A survey on fundamental physics of dusty plasma

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Abstract

Two omnipresent ingredients of the Universe are plasmas and charged dust. The interplay between these two, dusty plasmas have opened up a new and fascinating research area. Dust turns out to be ubiquitous in cosmic plasmas, planetary plasmas, plasmas near the earth and plasmas in the laboratory. In fact, one may speculate that except in the hottest regions of fusion plasmas where dust particles would not survive, most plasmas are dusty plasmas in the sense that some dust particles may be present. Thus dusty plasmas play a vital role in wide range of phenomenon and are of current research interest for a number of reasons. Despite the fundamental study they also have relevance to fusion plasmas. It is an unavoidable problem that the plasma in a Tokomak is contaminated by scrape-off from the walls (thus these plasmas are inherently ‘dusty’). Thus control and elimination of the dust produced is an important problem. Thus dusty plasma physics is one of the most rapidly growing and truly interdisciplinary fields of science, as indicated by the number of published papers in research journals and conference proceedings. Dusty plasma physics finds potential application in understanding not only astrophysical phenomenon like dust clusters, star formation, instabilities of interstellar molecular etc but also in the planetary magnetospheres of our solar system. Laboratory dusty plasma is used as a role model to understand these entire phenomena. In this paper, the basic physics of dusty plasmas is discussed. The main focus is on theoretical and experimental observations of dust charging processes, associated forces, crystallization, waves, the dynamics of rotating dust grains and scattering.

1. Introduction

Plasma is an ionized gas consisting of ions and electrons as well as atoms or molecules. Dusty plasma contains suspended particles (grains) of condensed matter in. These dust grains may have sizes ranging from few tens of nanometers to few hundreds of microns. This extra component, which increases the complexity of the system even further, is responsible for the name ``complex plasma."

These dust particles may be composed of dielectric (e.g. SiO_2 or Al_2O_3) or conducting materials (Mn_2O_s) and are much more massive (billion or trillion times) than the plasma electrons and ions. The interaction of these dust particles with the plasma and ambient environment results in a charging of the dust grains. Dust grains in a plasma usually acquire a net negative charge because of the greater mobility of the electrons compared with the ions. The charged grains can form ordered structures called plasma crystals, which can be observed by laser illumination. A typical dust grain may acquire a charge of 10^3 to 10^5 e, depending on the plasma condition and its size, where ‘e’ is the elementary electronic charge.

Dust turns out to be ubiquitous in cosmic plasmas, planetary plasmas, plasmas near the earth and plasmas in the laboratory. In fact, one may speculate that except in the hottest regions of fusion plasmas where dust particles would not survive, most plasmas are dusty plasmas in the sense that some dust particles may be present. Thus dusty plasmas play a vital role in wide range of phenomenon and are of current research interest for a number of reasons. Despite the fundamental study they also have

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relevance to fusion plasmas. It is an unavoidable problem that the plasma in a Tokomak is contaminated by scrape-off from the walls (thus these plasmas are inherently 'dusty'). Thus control and elimination of the dust produced is an important problem.

Experimentally, an enhanced level of plasma oscillation has been reported in which the collective properties of the strongly coupled dust plasma system can be assumed to play a significant role in the system [1-4]. In these experiments the chaotically moving charged dust grains have been reported to lead to a considerable modification of the collective properties and generation of new modes been confirmed. For example, the dust-grain dynamics were crucial for the dust-acoustic waves. Experiments on the dust acoustic wave [1-4] have verified theoretical predictions that the presence of the dust significantly modifies the frequency and growth rate of the ordinary ion-acoustic wave. These theoretical and experimental result also demonstrate that the relative number of free electrons, (i.e., those not attached to the dust grains) affect the wave characteristics. The project is applicable to industrial, laboratory, and space dusty plasmas, where small differences in free-electron concentration lead to large deviations in the product, behavior, and evolution, respectively.

It is possible to determine the positions of the dust grains by minimizing the electrostatic potential energy between them. The dust grains behavior also changes as the temperature of the plasma is varied. There will be a phase change below some critical temperature where dust-grain crystals 'freeze' in the plasma. This dust structure is known as Coulomb solid or dust – plasma crystal [7-8]. The collective properties of strongly coupled dusty plasma system can be assumed to play a significant role in the system. They modify the physical properties of the plasma, one consequence being that different kinds of waves can propagate. The interaction between the particles and the plasma is complex (indeed dusty plasmas are increasingly referred to as complex plasmas) so that in certain circumstances the dust crystal can become unstable, with the particles spontaneously undergoing wave, oscillatory or vortex motion. An additional rationale for the study of dusty plasmas is that they are models for real crystals, but in this case the individual motion of the particles (representing atoms) can be observed. Thus dusty plasmas are well suited to serve as a model system in studies of self – organization and phase transitions in non-equilibrium, open, dissipative systems, a hot topic of research recently. Further in strongly coupled dusty plasmas many phenomena like crystal structure phenomenon, instabilities [5-6], dust mass rotation [9-11], dust – dust scattering [12], formation of dust molecule [13], solid to liquid phase transition [14], etc are also of interest. In the last decade, the interest in dusty plasma emerged in research related to industrial and technological applications [15, 16], such as material coating, etching and in thermonuclear fusion devices such as tokamak.

