \tag{1.3}$$

$$\lambda_{Di} = \sqrt{\frac{\varepsilon_0 k_B T_i}{n_{i0} e^2}} \tag{1.4}$$

where T_e and T_i represent the temperatures of the electrons and ions, respectively, and n_{e0} and n_{i0} denote the equilibrium densities of electrons and ions, respectively. The symbol k_B stands for Boltzmann's constant.

Characteristic frequencies:

(a) Plasma frequency: In an electron-ion plasma, when charged species are displaced, it leads to the creation of space charge regions within the plasma. When a plasma is instantaneously disturbed from its equilibrium, the resulting internal space charge field gives rise to collective particle motions. This collective movement is referred to as plasma oscillation [11], which aims to preserve the quasi-neutrality condition in the plasma. Similar to electron-ion plasma, dusty plasma also displays oscillations, referred to as dust-plasma oscillations. The frequency of oscillations in a plasma medium, including electron-ion plasma and dusty plasma, is not the same for electrons, ions, and dust grains. Each species in the plasma has its own characteristic frequency of oscillation, determined by its mass and charge properties. Therefore, the oscillation frequencies in a plasma system will vary for different particle species based on their specific mass and charge. For example, electrons oscillate around ions with the electron plasma frequency (ω_{pe}). Ions oscillate with ion plasma frequency (ω_{pi}) and dust particles oscillate around their equilibrium positions with the dust plasma frequency (ω_{pd}). The expressions are given as

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \tag{1.5}$$

$$\omega_{pi} = \sqrt{\frac{n_i e^2}{\epsilon_0 m_i}} \tag{1.6}$$

$$\omega_{pd} = \sqrt{\frac{n_{d0} Q_d^2}{\epsilon_0 m_d}} \tag{1.7}$$

In a typical dusty plasma system, the characteristic frequencies can be arranged in the following manner: (a) The dust plasma frequency (ω_{pd}) is the smallest among the three frequencies. It is in the range of Hz (Hertz), indicating that the dust particles in the plasma system oscillate or respond to electric fields at a relatively low frequency. (b) The ion plasma frequency (ω_{pi}) is in the range of MHz (Megahertz) [24], which is much higher than the dust plasma frequency. This frequency represents the collective motion of the positively charged ions in the plasma. (c) The electron plasma frequency (ω_{pe}) is in the range of GHz (Gigahertz), significantly higher than both the dust and ion plasma frequencies. It corresponds to the collective motion of the negatively charged electrons in the plasma.

(b) Collision frequency: In a partially ionized plasma, the presence of neutral particles leads to frequent collisions between the charged plasma particles (electrons, ions, and dust particles) and the neutrals. These collisions can be characterized by three types of collision frequencies: Electron-Neutral Collision Frequency (ν_{en}), Ion-Neutral Collision Frequency (ν_{in}), and Dust-Neutral Collision Frequency (ν_{dn}). The general expression for the collision frequency (ν_{sn}) for the plasma species ‘s’ is given by

$$\nu_{sn} = n_n \sigma_{sn} V_{Ts} \tag{1.8}$$

ν_{sn} : Collision frequency between species s and neutral particles.

n_n : Number density of the neutral particles.

σ_{sn} : Collision cross-section between species s and neutral particles.

V_{Ts} : Thermal velocity of species s.

1.3 Some key aspects of dusty plasmas:

The physics of dusty plasmas is a topic of growing importance because of its abundance and applications in various fields. These include space and astrophysics, semiconductor technology, plasma chemistry, crystal physics, biophysics, fusion devices, etc. We will briefly explore some of these noteworthy aspects.

1.3.1 Astrophysical relevance of dusty plasma:

Dusty plasmas can be found in a variety of space environments, including planetary rings [25; 26; 27], cometary tails [28], interstellar medium [29; 30], circumstellar clouds, etc. Here are a few examples:

Noctilucent Clouds

Noctilucent clouds [31; 32], also known as polar mesospheric clouds, is a rare and beautiful atmospheric phenomenon observed in the night sky. Fig. 1.2 portrays an enchanting presentation of the night sky being illuminated by noctilucent clouds. They are typically seen in high-latitude regions during the summer months, although they have been reported at lower latitudes in recent years. Noctilucent clouds form in the Earth's mesosphere, which is the layer of the atmosphere located between 76 and 85 kilometers (47-53 miles) above the Earth's surface. They often appear as thin, wispy, and silvery-blue clouds that glow or shine during twilight hours, hence their name "noctilucent", which means "night-shining" in Latin. They can exhibit intricate patterns and structures, sometimes resembling waves or ripples in the sky. Noctilucent clouds are of scientific interest because they provide valuable information about the upper atmosphere. Studying these clouds helps scientists better understand the dynamics of the mesosphere, including the effects of climate change and the transport of water vapor and dust particles in the atmosphere.

Figure 1.2: A captivating display of noctilucent clouds illuminating the night sky. Photo credit: https://www.thoughtco.com/noctilucent-clouds

Planetary rings:

Planetary rings are fascinating features that can be found around several giant planets in our solar system, including Saturn, Jupiter, Uranus, and Neptune. The presence of such structures around Saturn and Jupiter was verified by the Cassini and Voyager missions [33; 34]. These rings are composed of a vast number of particles that orbit the planet in a disk-like structure [35]. The particles within the rings can vary in size, ranging from tiny micrometer-sized dust grains to larger particles several meters in diameter. The formation of planetary rings involves complex interactions between these particles, the plasma, and the surrounding electromagnetic fields. Galileo Galilei was the first to observe Saturn's rings in 1610, although he was unable to identify them as rings. It was Christiaan Huygens, in 1655, who correctly described them as a disk surrounding the planet. Saturn's rings are the most extensive ring system of any planet in the solar system. They are named alphabetically in the order they were discovered. The main rings are, from farthest from the planet to closest: D, C, B, A, F, G, and E [35; 36]. Each ring orbits at a different speed around the planet. Fig. 1.3 presents images (a) and (b) depicting spokes within Saturn's B Ring, which were captured by Voyager 2 in 1980. Image (c), on the other hand, was obtained by Cassini in 2005. The rings of Uranus were discovered in 1977 during a stellar event [37]. It has a complex ring system, composed of thirteen distinct rings. The rings are dark and composed mainly of larger particles, up to 10 meters in diameter. These rings are believed to be relatively young, with an estimated age of no more than 600 million years [37]. It is hypothesized that the ring system originated from the collisional fragmentation of several moons that once existed around the planet. When these moons collided, they fragmented into numerous particles, which managed to survive as thin and highly concentrated rings only within specific regions of maximum stability. The ring system of Jupiter was the third to be detected within our Solar System, following the discovery of Saturn's and Uranus's rings [38]. On March 4, 1979, the Voyager 1 spacecraft made the initial observation of Jupiter's rings. Jupiter's ring system is quite faint and is made up of three main segments: an inner torus of particles known as the "halo ring", a relatively bright and very thin "main ring", and a wide, thick, and faint outer "gossamer ring". Neptune's rings were found later in 1989 by the Voyager

