Chapter 1

Introduction

1.1 Dusty Plasma: a review

Dust is an ubiquitous component throughout the universe. It forms dusty plasma, when it co-exists with the ionized component of matter. It exits in interstellar, circumstellar, interplanetary, circumplanetary, and cometary environments. In interstellar clouds, grains are dielectric (ice, silicate etc.) or metallic (graphite, magnetite etc.) with a dust to gas mass ratio \( \rho_d / \rho_g \simeq 6 \times 10^{-3} \) [de Angelis 1992]. In circumstellar clouds, it is found from spectral features and infrared emission that the most common grains are found to be graphite, silicates and amorphous carbon with a size distribution \( 0.05 \mu m \leq a \leq 0.2 \mu m \) [de Angelis 1992]. Alfven had suggested long before that the coagulation of dust may lead to planetesimals from which comets and planets have been formed. Recent measurements show that the solar system is full of grains of various nature, size and origin, micrometeoroids, space debris etc. The evolution of the solar system from its solar nebula stage to its present form has passed through a stage during which almost all solid matter was in the form of dust. The existence of inter-planetary dust has been known from the zodiacal light which is explained as due to the scattering, absorption and
thermal emission of sunlight by grains. Dust grains present in inter-stellar, interplanetary environments are in fact, immersed in a magnetized plasma and ultraviolet radiation environment. This leads the dust to be electrically charged and consequently coupled to the plasma by means of electrical and magnetic forces. This coupling becomes stronger as the grain size decreases.

Dusty plasma is an ensemble of dust particles immersed in a plasma consisting of electrons, ions and neutrals. A plasma containing such charged dust grains may be referred to as a dusty plasma; however, there are different regimes characterized by the relative magnitudes of three characteristic length scales, viz. the dust grain size ‘a’, the plasma Debye length \( \lambda_D \) and average intergrain distance ‘d’ \( (\approx n_d^{-1/3}) \), where \( n_d \) is the dust number density:

\[
(i) \quad a \ll \lambda_D \ll d \quad \text{and} \quad (ii) \quad a \ll d \ll \lambda_D.
\]

In the first case, the dust may be considered as a collection of isolated screened grains ("dust in plasma"); in the second case, the dust also participates in the screening process and therefore in the collective behavior of the ensemble ("dusty plasma" in real sense). [Mendis et al.1994].

Usually, the strongest force acting on dust particles in the vicinity of stars or planets is gravity or radiation pressure. However, dust particles immersed in plasma are charged and therefore, are affected by electric and magnetic fields.

The dust particle may change the properties of the plasma itself and change the dispersion relation of various low frequency plasma waves.
Dusty Plasma in Various Environment:

Dust can play an important role in fusion devices. Plasma operation and performance in fusion devices may be affected due to the presence of dust grains. These grains are often found in the bottom areas of fusion devices after operational periods. Dust is an important safety issue for ITER (International Thermonuclear Experimental Reactor) and future fusion reactors. The finely dispersed dust particles are chemically reactive and may spontaneously react with oxygen or water vapor in the case of vacuum or coolant leak. Due to thermophoretic forces and due to repetitive evaporation and condensation, dust grains may accumulate in cold areas of the device and may block spacing and fill gaps. Dust in fusion devices spans a wide size distribution from a size scale of mm down to < 100 nm. Part of the dust is ferromagnetic although no magnetic bulk materials are used for the in-vessel components. The presence of particles of size < 100 nm requires adequate measures to prevent incorporation and health damage for the people working inside the fusion devices. Redeposited layers contain significant amount of hydrogen isotopes. In future machines, this may lead to high T inventory in a form that can be liberated during a vacuum accident or opening. The large surface area and chemical activation by the nuclear decay will make the dust chemically highly reactive and reactions in case of water and air ingress have to be considered. The magnetism of significant part of the dust fraction will lead to an interaction with the magnetic fields of fusion device. It can be expected that the dust particles are repeatedly sucked into the main volume of the discharge chamber and accumulate at the inner wall around the midplane, since the field is largest there [Berk et al. 1991; Nedospasov 1989; Berkadda et al. 1994]. Particulates are a sink for electrons and will change the balance between electrons and protons in the edge plasmas. This will result in a different sheath potential and heat transmission factor, and in a different dynamics of the edge plasma. Thus, dust particles in fusion devices can play an important role and they have
widespread consequences. [Winter 1998].