In this paper, we present the basic physics involving dusty plasmas and describe the progress that has been made in the area of collective processes in dusty plasmas during the last decade. We have discussed the properties of dusty plasma, charging processes of dust particles, and focus on waves, instabilities, and coherent nonlinear structures.

The manuscript is organized in the following fashion. In Sec. II, the general properties of dusty plasma are described. In Sec. III, the charging process is discussed. Section IV contains discussion on various forces acting on dust particle in plasma. Section V points out the review of different phenomena observed is strongly coupled dusty plasma and finally section VI contains a summary of the investigation.

2. Properties of Dusty Plasmas

The constituents of dusty plasmas are electrons, ions, neutral gas molecules, and massive (compared to the ions) charged dust grains. The three characteristic length scales for such a dust and plasma mixture are the dust grain radius 'R', the dusty plasma Debye radius 'λ_D', and an average inter-grain distance'd'. The latter is related to the dust number density 'n_d' by $\sim n_d^{-1/3}$. The dusty plasma Debye radius λ_D is given by

$$\frac{1}{\lambda_D^2} = \frac{1}{\lambda_{De}^2} + \frac{1}{\lambda_{Di}^2}..$$

where $\lambda_{De} = (\epsilon_o kT_e / n_{e0}\, e^2)^{1/2}$ and $\lambda_{Di} = (\epsilon_o kT_i / n_{i0}\, e^2)^{1/2}$ are the electron and ion Debye radius respectively; T_e & T_i are the electron & ion temperature; n_{e0} & n_{i0} are the unperturbed electron & ion number density, and e is the magnitude of the electronic charge. For $T_e \sim T_i$ and $n_{e0} \sim n_{i0}$, we have $\lambda_{De} \sim \lambda_{Di}$, while for $T_e \gg T_i$ and $n_{e0} > n_{i0}$, we have $\lambda_D \sim \lambda_{Di} \gg \lambda_{De}$.

Further in dusty plasmas, we typically have $R \ll \lambda_D$. One can treat the dust from a particle dynamics point of view when $R \ll \lambda_D < d$, and in that case we have a plasma containing isolated screened dust grains and known as "dust in plasma", Figure. 1. On the other hand, collective effects of charged dust grains become important when $R \ll d < \lambda_D$. Here, charged dust particulates, can be treated as massive point particles similar to multiply charged negative (or positive) ions in multispecies plasma and known as "dusty plasma", Figure.2. Under this condition the dusty plasma is also macroscopically neutral like electron – ion plasma and the quasi-neutrality condition for negatively charged dust grains is

$$n_{e0} = n_{i0} - Z_{d0}\, n_{d0}$$

Where n_{i0}, n_{e0} and n_{d0} are the unperturbed number density of the electrons, ions and dust grains respectively and Z_{d0} is the number of unperturbed electronic charges residing on the dust grain surface.

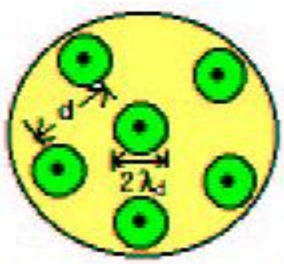

Fig.1:Schematic of dust in Plasma

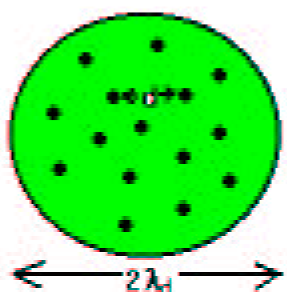

Fig.2. Schematic of dusty plasma

Another parameter to characterize a dusty plasma is Coulomb coupling parameter 'Γ', the ratio of the average Coulomb potential energy between dust particles to the average kinetic energy of the particles. It is given by

$$\Gamma = \frac{Q_d^2}{4\pi\varepsilon_0 a T_d} exp(-a/\lambda_D)$$

Where $Q_d = Z_{d0}e$ is the charge on the dust particle, T_d is the temperature of the dust grain, λ_D is the Debye length and a is the distance between the two dust particle. When $\Gamma \leq 1$, the plasma is said to be weakly coupled (space plasma), for $1 \leq \Gamma < 170$, the plasma is said to be strongly coupled (liquid state) and for $\Gamma \geq 170$, strongly coupled (Solid State). Strongly coupled dusty plasmas are created in low-temperature dusty plasma discharges for studying the formation and dynamics of dusty plasma crystals.

3.0 Dust Grain's charging

When dust particles are immersed in plasma, they acquire electric charges. The charge on the dust particle depends on the size of the grain and the background plasma parameters. Further, the charge is not a constant, but can fluctuate randomly, or in response to fluctuations in plasma parameters such as the electron density. These grains can be charged due to a variety of processes including the bombardment of the dust grain surface by background plasma electrons and ions, photoelectron emission by UV radiation, ion sputtering, secondary electron production, etc. In low-temperature laboratory plasmas, dust particles are mainly negatively charged when any plasma electrons hitting the surface of the dust grains are attached to it and simply lost from the background plasma.