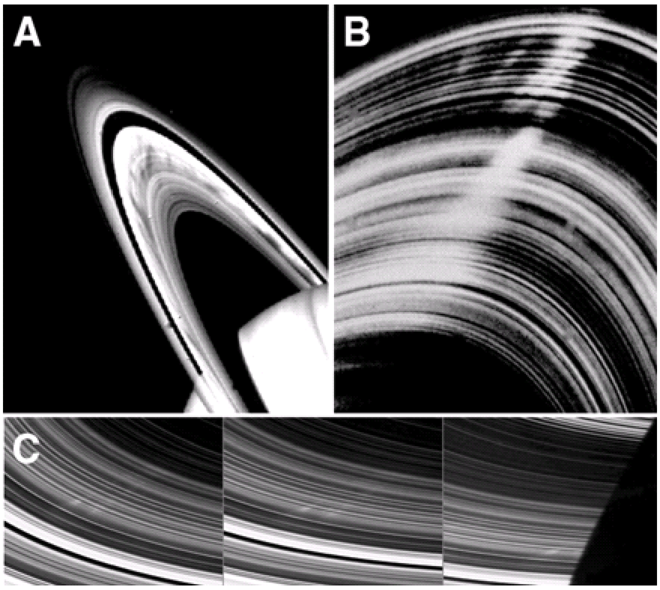

Figure 1.3: (a) and (b)- Spokes in Saturn's B Ring captured by Voyager 2 in 1980. (c) by Cassini in 2005 [1].

2 spacecraft [34]. It has five known rings, which are named, after astronomers who made important discoveries about Neptune: Galle, Le Verrier, Lassell, Arago, and Adams [39]. Neptune's rings are very faint and are made up of dust particles coated in ice [39].

Dust particles play a vital role in the complex and dynamic processes that shape planetary ring systems. Planetary rings are composed of various particles, ranging in size from micrometers to meters, which orbit around the planet. While the exact processes and origins of rings can differ depending on the planet, dust particles are fundamental in several key aspects of ring formation. The initial stages of ring formation involve the accretion of dust and small debris in orbit around the planet. Dust particles can collide and stick together due to mutual gravitational attraction or electrostatic forces, forming aggregates and larger particles. In some cases, dust particles in the ring system can originate from the gravitational breakup of moons or the disruption of asteroids or comets due to impacts on the planet or other moons. These collisions release debris that can then form part of the ring material. Dust particles participate in the dynamic processes of the ring system, including interactions with the planet's magnetic field and radiation belts. Their distribution and motion influence the structure and appearance of the rings. Dust particles constantly interact with each other through collisions, radiation pressure, and gravitational forces. These interactions can lead to the erosion and destruction of smaller particles, contributing to the continuous evolution and replenishment of the ring system. In conclusion, planetary rings are an area of active research. With future space missions and more sophisticated telescopes, we can expect to learn more about these beautiful and complex structures in our solar system and beyond.

Cometary tails:

Comets are some of the most intriguing objects in our solar system. Comets are composed of a mixture of ice, dust, and gas [28]. The central, solid structure of a comet is referred to as the nucleus. Cometary nuclei are made up of a combination of rock, dust, water ice, and frozen gases such as carbon dioxide, carbon monoxide, methane, and ammonia [28]. As a comet approaches the Sun, the solar radiation and solar wind ionize the gas and release dust particles, creating a dusty plasma tail that is observable from Earth. The comet structures are diverse and very dynamic, but they all develop a surrounding cloud of diffuse material, called a coma that usually grows in size and brightness as the comet approaches the Sun. Inherently, it consists of two tails that develop as the comet gets closer to the Sun. One tail is formed by dust, while the other consists of plasma [28].

1.3.2 Dusty plasmas in laboratories:

Nowadays, Dusty plasmas are extensively studied in laboratory setups, and researchers use different methods to introduce dust particles into the plasma environment. In some experiments, dust particles can grow in the plasma itself. This process involves introducing a precursor gas into the plasma chamber, which then undergoes chemical reactions to form dust particles. These particles grow over time and become charged due to the surrounding plasma. Alternatively, dust particles can be introduced into the plasma chamber, typically made of materials like silica, metal, or other dielectric substances. Fig. 1.5 displays the experimental

Figure 1.4: Spectacular glimpse of comet Halley's celestial journey. Photo credit: Photo credit: https://www.britannica.com/science/comet-astronomy

setup used to study structured patterns in dusty plasma.

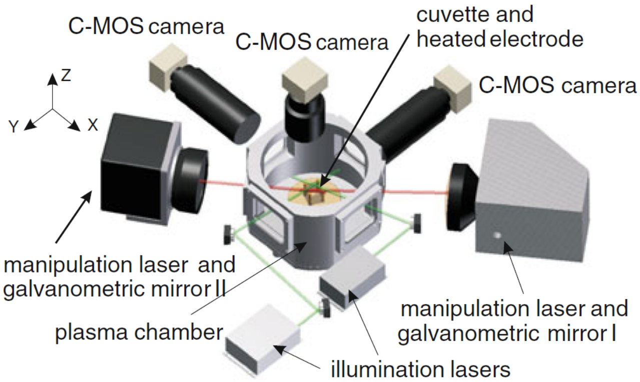

Figure 1.5: Schematic of the experimental arrangement used to study structured patterns in dusty plasma [2].

Plasma-based material processing technologies are widely used in the manufacture of very large-scale integrated circuits [40]. Unfortunately, these plasmas can also create dust particles that can introduce defects into the microelectronic devices, negatively impacting their performance [40]. In plasma processing reactors, the widespread use of low-pressure plasma and the availability of laser light scattering diagnostics have revealed that many of these discharges generate and capture significant amounts of macroscopic dust grains [40]. The study of dusty plasmas enables researchers to develop methods to control dust contamination, thereby improving the manufacturing process and the overall quality of these devices.

In the realm of nuclear fusion research, dusty plasmas present a significant challenge [41; 42]. Nuclear fusion, the power source of the Sun and stars, is widely regarded as an exceptional and highly desirable solution for clean and nearly limitless energy. However, fusion reactions require extremely high temperatures to overcome the natural repulsion between atomic nuclei [42]. At these scorching temperatures, the fusion fuel - typically isotopes of hydrogen such as deuterium and tritium - exists not as a gas, liquid, or solid, but as a plasma. However, this environment can be contaminated by dust particles, which present a significant obstacle to successful fusion reactions [42]. These dust particles, if present within the plasma, reduce the fuel's temperature below the threshold required for fusion. Consequently, the rate of fusion reactions declines, reducing the energy output [41; 42].

In summary, the importance of dust particles in laboratory settings arises from their capacity to exhibit intricate and diverse behaviors. These studies not only advance our fundamental understanding of plasma physics but also have practical applications across various scientific and technological fields [43; 44; 45].