Hence for future thermonuclear reactors such ITER, understanding of plasma-wall interaction is of fundamental importance. The contact of the plasma with the wall together with the enhancement of turbulence due to temperature and density gradients in the scrape-of-layer of tokamak (SOL) lead to irregular evaporation and ejection of particles from the wall which can be called “dust particles”. Turbulence in the SOL plasma can enhance the dust density flux from the wall by increasing the small scale sputtering effect. This leads to a feedback process which sustain the instability [Nedospasov 1989].

Dusty plasmas occur in a large variety of natural plasma and also present in laboratory devices. It is an ubiquitous component of cosmic plasma environment. Professor Hannes Alfven was one of the very first scientists to suggest the electromagnetic forces acting on small dust particles played an important role in the evolution of entire solar system. He recognized planetary rings, for example, as an important laboratory for studying processes that not only act today, but also shaped the evolution of the entire solar system billions of years ago [Alfven 1954].

Planetary rings have been widely studied in recent years to unravel their fine structure and to understand the dynamics of their formation and evolution. The generation, evolution and motion of spokes require the existence of a fairly dense plasma near the ring plane. Thomsen et al. [1982] and Hill and Mendis [1982] argue that the spokes consist of negatively charged dust particles. This requires presence of sufficiently dense plasma. The fly-by missions of the space-crafts (Pioneer 11, Voyager I & II) have provided detailed information about the fine structures of ring-system. The ring-disc is composed of tens of thousands of extremely narrow ringlets, some of which are eccentric (“rings within rings”). One of the most unexpected findings of the Voyager mission at Saturn was the periodically appearing, radially expanding dust clouds above the dense B-ring. The existence of “spokes” cannot be explained by gravity
alone. Successful models for the formation of spokes recognized the importance of the electromagnetic forces acting on small charged dust grains. The filamentation of a ring disc finds a natural explanation in terms of the tearing instability of the dust-ring current. The Voyager I polarimeter shows images of several strands within F-rings which are braided. The ring also contains bright clumps, knots and kinks in several places. Avinash and Sen [1996] have shown that formation of braids, kinks and filaments are consequences of electromagnetic force balance of moving grains. When plasma potential is large \((eV/T \gg 1)\) the grains experience an effective electrostatic pressure which is balanced by the “pinch” of the grain ring current. The resulting equilibrium then produce braids, kinks and filaments. Formation of these equilibria is a dynamic phenomenon which critically depends on the local plasma conditions.

Successful models for the formation of spokes recognized the importance of electromagnetic forces acting on small charged dust grains. Noting that spoke formation is a sporadic process, Goertz and Morfill proposed that such dense localized plasma columns are produced by meteor impacts with ring particles. Several studies based on dust plasma interaction have also been used to explain the sharp discontinuities observed at \(\sim 1.62R_{\oplus}\) at the inner edge of the B-ring at \(\sim 1.524R_{\oplus}\).

Horanyi et al. studied the dynamics of submicron sized dielectric grains ejected from the small Martian satellite Phobos due to micrometeoroid bombardment. They found that these grains were influenced not only by gravity but also by solar radiation pressure and Lorentz forces.

One of the most unexpected observations of the recent Ulysses mission to Jupiter was the detection of quasi-periodic streams of sub-micron-sized grains \((1.6 \times 10^{-16} \text{ g} < m_d < 1.1 \times 10^{-14} \text{ g})\) during its distant Jovian encounter. Horanyi et al. [1993] concluded that the initial source of these grains, which appear to come from the Jovian magnetosphere, are the observed volcanic eruptions on the Jovian satellite Io. They find that the Lorentz force on
these charged grains of radius \( \leq 0.1 \mu m \) is sufficient to overcome Io's gravity and inject them into the Jovian magnetosphere. The grains acquire a potential \( \sim -3V \) (outside the Io plasma torus) due to the dominance of secondary emission. The smallest grains \((a \leq 0.02 \mu m)\) remain tied to the magnetic field and tend to corotate with it. The particles in the size range \( 0.02 \leq a \leq 0.1 \mu m \) get slung out of the magnetosphere. These particles are in the correct mass range of the detected particles. Their calculated velocities \((30 \text{ km/sec} \leq v \leq 100 \text{ km/sec})\) roughly agree with the observed velocities. Thus, the Jovian ring system has a complex spatial structure. Its main ring is located at \( 1.71 R_J \leq r \leq 1.81 R_J \) with an optical depth \( \tau \sim 10^{-5} \). The small dust grains and the macroscopic bodies contribute approximately equally to the optical depth.