To estimate the charge of a particle, there are several theoretical models and experimental methods. In general, none of them yields a result with perfect precision. The most common model is called the "orbit-motion-limited" (OML) theory, which assumes collision-less ions, and this method will be reviewed here. Like other charging theories, this model is also useful for calculating the charge and potential of larger objects in a plasma, such as a spacecraft or a Langmuir probe.

Analytic models including the OML model typically assume that the dust grain is a spherical capacitor, and its surface is an equipotential. The charge Q_d is then related to the particle's surface potential ϕ_S, with respect to a plasma potential of zero, by

$$Q_d = C\phi_S$$

Where C is the capacitance of the particle in the plasma? For a spherical particle satisfying $R \ll \lambda_D$, the capacitance is

$$C = 4\pi\epsilon_0 R$$

If the particle is not made of a conducting material, and if it is positioned in an anisotropic plasma, then its surface might not be an equipotential, and above equations will not be useful in computing an accurate value for the charge Q_d.

For the collection of Maxwell an electrons and ions, characterized by temperatures T_e and T_i, the orbit-limited currents for an isolated spherical particle are [16-23, 25-27]

$$I_e = I_{0e} \exp\left(\frac{e\phi_s}{kT_e}\right) \qquad \phi_s < 0$$

$$I_e = I_{0e}\left(1 + \frac{e\phi_s}{kT_e}\right) \qquad \phi_s > 0$$

$$I_i = I_{0i}\exp\left(\frac{q_i\phi_s}{kT_i}\right) \qquad \phi_s > 0$$

$$I_i = I_{0i}\left(1 - \frac{q_i\phi_s}{kT_i}\right) \qquad \phi_s < 0$$

Here $q_i = Z_i e$ is the electronic charge of the ions. The coefficients I_{0e} and I_{0i} represent the current that is collected for $\phi_S = 0$, and are given by

$$\mathrm{I_{0e}} = 4\pi \mathrm{n_{e0}} \mathrm{q_e}\sqrt{\frac{\mathrm{kT_e}}{2\pi \mathrm{m_e}}} \qquad \mathrm{u/v_{th}} \ll 1$$

$$\mathrm{I_{0i}} = 4\pi \mathrm{n_{i0}} \mathrm{q_e}\sqrt{\frac{\mathrm{kT_i}}{2\pi \mathrm{m_i}}} \qquad \mathrm{u/v_{th}} \ll 1$$

$$\mathrm{I_{0e}} = \pi a^2 \mathrm{n_{e0}} \mathrm{q_e} \mathrm{u}\left(1 - \frac{2\mathrm{q_e} \mathrm{q}\phi_S}{\mathrm{m_e u^2}}\right) \qquad \mathrm{u/v_{th}} \gg 1$$

$$\mathrm{I_{0i}} = \pi a^2 \mathrm{n_{i0}} \mathrm{q_i} \mathrm{u}\left(1 - \frac{2\mathrm{q_i} \mathrm{q}\phi_S}{\mathrm{m_i u^2}}\right) \qquad \mathrm{u/v_{th}} \gg 1$$

Where u and $v_{th}(= 2kT/m)$ are drift velocity and thermal velocities. To calculate the dust grain charge, it can be assumed that the particle with zero charge is immersed in plasma and it gradually charges up by collecting electron and ion currents, according to

$$\frac{dQ_d}{dt} = \sum_{\alpha} I_\alpha$$

Where α is ion or electron, plasma species?

To find the equilibrium, we can set ${}^{dQ_d}/_{dt} = 0$ in above equation. This yields the steady-state potential ϕ_{fl} and steady-state charge $\langle Q_d \rangle$,

$$\phi_{fl} = \langle \phi_S \rangle = K_\phi T_e$$

$$\langle Q_d \rangle / e = K_Q R k T_e$$

Where the coefficients K_ϕ and K_Q are functions of ${}^{T_i}/_{T_e}$ and ${}^{m_i}/_{m_e}$, and the ion flow velocity. These coefficients can be determined numerically. The polarity of the dust particle's charge and surface potential will be negative if the particle does not emit electrons. That is so because electrons have a higher thermal velocity than ions. On the other hand, the particle can charge positively.