1.4 Dynamics of dust particles in plasmas:

The dynamics of dust particles in plasmas present a unique and compelling area of study within the field of plasma physics. As mentioned earlier, these particles, when immersed in plasma, acquire a high charge due to the surrounding electrons and ions. This, in turn, induces strong electrostatic interactions between them, which can lead to the formation of complex patterns and structures. Examples include Coulomb crystals [46; 47; 48; 49; 50; 51], dust voids [52; 53; 54], unique patterns like rings, spirals, dust lanes [55; 56; 57; 58; 59] etc. The forces acting upon the dust particles, such as gravitational, electric, ion drag, neutral drag, and thermophoretic forces, significantly affect their behavior and dynamics. The interplay of these forces influences not only the motion of individual dust particles but also their collective behavior, which can be remarkably diverse. The relatively large size and mass of the dust particles allow for the direct observation of these phenomena, making dusty plasmas an excellent experimental platform for understanding many fundamental aspects of soft matter physics as described earlier. Furthermore, the ability to control dust transport through the manipulation of these forces has numerous practical implications, from plasma processing techniques in the semiconductor industry to the study of astrophysical phenomena. Understanding and modeling the dynamics of dust particles in plasmas thus continue to provide crucial insights into both theoretical physics and applied science. A concise overview of the characteristics of these forces in dusty plasmas is provided below:

1. **Electromagnetic (EM) force:** The electromagnetic force acting on charged dust particles in a dusty plasma is the sum of the electric force (F_e) and the Magnetic force (F_m). In laboratory experiments involving dusty plasmas, the dominant force acting on dust particles is often the electrostatic force arising from the sheath around the lower electrode. This force is a result of the potential difference between the plasma and the electrode, creating an electric field that interacts with the charged dust particles. The electrostatic force can attract or repel the dust particles depending on their charge polarity. When dust particles move in the presence of an external magnetic field, they experience magnetic force. Thus the electromagnetic force experienced by a particle is given as

$$\mathbf{F}_{\mathrm{em}} = \vec{\mathbf{F}}_e + \vec{\mathbf{F}}_\ell = Q_d \left(\vec{\mathbf{E}} + \vec{\mathbf{V}}_J \times \vec{\mathbf{B}} \right) \tag{1.9}$$

   Where, $\mathbf{F}_{\mathrm{em}}$ represents the electromagnetic force. $\vec{\mathbf{F}}_e$, $\vec{\mathbf{F}}_\ell$ represents the electric and Lorentz force respectively. Q_d denotes the charge of the particle. $\vec{\mathbf{E}}$, $\vec{\mathbf{B}}$ represents the electric field and magnetic field respectively. $\vec{\mathbf{V}}_J$ denotes the velocity of the particle.

2. **Gravitational Force :** Dust particles in plasma also experience a gravitational force due to their mass. The expression for the gravitational force can be written as

$$F_G = m_d g = \frac{4}{3}\pi r_d^3 \rho g \tag{1.10}$$

Where F_G represents the gravitational force. m_d is the mass of the dust particle, g denotes the acceleration due to gravity. r_d represents the radius of the dust grain and ρ denotes the density.

3. **Ion drag force:** The ion drag force arises from the sudden exchange of momentum between ions and dust particles. The ion drag force in a dusty plasma can be attributed to three main mechanisms: (i) a physical collision between the two (ii) collision via electric fields (iii) streaming ions that distort the regular shape of the Debye sphere that surrounds the dust particle. This force is determined by the velocity-dependent collision cross section and the associated ion-dust collision is of the momentum exchange type. The expression for ion drag due to the attachment of ions on the dust surface is given as

$$F_{di}^{coll} = \pi r_d^2 n_i m_i V_{Ti} u_i \left(1 - \frac{2e\phi_d}{m_i v_i^2}\right) \tag{1.11}$$

where n_i, m_i are ion density, the mass of ions. V_{Ti} is the thermal velocity, and u_i is the drift velocity of ions. The force due to the Coulomb collision is given as

$$F_{di}^{coul} = 2\pi b_0^2 n_i m_i V_{Ti} u_i ln \left(\frac{b_0^2 + \lambda_{De}^2}{b_0^2 + b_c^2}\right) \tag{1.12}$$

Here $b_0 = r_d \frac{e\phi_d}{m_i v_i^2}$ is the impact parameter for orthogonal scattering against dust, ϕ_d is the surface potential of dust grains, $b_c = r_d \left(1 - \frac{2e\phi_d}{m_i v_i^2}\right)^{1/2}$ is the impact factor for direct ion dust collision.

4. **Neutral drag force:** The neutral drag force is a key factor influencing dust particles in a plasma. It arises from the momentum exchange between dust particles and the neutral gas due to collisions, particularly when there is relative movement between the dusty fluid and the background gas. The intensity of this force depends on the hydrodynamic regime and the Knudsen number (K_n), (The Knudsen number (Kn) is a dimensionless number defined as the ratio of the molecular mean free path length to a representative physical length scale.) If K_n is much less than unity, the drag force aligns with Stoke's law and is proportional to the velocity and radius of the

dust particle.

$$F_{nd} = -6\pi\eta r_d u_d \tag{1.13}$$

However, if the value of K_n is large and the relative velocity between the neutrals and the dust is smaller than the thermal velocity of neutrals ($u_d \ll v_{Tn}$), then $F_{nd} = -m_d \nu_{dn} u_d$, where ν_{dn} is the momentum exchange dust neutral collision frequency. Here, the negative sign indicates that the force acts in a direction opposite to the relative velocity between the species. For the reverse condition ($u_d \gg v_{Tn}$), the neutral drag force is estimated as $F_{dn} = -\pi r_d^2 n_n m_n u_d^2$, where n_n and m_n are the density and mass of the neutrals.

5. **Thermophoretic force :** A dust grain immersed in a plasma with a background of neutral gas can experience a force due to a temperature gradient in the neutral fluid. This force, known as the thermophoretic force, arises due to an asymmetry in momentum transfer from the regions of high and low temperatures of the gas to the dust grain. The force propels the dust grain toward the area with a lower gas temperature. For neutrals undertaking significant collision against the dust, the expression for thermophoretic force is

$$F_{th} = -\frac{4\sqrt{2\pi}}{15}\frac{r_d^2}{v_{Tn}} \tag{1.14}$$

Here, F_{th} represents the thermophoretic force, r_d is the radius of the particle and v_{Tn} denotes the thermal velocity of the neutral particles.

1.5 Waves in dusty plasma:

The charged particles within a plasma exhibit random movements and interact with each other through electromagnetic forces. Additionally, they respond to external perturbations. As a result, the collective motions of these plasma particles give rise to a diverse range of wave phenomena. These waves emerge from the coherent behavior of the particle ensemble. In a dusty plasma, the presence of charged dust grains can modify or even dominate wave propagation. This modification happens because of the inhomogeneity caused by the random arrangement of charged particles and the deviation from the usual quasi-neutrality condition. Here, we describe the underlying physics as well as the mathematical details associated with some of these wave modes.