The comet Shoemaker-Levy-9 (SL9) produced a lot of dust while breaking apart during its close encounter with Jupiter in July 1992, and perhaps also on its final return path through the magnetosphere as its fragmented nuclei plunged into Jupiter's atmosphere in July 1994. The orbital evolution of these grains strongly depends on their size; some of them can get captured to form a new ring about Jupiter [Horanyi 1996]. This process of magnetospheric capture is a suggestion for the origin of the Jovian ring from captured small fragments of a hypothetical broken-up comet. Particles in the micron-size range from SL-9 will be strongly perturbed by radiation pressure and electromagnetic forces, and while unlike the bigger grains, they will avoid collision with Jupiter. Particles with \( a_\mu \sim 2 \) can be shown to lose energy and angular momentum during their consecutive trips through the magnetosphere and settle into circular orbits, perhaps forming a new ring around Jupiter [Horanyi 1996].

The dusty cometary environment is an ideal cosmic laboratory for the study of physical and dynamical consequences of dust-plasma interaction. The cometary dust particles, which are entrained by the gas sublimating from the
nucleus, are immersed in a plasma and radiative environment, and are thus, electrically charged [Mendis 1994]. The two tails of a comet is generally considered to be formed by dust and plasma. It is quite possible that the space between the two tails are filled with some dusty plasmas which are invisible [Saito et al.1994]. After the encounters of the Vega and Giotto probes with comets Halley and Giacobini-Zinner, much more is known on cometary dust. A large number of very small grains has been found with a size distribution of the form $n(a) \sim a^{-s}$ (s still uncertain) and the number densities $\sim 10^{-7} - 10^{-10} \text{cm}^{-3}$ [de Angelis 1992].

Presence of dust grains in interstellar clouds has been known for a long time. Reddening of the light from stars and the wavelength dependence of interstellar excitation in the visible and near ultraviolet provided the first clue of the size of the interstellar dust particles, but provide little insight into their composition. The major components of the interstellar dust are: small $\text{Mg}_2\text{SiO}_4$ particles containing $\text{OH}^-$ ions, larger $\text{Fe}_2\text{SiO}_4$ particles and thin ($\leq 50 \text{ Å}$) layers of amorphous carbon and hydrogenated amorphous carbon on these silicate particles [Duley 1988]. Many types of galaxies exhibit large luminosity in the infrared region. The continuum energy distributions are quasi-thermal, with peak flux densities more than a thousand times those in the visible light. In most cases, this emission is understood to be thermal re-radiation of dust, which has absorbed harder radiation emitted by the embedded energy source. Understanding the physical properties of interstellar dust and its global distribution in galaxies is required for understanding the energetics of galaxies [Joseph 1988]. The presence of dust grains around classical novae has been the subject of some intense study, particularly in recent years. The Infrared astronomical Satellite (IRAS) has completed a sky survey in the four bands of 12 to 100 $\mu$m, which provides a very comprehensive picture of dust emission from galaxies. A relatively cool component of dust is found to extend throughout the galactic disc [Joseph 1988].
Besides naturally occurring dust, there is now a significant component of anthropogenic dust in the terrestrial magnetosphere. Small (0.1-10\mu m) Al$_2$O$_3$ spherules are dumped into the earth’s lower magnetosphere during solid rocket motor burns used for transfer of satellites from low earth to geosynchronous flux in that size range. Although solar radiation pressure plays the dominant role of the orbital evolution of much of its dust, electromagnetic effects, as described for the more distant magnetospheres of Jupiter and Saturn, play a crucial role at the lower end of the dust mass spectrum ($a \leq 0.1\mu m$). In that case, these electromagnetic forces combined with solar radiation pressure to eliminate these grains from the magnetosphere in a comparatively short time, while significantly changing the residence time of large ($0.1\mu m \leq a \leq 1\mu m$) grains [Mendis 1994].

1.2 Charging of dust grains: existing theories

Dust grains of dusty plasma are highly charged ($z_d \sim 10^3 - 10^4$) and have a size much less than the plasma Debye length. This charge results from a balance of competing process (electrons and ion fluxes), and therefore it is not fixed. An important consequence of the dynamical charging of dust particle is the appearance of new collective wave modes and modification of plasma dielectric properties. The modes with frequencies much less than the characteristic dust charging frequency are substantially charged. The charge on the dust grains is of fundamental interest, for it allows the coupling between the fields and the particles. Dust particles can be charged by various means, for example, by photoionization or absorption of charged particles. Hence, the charge on the dust grains is not fixed, but depends on properties of the surrounding plasma, on photo and secondary emission and on field emission limitations. If such charged dust particles exist in plasma, i.e. in a conducting fluid, the interaction between the particles and externally applied electric and
magnetic fields is modified.