4. Forces on Dust Particle

After being charged a dust grain get levitated in the plasma, where various forces act simultaneously on the dust grain, fig. 3. The motion of dust grains in plasma follows the following equation [24]

$$m\frac{d\vec{v}}{dt} = \vec{F_L} + \vec{F_g} + \vec{F_P} + \vec{F_D} + \vec{F_T}$$

Where terms are for the Lorentz force, the gravitational forces, and forces due to radiation pressure, the drag forces and the thermophoretic force respectively

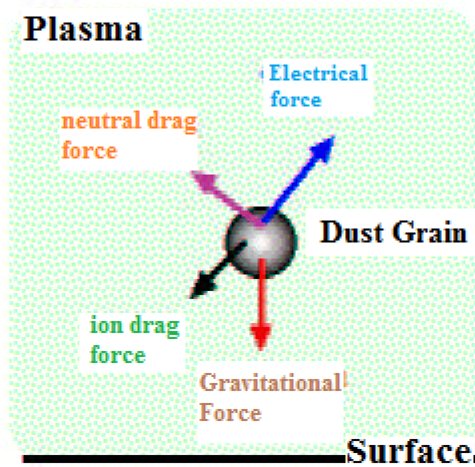

Fig. 3. Schematic of different force acting on dust grain

The Lorentz force, the contributions from the electric and magnetic force, is given by:

$$\vec{F_L} = Q_d\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right) = 4\pi\epsilon_0 R\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right)$$

Where $\vec{E}$ is the electric field, c is the velocity of light, $\vec{v}$ is the velocity and $\vec{B}$ is the magnetic field

The gravitational force simply is

$$\vec{F_g} = m_d\vec{g} = \frac{4}{3}\pi R^3 \rho_d \vec{g}$$

Where $\vec{g}$ is the gravitational acceleration and ρ_d is the dust mass density. This force is proportional to R^3, hence most dominant force for large size (micrometer) dust particle and become negligible for small size (nanometer).

$\vec{F}_P$ is the force contribution from radiation pressure. Radiation pressure is the momentum per unit area and unit time transferred from photons to a surface. If a beam of photons strikes the particle, some photons will be reflected and others will be transmitted or absorbed. All three processes contribute to the radiation pressure. In general for a laser beam of intensity I_{laser}, the radiation pressure force is

$$\vec{F}_P = \gamma \frac{\pi R^2}{c} I_{laser}\, \hat{e}_i$$

Where $\hat{e}_i$ the direction of the force is vector and γ is a dimensionless factor that is determined by the reflection, transmission or absorption of the photons on the particle. If all photons are absorbed $\gamma = 1$ and for complete reflection$\gamma = 2$

For the drag force there are two major components of interest, those from positive ions-dust particle interactions ($\vec{F}_{ion}$), and neutral-dust particle interactions ($\vec{F}_n$).

$$\overrightarrow{F_D} = \vec{F}_{ion} + \vec{F}_n$$

Ions streaming past a dust particle exert a force on the dust by scattering of the ions in the electric field of the dust or by collection on the dust surface. This force is one of the major forces on dust particles. Ion-dust interactions are further broadly divided into two different interactions, through regular collisions ($\vec{F}_{coll}$), and through coulomb collisions ($\vec{F}_{Coul}$). The neutral drag is the resistance experienced by a particle moving through a gas.

The thermophoretic ($\vec{F}_T$) is the force that arises due to a temperature gradient in the neutral gas. In a simplified picture, neutral gas atoms from the "hotter" side that hit the dust grain transfer a larger momentum to the dust than atoms from the "colder" side. Consequently, a force towards regions of colder gas is established. From gas kinetic theory this force is

$$\vec{F}_T = -\frac{32}{15}\frac{R^2 k_n}{v_{th,n}} \nabla T_n$$

Where T_n is the temperature gradient in the neutral gas and k_n the thermal conductivity of the gas. This formula holds if the mean free path of the gas molecules λ_{mfp}, is much larger than the particle radius (R).

In table 1 we have calculated the magnitude of different force for the capacitive coupled argon plasma. The parameters are neutral pressure $20Pa$, plasma density$5 \times 10^{15} m^{-3}$,$T_e = 3eV$; $T_i \sim T_n = 0.03eV$, dust particle density (melamine formaldehyde)$\rho_d = 1514 kg/m^3$ particle, particle radius $R = 4.9\mu m$ and the velocity of particle $16 mm/sec$.

Gravitational	7×10^{-12}N
Electrostatic	9×10^{-12}N
Neutral drag	2×10^{-13}N
Ion drag	2×10^{-12}N
Thermophoretic	5×10^{-13}N
Radiation pressure	6×10^{-16}N

5. Review of Experimental And Theoretical Work

The study of strongly coupled dusty plasmas has been a subject to study from a long time [28]. It exhibits fascinating phenomenon like formation of more ordered structures [7-8], waves [1-4], rotation of dust grains [9-10], dust-dust scattering [12] and formation of dust molecule [13], etc. A number of laboratory experimental investigations pertaining to such phenomenon have been carried out in different RF and DC discharges geometries to study different aspect of it.

5.1. Plasma Crystallization:

Making of plasma crystal is one of the interesting subjects for the study of strongly coupled dusty plasma. It was first pointed out by Ikezi [29] in 1986 that the negatively charge dust grains in a low temperature weakly ionized plasma form solid as Γ exceeds than170. This solid form is also known as "Coulomb crystal" or "plasma crystal" [7,8] and can be formed at room temperature. It is a regular arrangement of fine dust grains like an atomic crystal, where the "atoms" are represented by the highly negatively charged and highly ordered dust grains and the "electrons" by the mobile plasma ions and electrons. Thus these structures are ideal for experimental studies of lattice vibrations, solid-liquid phase transitions and other microscopic effects [14] because of their similarity to real solid-state crystals.