1.5.1 Dust Acoustic (DA) wave:

Dust Acoustic Waves (DAWs) are a type of longitudinal wave that can propagate in a dusty plasma. In a study on multicomponent collisionless dusty plasmas, Rao *et al.* proposed a theoretical prediction regarding the existence of DA waves in 1990 [60]. DAWs are characterized by oscillations of the dust component of the plasma. In other words, the particles of dust move back and forth along the direction of the wave with the inertia of the dust particles playing a key role. The basic form of the dispersion relation for DAWs can be represented as:

$$\omega^2 = 3k^2 v_{thd}^2 + \frac{k^2 C_D^2}{1 + k^2 \lambda_D^2} \tag{1.15}$$

Here, ω is the wave frequency, k is the wave number, v_{thd} is the dust thermal velocity, and $C_D = \omega_{pd}\lambda_D$ is the dust acoustic speed. In the limit $\omega \gg kv_{thd}$, the DA wave frequency becomes

$$\omega = \frac{kC_D}{\left(1 + k^2\lambda_D^2\right)^{1/2}} \tag{1.16}$$

When the wavelength of the DA mode is large enough then the DR can be written in a form

$$\omega = kZ_{d0}\left(\frac{n_{d0}}{n_{i0}}\right)^{1/2}\left(\frac{K_B T_i}{m_d}\right)^{1/2}\left[1 + \frac{T_i}{T_e}\left(1 - \frac{Z_{d0}n_{d0}}{n_{i0}}\right)\right]^{-1/2} \tag{1.17}$$

The dispersion relation mentioned above can be derived considering electrons and ions as inertia-less species in the presence of massive dust particles. These dust particles have oscillation times significantly larger than the response time of plasma species to any perturbation. As a result, the restoring force in the dispersion relation arises from the contribution of electrons and ions, while the dust mass provides the necessary inertia to sustain the mode. Different aspects of DA waves have been extensively studied with the help of theoretical analysis and laboratory experiments [61; 62; 63; 64; 65]. With the observed frequencies falling within the 10-20 Hz range, it becomes possible to record video images of the DA wavefronts. Moreover, these wavefronts are readily visible without the aid of any magnifying devices and can be seen directly by the naked eye.

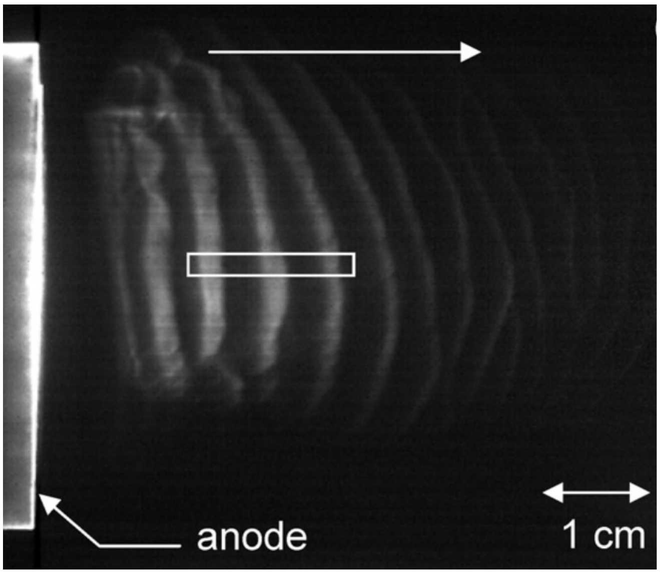

Figure 1.6: Dynamic evolution of nonlinear dust acoustic waves in the ion drift direction [3].

1.5.2 Dust Ion Acoustic (DIA) wave:

These are modified ion acoustic waves mediated by ion oscillation [66; 67; 68; 69; 70]. The phase velocity satisfies the relation $v_{th(i,d)} < v_p < v_{th(e)}$, where $v_{th(e,i,d)}$ are the thermal speeds of the respective species and v_p is the phase velocity of the DIA mode. The dynamics of dust do not contribute to the characteristics of this mode, but its presence can modify the wave dynamics through collective effects. The dispersion relation of the DIA wave can be obtained by considering the ion dynamics for a system of Boltzmann-distributed electrons and stationary dust. The dispersion relation is mathematically described as.

$$\omega^2 = \frac{k^2 C_S^2}{\left(1 + k^2 \lambda_{De}^2\right)} \tag{1.18}$$

Here, the term $C_s = \omega_{pi}\lambda_D$ represents the phase velocity of the wave. In the long-wavelength limit, i.e., when $k^2\lambda_{De}^2 \ll 1$, the dispersion relation takes the form:

$$\omega = k\left(\frac{n_{i0}}{n_{e0}}\right)^{1/2} C_s \tag{1.19}$$

1.5.3 Electrostatic Dust Cyclotron wave (EDC):

Electrostatic Dust Cyclotron wave (EDC) waves arise in the presence of an external magnetic field [71; 72]. These waves have a frequency much lower than the ion cyclotron frequency ($\omega \ll \omega_{ci}$). Dust grains within a background of Boltzmann-distributed ions undergo oscillations, with their trajectories influenced by the magnetic field. Considering a 2-D Cartesian geometry (x-y), where the magnetic field aligns with the y direction and the wave vectors are denoted as k_x and k_y, associated with the propagating fluctuation, the dispersion relation for this cyclotron mode is given by

$$\omega^2 = \omega_{cd}^2 + k_x^2 \left[\frac{K_B T_d}{m_d} + \frac{n_{d0}}{n_{i0}} Z_d^2 \frac{K_B T_i}{m_d} \frac{1}{1 + \frac{T_i}{T_e} \left(1 - \frac{n_{d0}}{n_{i0}} Z_d \right)} \right] \tag{1.20}$$

Here, $\omega_{cd} = \frac{Q_d B}{m_d}$ represents the dust cyclotron frequency. The remaining symbols carry their usual meanings.

1.5.4 Electrostatic Dust Ion Cyclotron wave (EDIC):

These are cyclotron modes excited through ion oscillation in the presence of an external magnetic field [73]. While dust grains do not participate directly in the wave motion, they do influence the characteristics of the mode. EDIC waves have frequencies comparable to the ion gyro frequency, making them high-frequency waves. The dispersion relation for EDIC waves is given by

$$\omega^2 = \omega_{ci}^2 + k_x^2 \left[\frac{K_B T_i}{m_i} + \frac{K_B T_e}{m_i \left(1 - \frac{n_{d0}}{n_{i0}} Z_d \right)} \right] \tag{1.21}$$

where k_x and k_y are the wave vectors perpendicular and parallel to the direction of the magnetic field.

In summary, the investigation of wave phenomena in dusty plasmas not only advances our understanding of fundamental plasma physics but also has practical implications in a wide range of fields, from space exploration and astrophysics to industrial processes and material science. Researchers in these areas are actively investigating the possible uses and consequences of the dynamics of waves in dusty plasmas.