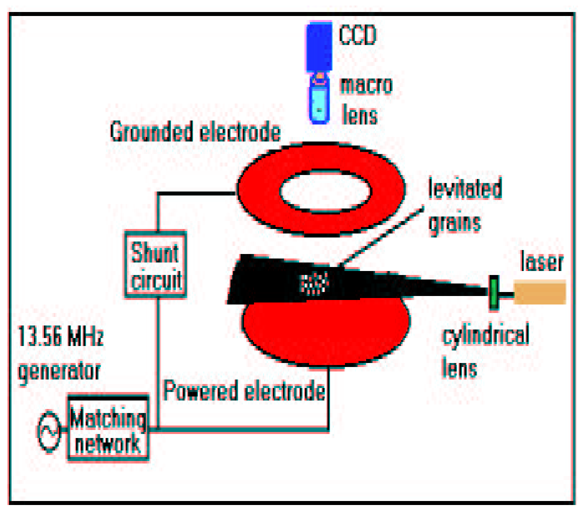

Figure.4. Schematic of the typical experimental setup used for the generation of plasma crystal in RF plasma.

The formation of plasma crystal was first experimentally observed independently by three groups [7, 8, 30] using RF plasma. Fig. 4 shows the schematic of a typical experimental configuration used for the production of such "plasma crystal". Plasma is produced between a parallel plate geometry using RF discharge. The lower electrode was a disk while the upper electrode was ring shaped. Here the RF field periodically transfers electrons deep into the cathode sheath and help in levitation of dust grain. A plasma crystal was formed near the bottom electrode at the boundary of the cathode sheath, where the gravity is balanced by the sheath electric field. Chu and Lin [7], formed a $3D$ plasma crystal in a cylindrical symmetric RF plasma system. By properly controlling the discharge parameters they were able to form crystals with fcc (face center cubic), bcc (body center cubic), hcp (hexagonal close pack) and hexagonal structures. The SiO_2 grains were produced in the RF, Ar plasma. The experimental parameters were $= 10\mu m,\ n_d = 2 \times 10^5 cm^{-3}, n_i = 10^9 cm^{-3}, T_e = 2eV \;\&\; T_i = 0.03eV$ the Coulomb coupling parameter was about a few hundred, falls in the right regime in which the Coulomb solid ($\Gamma \geq 170$) can be formed. Later Thomas et. al. [8] formed a 2D ordered structure using 7μm diameter melamine formaldehyde grains in RF discharge. Image analysis revealed that these crystalline structures have large value of Coulomb coupling parameter$\Gamma > 20000$). Hayashi and Tachibana [30] also observed a 3D dust cloud in RF plasma system. In another RF plasma experiments Peiper et. al. [31], Mohidden et. al. [32] also formed Coulomb crystals.

Fortov et. al. [33], formed a quasicrystalline structure using hollow thin wall spherical glass grains with diameter of $50 - 63$μm in the standing striations of a stationary glow discharge in Ne plasma. The dust grain wall was approximately 5 thick. The crystalline structure did not occurred in the cathode sheath, but in the standing striations where the electric field intensity and the electron density both were high. Later Nunomura et. al. [34] formed plasma crystal in the DC Ar plasma sheath boundary at a very low pressure, generated by DC discharge between the hot filaments and the grounded vessel. A simple hexagonal structure of spherical grains of radius 2.5μm was formed on horizontal plane. The experimental parameters were$n_e = 10^{-8} cm^{-3},\ T_e = 2eV,\ T_i = 0.03eV \;\&\; d = 430\mu m.$ For these experimental parameters,$\Gamma > 170$. In another experiment Agarwal et. al. [35] formed Coulomb dust cloud using spherical alumina dust grain with diameter $50 - 120$μm in the sheath boundary of hollow cathode DC plasma. They attributed it to additional attractive force between the grains.

Plasma crystals also allow access to nonlinear phenomenon like phase transitions. Quinn et.al. [36] attributed that the phase of the plasma crystal can be determined by using the pair correlation function g(r) the probability of finding two grains separated by a distance 'r', also known as the radial (pair) density distribution) and the static structure factor. In their experiments, Chu et.al. [7] Showed that a change in discharge parameters can decrease the relative strength of the Coulomb coupling and leaded to phase transition. Morfill et.al. [37] and Melzer et. al. [14], showed that plasma crystal exhibit phase transition either by increasing the RF power or by decreasing neutral gas pressure. In simulation of Zheng and Earnshaw [38] it was observed that when the RF power was raised, dust grains moved more violently. Many of these violently moving grains appeared to have no equilibrium positions and cause melting of plasma crystal. Hayashi and Takahashi [39] observed a melting transition of 3D Plasma crystaldue to a change in the direction of force. They further quantitatively analyzed their results using the Manto-Carlo simulation. Nefedov et.al. [40] proposed a model for the random motion of dust grains. They suggested that an anomalous increase in the part of the kinetic energy of these dust grains, cause the melting transition. The temperature of the dust grain is determined exclusively by the temperature of the surrounding, given by [40]

$$T_d = T_n + \frac{2m_d D_0^2}{a^2}\left(\frac{D_c}{D_0}\right)^2$$

Where $D_c \& D_0$ are the diffusion coefficient of collective interaction between the dust grains and Brownian dust grain. As the system pressure decreases, D_0 increases, which qualitatively explains the observed phenomenon of increased macro particle kinetic energy. Afterwards they have verified their model with experimental results of Melzer et al. [14].

5.2. Formation of Dust Acostic Waves

Another interesting phenomenon which has attracted much interest is the propagation of very low frequency waves in dusty plasma. The addition of charged particulates in electron-ion plasma is found to modify or even dominate wave propagation, wave instability, wave scattering, etc. The modifications occur owing to the in homogeneity associated with the random distribution of charged particulates and the departure from the conventional quasineutrality condition in electron-ion plasma due to the presence of charged dust grains. Due to the very high mass of the dust grains with respect to plasma particles (electrons and ions) their response to the electric field is very slow. Thus the resultant waves are of very low frequency ($< 50Hz$). In the theoretical description of these low frequency modes two types of waves are discussed: the dust acoustic wave (DAW), first discussed by Rao et al. [1] and the dust lattice wave (DLW) [41]. The DAW is a modified version of the usual ion acoustic mode of ordinary plasma but here the inertia is provided by the dust grains and the pressure by the plasma particles (electrons and ions). The theory of this DAW is based on a weak-coupling parameter $\Gamma < 1$. Pieper et al. [42] and Pramanik et. al. [5] have shown that it should be valid also in a more strongly coupled regime with $1 < \Gamma < 170$. In case of DLW (where the wave length is of the order of lattice constant) the dust grains are treated as strongly coupled. Their model includes strong intergrain interactions between the neighboring dust grains. Such waves are very helpful to obtain many fundamental quantities for the characterization of plasma crystals from the analysis of wave propagation through them [43].

Experimentally self excited and driven DAWs have been studied in both DC [3-5, 44-46] and RF [42-43, 47-48] discharges. Barken et al. [3] have observed DAW modes in Q machine. These waves were excited using kaolin dust grains of an average diameter $5\mu m$, confined in an anodic double layer. These waves had typical values of phase velocity $9 cm/s$, frequency 15Hz and wavelength 0.6cm. The measured phase velocity was in good agreement with the theoretically predicted one. Prabhakara and Tanna [4] trapped negatively charged dust grains in a hot filament plasma discharge which was exposed to a layer of dust. They observed coherent fluctuations of $1 - 15$Hz in the spectrum of scattered He-Ne laser light. Thompson et al. [44] trapped kaolin dust grains of diameter $0.8\mu m$ in a DC glow discharge. The glow discharge was formed between the anode disk and grounded wall of the vacuum chamber, filled with nitrogen gas at a pressure of about $100mTorr$. They have excited DAW by modulating the discharge voltage in the range of $5 - 40$Hz.

Self excited DAW modes were observed by Molotkov et al. [46] in the standing striations of a DC glow discharge. These DAW modes were excited either by decreasing the neutral gas pressure or by increasing the number of dust grains in the dust cloud. They have proposed a simplified linear model of ideal collision less plasma to explain the observed phenomenon and concluded that the observed DAW is caused by the drift motion of ions relative to the dust. In literature there are many theoretical models to explain DAW. Zuzic et al. [47] excited low frequency waves in a plasma crystal by sinusoidal electromagnetic waves. Spherical melamine formaldehyde grains of $6.9\mu m$ in diameter were levitated in RF Kr plasma. They have first investigated the oscillation modes of one and two particle systems for the basic understanding of conditions and processes. Afterwards single layer plasma crystal was investigated using the same technique. They have observed an induced spontaneous transition from the solid to the gas phase. Pieper and Goree [42] found DAW in a horizontally extended crystal by suspending $9.4\mu m$ polymer spheres in RF Kr plasma. DAW was launched by applying a modulated voltage to a wire positioned close to the dust grains. In this technique the confining potential of the plasma crystal and the plasma environment were perturbed due to the presence of wire. Both parts of the complex wave number were measured to determine the dispersion relation. It matches with the theoretical model of damped DAW, ignoring strong coupling. Experimental measured values of dust plasma frequency, charge, Debye length and damping rate, support the applicability of fluid-based dispersion relations to strongly coupled dusty plasma, which has been a controversy [42].

Homann et. al. [43] investigated the propagation of waves in a two dimensional dust crystal. The dust crystal was formed by trapping spherical grains in the sheath of RF discharge. The wave was excited using the radiation pressure of a laser beam of an Ar-ion-laser of $5 - 8W$ power. Thus the confining potential of plasma crystal and the surrounding plasma environment was not disturbed. The observed wave motion was described by two dimensional DLW. The obtained dispersion relation was found in good agreement with DLW, where as deviated from DAW. They also determined the screening length of the particle in the RF sheath using DLW dispersion.