1.5.5 Electromagnetic waves in dusty plasma

Electromagnetic waves, like the electrostatic waves stated above, are also possible in dusty plasmas, particularly within astrophysical settings. Electromagnetic waves in dusty plasmas are a significant area of study, especially due to their prevalence in space and astrophysical contexts. Electromagnetic waves can result from the oscillation of the charged particles and can propagate through the plasma, affecting its behavior and properties. In astrophysical settings, such as in the vicinity of stars or in nebulae, electromagnetic waves can influence the charge of the dust particles, leading to changes in the plasma's dynamics. These waves are essential for understanding various cosmic phenomena, such as star formation, planetary ring dynamics, and interstellar communication pathways. There also exists a number of different low-frequency electromagnetic waves in a homogeneous dusty magneto plasma. The dispersion properties of these electromagnetic oscillations are detailed in the following section:

(i) Circularly polarized waves:

Here, we examine the propagation of electromagnetic waves that oscillate at a low frequency and are right-hand circularly polarized. These waves travel in a direction that aligns with an established external magnetic field that points along the z-axis and has a magnitude of B_0. Specifically, the electric component of these waves is described by a vector field. The expression for the electric field vector **E** is:

$$\mathbf{E} = E_0(\hat{x} + i\hat{y})e^{-i(\omega t - k_z z)}$$

Here, the exponential term $e^{-i(\omega t - kz)}$ denotes the wave's propagation through space and time, with t representing time and $-i(\omega t - k_z z)$ giving the phase of the wave. The negative sign in the exponent indicates the wave is moving in the positive z direction, while the wave's frequency and wave number are given by ω and k, respectively. The dispersion relation for $\omega << \omega_{ce}$, is

$$\frac{k_z^2 c^2}{\omega^2} = 1 + \frac{\omega_{pe}^2}{\omega \omega_{ce}} - \frac{\omega_{pi}^2}{\omega(\omega_{ci} + \omega)} + \frac{\omega_{pd}^2}{\omega(\omega_{cd} - \omega)}. \tag{1.22}$$

Where, ω_{ce}: Electron gyro-frequency, ω_{pe}: Electron plasma frequency, ω_{cd}: Dust gyro-frequency, ω_{pd}: Dust plasma frequency.

(ii) Mixed EM modes:

The behavior of hybrid oscillations is characterized by the magneto-hydrodynamic (MHD) framework applicable to dusty plasma environments, particularly where the inertia of dust particles is significant. The dispersion relation for such low-frequency electromagnetic wave is

$$(\omega^2 - \omega_{DA}^2)D_m(\omega, k) = \frac{\omega_{DA}^2}{\omega_{cd}^2}\omega^2 k^2 V_A^2(\omega^2 - k^2 V_{da}^2) \tag{1.23}$$

Where, $\omega_{DA} = k_z V_{DA}$ is the dust-Alfvén frequency and

$$D_m(\omega, k) = \omega^4 - \omega^2 k^2(V_{DA}^2 + V_{da}^2) + \omega_{DA}^2 k^2 V_{da}^2 \tag{1.24}$$

$V_{DA} = \frac{B_0}{(4\pi n_{d0} m_d)^{1/2}}$ is the dust Alfvén speed and $V_{da} = \left(\frac{(Z_{d0} k_B T_i + k_B T_d)}{m_d}\right)^{1/2}$ is the modified DA speed.

In some of their pivotal research, Gurudas Ganguli and Leonid Rudakov explored the existence of various low-frequency electromagnetic waves in homogeneous dusty magneto plasmas, with a focus on magnetic drift waves, which are particularly relevant due to their implications in space and astrophysical contexts [74; 75]. They discussed modifications to the magnetic drift modes in dusty plasmas and established a relationship with the rotation modes. They also discussed how these low-frequency electromagnetic variations can influence broader plasma dynamics. The 2004 study published in *Physical Review Letters* introduced the concept of distinctive rotational behaviours in light ion fluids within plasmas, highlighting how these rotations at characteristic low frequencies influence plasma oscillations and potentially lead to strong structural turbulence at magnetohydrodynamic (MHD) scales [74]. Their follow-up study in 2005 further developed these ideas, identifying the fluid rotation of the light component at a particular frequency as the crucial factor responsible for the observed low-frequency cut-off in these systems [75]. Their extensive analysis detailed how these rotations affect the overall behavior of the plasma, emphasizing the role of light ions as current carriers, which significantly influences the plasma's low-frequency behavior and its nonlinear properties. This led to the identification of rotation waves, analogous to cyclotron waves, but distinct in their influence on the wave properties and stability of the plasma. Additionally, the inclusion of massive charged dust particles in their models provided clarity on the physical mechanisms driving these phenomena, offering insights into the origins of the cutoff frequency and its implications across various scales.

1.6 Strongly coupled dusty plasmas:

Dusty (or complex) plasmas are characterized by several parameters, each of which represents different physical states of the system. These parameters have a significant influence on the structural, dynamic, and collective behavior of the ensemble of dust particles within the plasma. The Coulomb coupling parameter (Γ), also known as the Coulomb coupling strength or the Coulomb coupling constant, is a dimensionless parameter that characterizes the strength of the Coulomb interactions in a plasma system. It quantifies the relative importance of the electrostatic forces between the charged particles compared to other forces. The ratio of potential energy to the thermal energy of dust particles is defined as the Coulomb coupling parameter. Mathematically,

$$\Gamma = \frac{Q_d^2}{4\pi\epsilon_0 r_{av} K_B T_d} \tag{1.25}$$

where r_{av} is the average inter particle distance, T_d is the dust temperature. Plasmas are known to exhibit screening of charges, and this screening effect also applies to dusty plasmas. Consequently, characteristic length scales in dusty plasmas include not only the average inter-particle spacings but also the Debye screening radii of each species and the radii of the dust particles. Therefore, the Coulomb potential energy is replaced by the screened potential energy due to Debye shielding, leading to a “screened” coupling parameter.

$$\Gamma_s = \frac{Q_d^2}{4\pi\epsilon r_{av} K_B T_d} exp\left(-\frac{r_{av}}{\lambda_D}\right) \tag{1.26}$$

Here, Γ_s : Screened Coulomb coupling parameter Q_d : Charge of the dust grain ϵ_0 : Permittivity of free space r_{av} : Average inter-particle distance K_B : Boltzmann constant T_d : Temperature of the dust particles λ_D : Debye length.

The Coulomb coupling parameter Γ is a measure of the degree of correlation, or coupling strength, between the particles in a plasma. For low values of Γ ($\Gamma \ll 1$), the interactions between the dust particles are weak, and the particles behave as

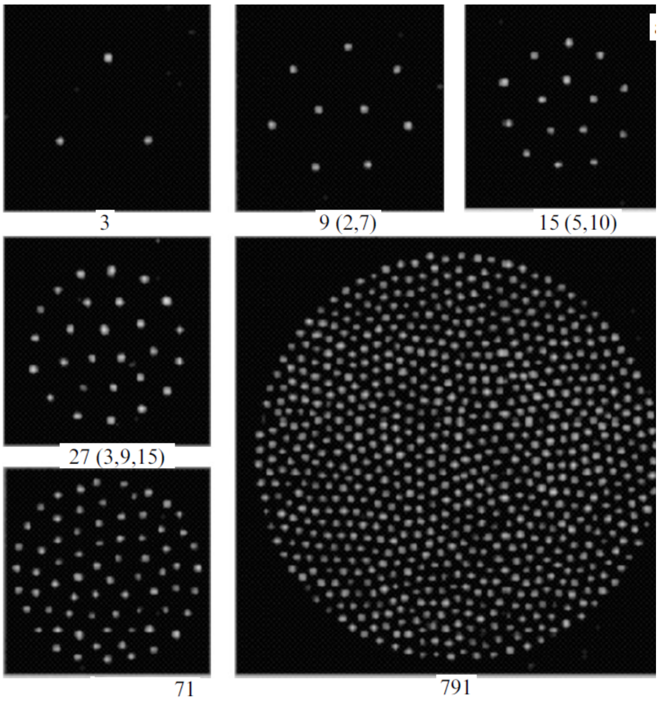

Figure 1.7: Images of experimentally found typical dust clusters consisting of different numbers of particles [2].