5.3 Rotation of Dust Grains

Further inducing mass rotation of the dust component has been another interesting fundamental issue and has formed the subject of a few recent laboratory experiments [49-53]. In these experiments the dust component was found to rotate only on imposition of an external magnetic field exceeding a certain critical magnitude.

Further rotation of the dust component has been another interesting fundamental issue in astrophysics and laboratory plasma. Rotating dust gas clouds and dusty plasmas often form the primordial material from which new stars are born in young galaxies. This new vorticity source may have interesting applications for understanding the dynamics of such configurations. In few recent laboratory experiments [49-53], the dust component was found to rotate only on imposition of an external magnetic field exceeding a certain critical magnitude. However, the magnetic field was not large enough to magnetize the dust grain because of its heavy mass. Maemura et al. [51] proposed a model for the dust grain drift in the presence of magnetic field, **B**, perpendicular to a discharge electric field, **E**. In Fig. 5, the schematic of the driving mechanism of grain transport in ambipolar $\mathbf{E} \times \mathbf{B}$ drift of plasma is shown. Here the applied magnetic field strength is such that only electrons are magnetized (neither the ions nor the dust grains). Applying the cross magnetic field enhances the electric field in the y-direction because of the charge separation between the magnetized electrons and the un-magnetized positive ions and negatively charged massive dust grains. These particles (electrons, ions and dust grains) further should drift to cancel the effect of space charge electric field (also called am-bipolar electric field) of one another. Electrons are transported in the $\mathbf{E} \times \mathbf{B}$ direction at a faster speed while the ions are transported with a slower speed in the same direction. The negatively charged massive dust grains are drifted in the direction opposite to the $\mathbf{E} \times \mathbf{B}$ direction with a slower speed to ions.

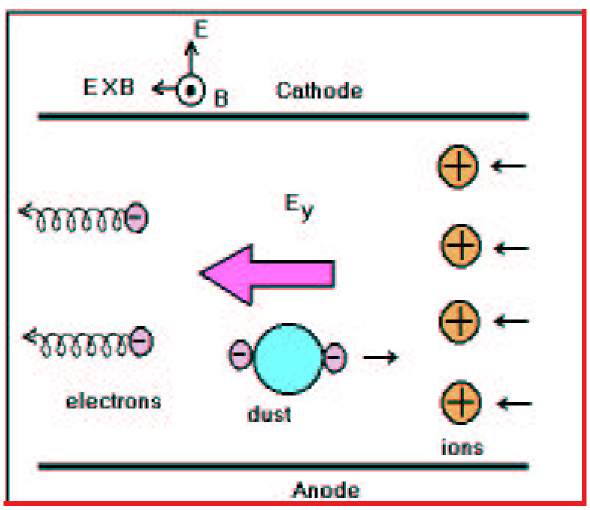

Figure.5. Schematic diagram showing the rotation mechanism of dust grain in magnetic field.

Konopka et al. [52], showed that plasma crystals of fine melamine formaldehyde dust grains (diameter 8.9μm), suspended in the sheath of a RF discharge, rotate under the influence of a vertical magnetic field. Depending on the discharge conditions, two different cases were observed: a rigid body rotation (all the dust grains move with a constant angular velocity) and sheared rotation (the angular velocity of dust grains had a radial distribution). These dust grains reversed the direction of motion when the discharge voltage was sufficiently increased. A simple theoretical model based on azimuthal ion drag was proposed to explain the cluster rotation in a constant magnetic field. In another experiments Sato et al. [53] levitated fine dust grains of $10\mu m$ diameter in configurations of DC and RF discharge plasma. A vertical magnetic field was applied to provide a vertically long cylindrical column of fine dust grains. The strength of the magnetic field was varied between 0.4 kG (weak) and 40kG (ultra strong). Fine dust grains cloud rotate in the azimuthal direction on the horizontal plane. With an increase of the magnetic field, the rotation speed increased, being followed by subsequent saturation. The rotation was induced under the condition that the inter-grain distance was small enough for the strong Coulomb coupling among the fine dust grains. Their speed and direction was controlled by varying the radial plasma potential and/or plasma profiles. Shukla [54] pointed out that dust plasma system with spatial variation of dust charge together with external or internal electric field becomes unstable. In their model Kaw et al. [55] explained the dependence of the azimuthal rotation speed on the strength of the magnetic field. They used a collisional fluid theory of magnetized ions and the associated azimuthal drag of the dust component. The effect of magnetic force on the dust grain was negligible as the dust neutral frequency was much larger than the dust rotation frequency $\nu_{dn}/\omega_d \gg 1$. The rotation was attributed to ion drag effects, where the dust component experienced a collisional drag force from the highly magnetized rotating ions.