independent entities. On the other hand, for high values of Γ ($\Gamma \gg 1$), the dust particles strongly influence each other's motion, leading to the formation of various complex structures like dust crystals, dust acoustic waves, etc. When $\Gamma \geq 1$, the system is said to be "strongly coupled", and the behavior of the plasma is largely dominated by the interactions between particles rather than their individual motion [76]. In 1986, Ikezi put forward a hypothesis suggesting that under specific conditions in a gas discharge plasma, the formation of dust/Coulomb crystals occurs when the coupling parameter (Γ) surpasses a critical value of 170. This critical value, denoted as Γ_c, serves as a threshold for the crystallization process to take place. To achieve the necessary conditions for this crystallization, the plasma system must exist in a state of high density and low temperature, with the parameter values satisfying $\Gamma > \Gamma_c$. The theoretical prediction for the existence of such a crystal is verified by a few important experiments conducted independently by different groups. Many authors and researchers have studied dusty plasma crystals using a combination of theoretical analysis, computer simulations, and experimental techniques [77; 78; 79; 80]. J.H. Chu and Lin. I performed an experiment in Radio Frequency (RF) discharge plasma with SiO_2 particles [77]. The observation of stable body-centered cubic (bcc), face-centered cubic (fcc), and hexagonal crystals, along with their coexistence, was reported. As the Radio Frequency (RF) power was increased, the crystalline structure underwent melting. In an experiment, Thomas *et al.* successfully designed conditions leading to the formation of hexagonal crystals in plasma at very large coupling parameter values [78]. Fig. 1.7 presents visual representations of dust clusters that have been identified through experimental means. These clusters comprise differing quantities of particles, demonstrating their diversity in terms of size and composition. Fig. 1.8 illustrates the phase diagram of Debye-Hückel systems as a function of two defining parameters (Γ and κ). The phase diagram of systems influenced by the Debye-Hückel potential has been studied comprehensively across various physical contexts, spanning from elementary particles to colloidal suspensions [81; 82; 83; 84; 85].

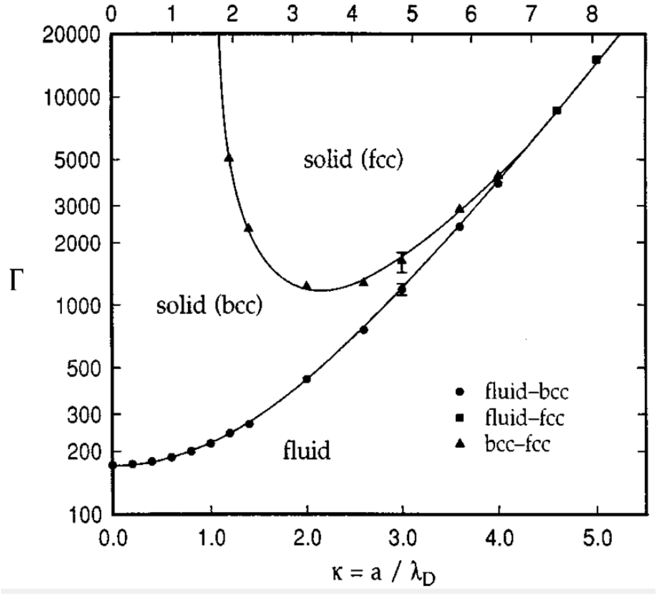

Figure 1.8: A phase diagram of Debye-Hückel systems [4].

The screening parameter (κ) characterizes the strength and extent of the screening effect in a dusty plasma [76; 86]. This effect is crucial in determining the interactions among the charged dust particles. The screening parameter is given as the ratio of the average inter-particle separation (r_{av}) to the Debye length, providing a measure of the range of the screening effect relative to the typical distance between particles. Mathematically, it is defined as

$$\kappa = \frac{r_{av}}{\lambda_D} \tag{1.27}$$

Strongly coupled plasmas exist in various contexts throughout the universe, from astrophysical phenomena to laboratory experiments. White dwarf stars are a prime example of strongly coupled plasmas in our universe [87]. These stellar remnants are characterized by their incredibly high densities, where matter is packed tightly together [88; 89]. In the core of a white dwarf, the material is composed of electrons and ions (usually carbon and oxygen), which are held together by intense gravitational forces. The particles in a white dwarf's core are so densely packed that their average separation becomes comparable to or even smaller than their Debye length. When this happens, the plasma becomes strongly coupled, and the interactions between particles dominate their behavior, and the traditional assumptions of weak coupling break down. The study of white dwarf stars' cooling rates, spectral properties, and other observable features provides valuable insights into the characteristics of strongly coupled plasmas. By analyzing the light emitted from these stars as they cool over time, scientists can infer the state of the plasma and the collective behaviors of the particles within. This information contributes to our understanding of both the behavior of matter in extreme conditions and the behavior of strongly coupled plasma.

Neutron stars are another compelling example of strongly coupled plasmas in the universe [90]. These incredibly dense remnants are formed when massive stars undergo supernova explosions, leaving behind a core primarily composed of tightly packed neutrons. The matter in a neutron star is so dense that individual atomic nuclei break down, and the protons and electrons combine to form neutrons through a process called neutronization. As a result, the core of a neutron star is essentially a sea of neutrons, along with a smaller fraction of other particles like protons and electrons [91].

1.7 Interaction mechanism in complex plasma:

The way dust particles interact in plasmas is different from the typical Coulomb interaction between charged particles in vacuum. The interaction potential among dust particles is more complex and is not solely defined by electrostatic interactions. The interaction potential between macroscopic dust particles depends on their own physical parameters and those of the ambient plasma. The question of the correct potential between dust particles is not purely fundamental and still remains open. The anisotropic plasma flows, dipole effects for larger dust particles, and long-range attractive interactions due to wakefield and shadowing effects may play significant roles. The majority of the existing theories that aim to explain the characteristics of dusty plasmas utilize a common framework. In this framework, negatively charged particles are constrained within the plasma volume by a confining force, typically of an electrostatic nature. These particles then mutually interact through an isotropic screened Coulomb potential. In this framework, the screening process is controlled by the presence of plasma electrons and ions. The electrostatic potential $\phi(r)$ surrounding an isolated spherical dust particle with a charge Q_d in an isotropic plasma satisfies the Poisson's equation

$$\nabla^2\phi = -4\pi e(n_e - n_i + n_d Z_d) \tag{1.28}$$

Where: n_e, n_i, and n_d represent the electron, ion, and dusty densities respectively. Treating the electrons and ions as Boltzmannian, i.e.,

$$n_e = n_{e0} \exp\left(\frac{e\phi}{k_B T_e}\right) \tag{1.29}$$

$$n_i = n_{i0} \exp\left(\frac{e\phi}{k_B T_i}\right) \tag{1.30}$$

when the inequality $|e\phi/k_B T_e(i)| < 1$ is satisfied, the solution to the Poisson equation is as follows:

$$\phi(r) = \frac{Q_d}{r} \exp\left(-\frac{r}{\lambda_D}\right) \tag{1.31}$$

Here, λ_D is the Debye length. The above potential is the screened Coulomb potential, frequently used to characterize the electrostatic interaction between particles in dusty plasmas. In different physical systems, this potential formulation is also recognized as the Debye-Hückel or Yukawa potential [92; 93; 94; 95; 96; 97]. While this potential simplifies the understanding of dusty plasma behavior, it is inadequate for certain experiments, particularly when plasma anisotropy plays a considerable role. Additionally, this model doesn't account for factors such as variations in particle charges, long-range interactions, the specific form of the confining potential, and others. Nonetheless, despite its limitations, this model has proven valuable in producing qualitative results that align with experimental observations. As a result, it serves as a foundational framework upon which more sophisticated models can be developed to accurately represent real dusty plasmas under diverse conditions.

Konopka *et al.* initiated a pioneering study to investigate the nature of interactions among dust particles in a plasma environment [98]. Their experimental setup was specifically aimed at examining the horizontal forces that might link the particles together within the sheath region. In their experiment, the trajectories of two colliding melamine formaldehyde particles are monitored to track the governing interaction. From their observations, they established the presence of a repulsive Debye Hückel potential. However, they found no evidence of any attractive potential acting horizontally among the dust grains. Takahashi and his team explored a new approach by applying radiation pressure from laser illumination to influence the particles [99]. The movement of the laser-driven particles creates a drag effect on adjacent particles in the vertical direction. This suggests the presence of an attractive interaction that binds the particles together. In addition to forming a 2D hexagonal structure on a plane perpendicular to the ion flow, the particles within the hexagon are also bound along the direction of the ion flow. To account for this ordered arrangement of particles, it is necessary to consider not only the repulsive Debye Hückel potential but also an additional attractive potential. Thus, their experiment demonstrated the need for an attractive potential in the dynamics of dusty plasma. Melzer *et al.* also conducted experiments to understand the nature and types of interactions between two isolated particles [100]. They extensively discussed how dust molecules form through asymmetric interactions between particles. The authors clarified the role of an attractive potential, experienced by a downstream grain due to an upstream grain, in the formation of dust molecules.

Both analytical and simulation studies were conducted by Ganguli *et al.*, to investigate the microphysical mechanisms that were triggered by ion flows in dusty plasmas, leading to phase changes [101]. When the pressure was below a critical condensation pressure P_c, high random kinetic energies were acquired by the dust particles, resulting in a weakly bonded fluid state [101]. In contrast, as the pressure P was increased beyond P_c, the kinetic energy of the particles was reduced, and a transition into a strongly bonded crystalline phase was observed. The increase in thermal energy in the fluid phase was found to be caused by an ion-dust two-stream instability, which was stabilized at pressures above P_c through the collective effect of ion-neutral and dust-neutral collisions. Joyce *et al.* investigated the Instability-Triggered Phase Transition to a Dusty-Plasma Condensate [102]. They discovered that the two-stream instability was responsible for the high kinetic temperatures observed in dust grains during low-pressure experiments. Additionally, when these instabilities were stabilized through collisions, it led to the condensation of the dust into a solid state. Their theoretical calculations matched well quantitatively with dust cloud simulations and qualitatively with experimental outcomes, despite the theory being originally intended for an infinite homogeneous medium.

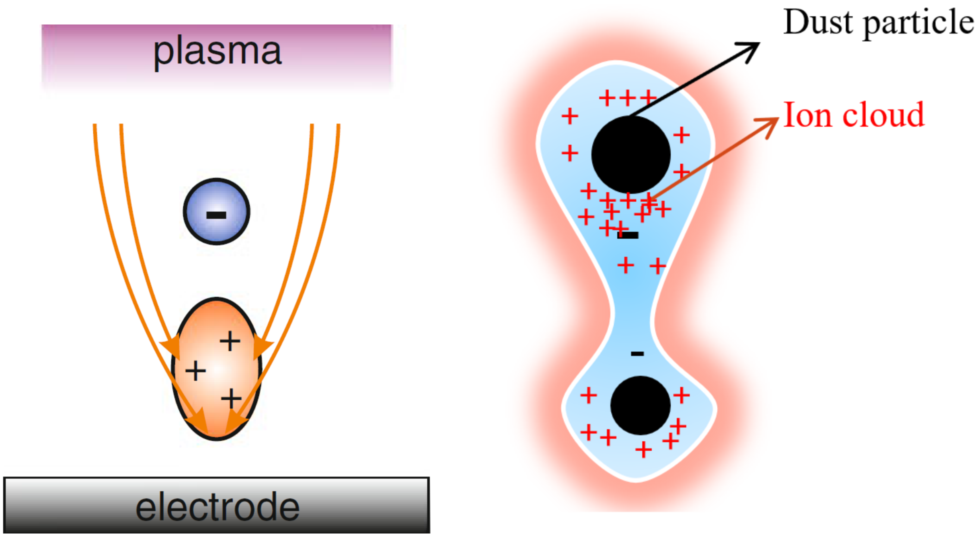

Figure 1.9: Illustration of the wakefield mechanism [5].

Figure 1.9 illustrates the mechanism of wakefield generation in a dusty plasma.

In dusty plasma, the ions undergo acceleration due to strong electric fields in the sheath region. As depicted in the figure, when the ions stream toward the lower electrode, their trajectories are deflected by the substantial charge carried by the dust grains. This charge on the grains exerts a focusing effect, resulting in the formation of a positive space charge beneath the grains. This results in the distortion of the Debye cloud surrounding the dust particles. This process introduces an overshielding effect, leading to an excess accumulation of ions behind the dust grain. This excess accumulation of ions can result in an attractive force experienced by a downstream grain due to an upstream one. As a result, the ion focus produces an effective non-reciprocal attraction among the grains, ultimately causing the alignment of the grains in a vertical orientation. There are many theoretical and simulation works that discuss the possibility of attractive forces existing between any two grains with similar charges embedded in a plasma. Different mechanisms involving ion-mediated attractive forces have been suggested by many authors. The existence of such attractive potential has been extensively studied theoretically and confirmed by several experimental and simulation works [103; 104; 105; 106; 107; 108; 109; 110; 111]. In a pioneering work by Nambu *et al.,* it was presented that collective effects involving interaction between low-frequency waves in the presence of flowing ions and dust particles levitated in the electrostatic sheath of a plasma chamber gives rise to an oscillatory wake potential along the direction of ion flow [103]. Formation of vertical strings of dust grains along the ion flow direction has been observed which may be attributed to the attractive, anisotropic wake potential [112; 113]. The effect of the wake potential on the behavior of strongly coupled plasma systems has also been studied by several groups [114; 106; 107; 108; 109; 110; 111]. We will examine the details of the wake potential in Chapter 3, providing a thorough and comprehensive discussion.