Law et al. [56], observed rotation in plasma crystal, induced by the biased probe immersed in plasma in absence of magnetic field. It was suggested that ion wake fields generated due to the biased probe, giving rise to the space charge accumulation. In another experiment of DC discharge Vaulina et. al. [57] observed self excited vortex motion of dust grains. Self excited rotation in dusty plasma differ from rotation in presence of magnetic field, as there is both the dissipative losses of energy and the generation of energy with the help of one or more mechanisms. One possible mechanism capable of transforming the potential energy of an external electric field into kinetic energy of the dust grains is the spatial (or temporal) variation of dust charge [58]. Usually the dust grains achieve electrostatic equilibrium with respect to the plasma by acquiring a negative charge. This charge is not fixed, but is coupled self consistently to the surrounding plasma parameters. It causes instability and lead to the excitation of dust motion can develop. Vaulina et. al. [58] has also carried out theoretical and numerical analysis of dust-plasma system having macro-particle charge gradient perpendicular to the direction of gravity (g) [58]. They attributed that the major source for these vortex motion is spatial variation of macroscopic particle charge (MPC) in dusty plasma. The MPC gradient arises due to gradients in plasma parameters such as density, electron temperature, etc. Agarwal et. al. have also observed self excited dual vortex motion in un-magnetized, hollow cathode DC discharge [10,11]. The dust mass rotation was observed at spatial location where the steep density and potential gradients were present. These gradients were shallow in the direction of gravity and steep in the direction perpendicular to gravity.

5.4. Scattering of Dust Grains

Dust grains levitated in plasma interact with each other in complex ways leading to several interesting phenomena like collision [12, 63], scattering [13], transport, dust-dust attraction [59] etc. They in turn give rise to dust molecule formation [60], agglomeration [32, 61], cloud formation and ordered structure formation [7, 8, and 62]. These topics are studied in different context ranging from industrial environment to star formation. Laboratory experiments have focused on controlled dust-dust collision to study the nature of interaction of charged dust grains and to obtain electro-static charge [12, 63, and 64]. Knopka et al. [63] have concluded that interaction potential between two dust grains can be described by screened Coulomb potential. Experiments where dust grains of few tens of microns were confined showed that dust-dust attraction leads to agglomeration and growth of grains [32, 61]. Mohideen et al. [32] and Lee et al. [65], have found that dipole-dipole attraction was responsible for the formation of field aliened structure.

Several mechanisms have been proposed to explain the causes of dust-dust attraction. They include electric field induced dipole interaction [65], asymmetry of charge between leading and trailing hemispheres of a dielectric grain in the flowing plasma [66], polarization of Debye sheath around the grain by external potential [67]. Other mechanism are based on focusing of ions flow in the sheath by dust grains [68], wake potential effects in the plasma [59, 69], balance between attractive dipole-dipole field with repulsive monopole field [32, 35], shadowing effect of one dust grain on the other [70 – 72], etc. When the dust grain sizes are large (radius exceeds a few microns), there appears to be a strong intergrain attractive coupling [32, 35, 65] which leads to the formation of distinct grain column along the sheath electric field. Mohidden et al. [32] attributed this to an electric field induced dipole-dipole interaction between the dust grains. This possibility was also proposed by Lee et al. [65] by the analysis of phase diagram of Coulomb crystals. The sheath electric filed can also induce polarization on the dust grains with dipole moment $\mathrm{P} = 4\pi\epsilon_0 \mathrm{E}\mathrm{R}^3$. It is clear that the dipole moment is very sensitive to the grain size and has a cubic dependence on it. This dipole moment of dust grains leads to an additional attractive force between the aligned grains [32, 35, 65, 69, and 73].

6. Discussion and Conclusions

In this paper, various collective processes in dusty plasmas have been described. Starting from the occurrence of dusty plasmas, we have described the properties of dusty plasmas as well as discussed charging of dust grains and various forces acting on the dust particles. We have given a brief survey of experiments in dusty plasmas. The main properties of multi-component dusty plasmas compared to usual ion – electron plasmas can be compiled below –

- Dusty plasmas have additional dust particle component in comparison no “usual” electron – ion plasmas. In this sense, dusty plasmas are comparable to negative ion plasmas.
- The typical charge on the dust particles are of the order of $10^3 - 10^5$elementary charges. This variable dust charge depends on the local plasma parameters, which indirectly depend on experimental working parameters, like pressure, applied power, etc. Thus, the charge on dust particles is a dynamic variable.
- The dust mass is many orders of magnitudes larger than that of electrons and ions. Thus the dominant time scale is that of the dust plasma frequency (ω_{pd}) which is by orders of magnitude smaller($< 50\ Hz$) than that of electrons and ions leading to convenient time scales for the observation of dynamic processes. The slow time scales allow that electrons *and* ions contribute to shielding which should result in different shielding scales.
- The dust size is not negligibly small leading to surface phenomena and forces which are unimportant in “usual” plasmas.
- Furthermore, we have discussed the properties of dusty plasma containing rotating dust grains. It is found that the rotational energy of the dust grains can be coupled to plasma oscillations when the wave frequency is close to the rotational angular frequency of the dust grain.

- The study dusty plasmas can be used as a model to study different physical phenomena like new force, new types of waves, crystallization processes, phase transitions, observation of processes on the kinetic level and many more.

The authors hope that they have demonstrated why dusty plasmas have become one of the very interesting fields in plasma physics and this paper will stimulate further studies of collective processes.

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