Several experiments have been conducted to study short-range repulsive and long-range attractive interactions between charged dust grains. Konopka *et al.,* experimentally investigated the interaction potential between two micro-spheres that were suspended in the sheath region of a radio-frequency (rf) argon discharge [115]. This was achieved by analyzing their trajectories during head-on collisions.

The results demonstrated that the interaction, aligned with the sheath boundary, could be described using a screened Coulomb potential. Consequently, effective charge values and a screening length were obtained. The horizontal component of the interaction potential was determined for various plasma conditions. However, within the precision of the measurements taken and the specific plasma conditions considered, there was no indication of an attractive component within the potential. An experimental investigation was conducted on the interaction between a negatively biased wire and a mono-layer lattice composed of negatively charged particles by Samsonov *et al* [116]. These particles were suspended at the same height as the wire within a radio-frequency discharge sheath. The results indicated that particles situated in proximity to the wire experienced a repulsive electrostatic effect, causing them to move away from the wire. Conversely, particles located at a greater distance were attracted towards the wire due to the influence of ion flow being redirected towards the wire. The ion drag force dominates at considerable distances from the wire, whereas the electrostatic force exhibits greater strength in the immediate vicinity of the wire. Importantly, the range of these forces extended over one to two orders of magnitude beyond the screening length.

1.8 Complex plasma—the plasma state of soft matter:

The soft matter field is a highly multidisciplinary field of research. It explores the properties and behavior of materials with intermediate characteristics between conventional solids and liquids [117; 118]. One of the most fundamental properties of soft matter is its deformability. It indicates the ability of a material to change its shape under external forces. Soft matter is highly sensitive to thermal fluctuations, this sensitivity to thermal fluctuations is what allows soft matter to be tuned or manipulated by changes in temperature, making them adaptable for a wide range of applications, from industrial (like thermoresponsive polymers) to biological (like the temperature-dependent behavior of cell membranes and enzymes) sectors. Soft matter often has a strong response to external stimuli, such as light, electric or magnetic fields, shear stress, and changes in pH or solvent conditions. These stimuli can cause a range of responses, including changes in color, consistency, and even shape. The response of soft matter to external stimuli can be used to design "smart" materials that dynamically adapt to their environment. Soft matter often shows complex phase behavior, including the ability to form a range of different phases (such as solid, liquid, and gas) under different conditions. Self-assembly is a process in which components, either separate or linked, spontaneously organize into ordered structures based on their inherent properties and local interactions. self-assembly is a key feature of many soft matter systems. This process refers to the spontaneous organization of individual components into an ordered structure, driven by specific local interactions among the components, without external factors. Soft matter often demonstrates viscoelastic behavior, which means it exhibits both viscous (fluid-like) and elastic (solid-like) characteristics. Understanding these properties and how they can be manipulated is key to the application of soft matter in a variety of fields, including materials science, chemical engineering, biophysics, and nanotechnology.

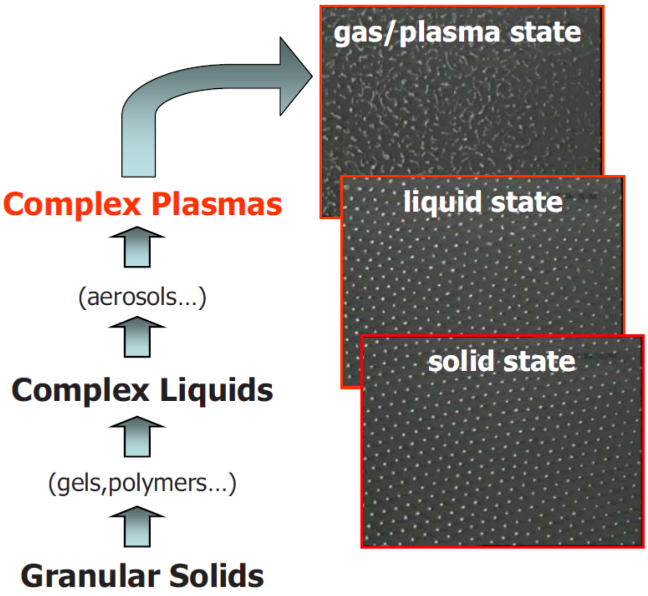

Figure 1.10: Classification of complex plasma: exploring the plasma state in soft matter [6].

Complex plasma is the latest addition to this fascinating, interdisciplinary research field, and it can be regarded as the plasma state of soft matter [119]. As mentioned earlier, a complex plasma is an ensemble of charged dust particles immersed in a plasma medium. Under suitable conditions, complex plasma may behave as soft matter, exhibiting macroscopic softness or elasticity and sensitivity to external conditions [119]. Due to the relatively large size and mass of dust particles, it is easier to observe and resolve structural properties, phase transitions, etc. in such plasma, and it provides an opportunity to study the phenomena shown by soft matter in such a medium [120; 119].

The thermodynamics of strongly coupled dusty or complex plasma is mainly governed by two parameters: Coulomb coupling parameter $\Gamma = \frac{Q_d^2}{4\pi\epsilon_0 r_{av} K_B T_d}$, and screening strength $\kappa = \frac{r_{av}}{\lambda_D}$ where, r_{av}, λ_D, T_d and Q_d are the average inter-particle distance, Debye screening length, dust temperature, and dust charge respectively. For a suitable range of values of these two parameters, complex plasma may behave as a soft matter exhibiting macroscopic softness or elasticity and sensitivity to external conditions [119].

In 2008, Ivlev *et al.* reported the experimental discovery of a unique class of plasmas known as electrorheological (ER) complex plasmas [121]. Complex plasma exhibits intriguing behavior where the interparticle interactions can be controlled by an externally applied electric field, which is achieved through the distortion of Debye spheres surrounding the micro-particles [121]. The research demonstrates that the interactions observed in ER plasmas under weak alternating current (AC) fields are mathematically equivalent to those observed in conventional ER fluids. Through microgravity experiments and molecular dynamics simulations, it is revealed that as the electric field strength is increased, a phase transition occurs in these ER plasmas, transforming them from an isotropic state to an anisotropic state characterized by the formation of string-like structures [121]. The findings of this study provide valuable insights into the intricate dynamics and properties of ER complex plasmas, revealing their behavior under different electric field conditions.

In Chapter 5, we have explored how an external magnetic field influences the rheological properties of complex plasma via tunable interaction potential. It has been observed that the rheological property of such plasma depends on the dominant interaction operating among the particles and can be controlled by applying an external magnetic field [122]. A novel regime of the magnetic field is observed in which strongly correlated complex plasma liquid exhibits a sharp response to an external magnetic field. Due to this unique property, complex plasma may be used as a platform to study magneto-rheological characteristics of soft matter and there is a possibility of using dusty plasma as a magneto-rheological material in the near future [122].