The evolution of the electrical charge \( q_d \) of a dust grain in plasma is described by the current balance equation:

\[
\frac{dq_d}{dt} = \sum_k I_k = I
\]

Where \( I \) is the total charging current to the grain. Contribution to \( I \) may be in various ways:
(a) electron and ion collection
(b) photo emission
(c) secondary electron emission due to energetic electron impact
(d) secondary electron emission due to energetic ion impact
(e) electric field emission
(f) thermoionic emission
(g) triboelectric emission
(h) radioactive emission of electrons and \( \alpha \) - particles.

Electron-ion collection, photo-emission and secondary electron-ion emission are most important in cosmic environment while electric field emission is important for very small grains. Friction-mediated (tribo-electric) emission is known to be important in the charging of dust in volcanic plumes, and may also have played some role in the early protoplanetary nebula.

The currents to the grains depend on the properties of both the dust grains and the ambient medium. For instance, the electron and ion collection currents depend not only on the size and shape of the grains, but also on the electron and ion velocity distribution and densities, motion of the grains relative to the plasma and the potential difference between the grain surface and the ambient dusty plasma, \((\phi_s - \phi)\). The photo-electric current depends on the electric properties of the grain, the grain surface potential, and on the photo-ionizing (uv) flux of radiation. The secondary electron emission current due to energetic
electron impact depends on the secondary emission yield, which is dependent on the grain size.

In steady state, grains may reach an equilibrium surface potential $\phi_s$ w.r.to plasma. Then

$$\frac{dq_d}{dt} = 0$$

and $q_d = c(\phi_s - \phi)$

where $\phi$ is the average potential of the ambient plasma and ‘$c$’ is the grain capacitance. The value of ‘$c$’ and $\phi$ depend on how closely the grains are packed together. For instance, when $d >> \lambda_D$, the grains may be regarded as being isolated. (Here $d$ is the inter-grain distance and $\lambda_D$ is the Debye shielding distance ). Then

$$c = c_{iso} = a \left( 1 + \frac{a}{\lambda_D} \right)$$

where $a \rightarrow$ dust grain radius and $\phi$ may be taken to be zero. On the other hand, when $d << \lambda_D$, $c$ increases slightly above $c_{iso}$ but $\phi$ approaches $\phi_s$ and consequently, grain charge becomes very much smaller than $q_{iso}$ [Mendis 1994].

1.2.1 Charging equation for isolated grains in plasma:

A dust particle in a plasma acquires electric charge collecting electrons and ions form the plasma and respond to electric forces. The charge can range from zero to hundreds of thousands of electron charges, depending on the particle size and plasma condition.

As a dust grain collects charges, it changes the electrostatic potential distribution in its environment. If a grain initially collects more electrons than ions, the developing negative potential well around it will enhance the ion flux
and lower the electron flux. The electrostatic charge on the grain that balances the fluxes is the equilibrium charge. In general, the collisional mean free path $\lambda$ is larger than the electrostatic size of the potential well, the Debye shielding distance $\lambda_D$. Hence the distribution function of the ambient plasma can be easily related to the distribution function at the surface of the dust particle.

**Electron and ion currents**

**Orbit limited theory:**

The flux of electrons and ions bombarding a dust grain, with radius $a'$ for the case $a << \lambda_D << \lambda$, give following electron and ion collection currents respectively:

$$I_e = -\pi a'^2 e \sqrt{\frac{8 T_e}{\pi m_e}} n_e \exp \left( \frac{e (\phi_e - \phi)}{T_e} \right)$$  

$$I_i = +\pi a'^2 e \sqrt{\frac{8 T_i}{\pi m_i}} n_i \left[ 1 - \frac{e (\phi_e - \phi)}{T_i} \right]$$  

**Equilibrium potential of a grain:**

When the electron and ion thermal currents are the only charging currents, the equilibrium potential of grain in a plasma with $T_e = T_i = T$ is,

$$\phi_{eq} = -\beta \frac{KT}{e}$$  

where e.g. $\beta = 2.5, 3.6, 3.9$ for $H^+$, $O^+$ and $S^+$ plasma, respectively. At this grain potential,

$I_e(\phi_{eq}) = I_i(\phi_{eq})$
Secondary electron current

Even at relatively low plasma temperatures, some of the bombarding particles can be energetic enough to ionize the material of the grain and produce secondary electrons. The escape flux of the secondary electrons represents a positive grain-charging current. The ratio of the emitted secondary electrons to incident ones is a function of the primary electron’s energy and also the material and surface properties of the dust grains.

It generally exhibits a maxima, $\delta_M$, at an optimum incident energy $E_M$, which indicates that low energy primary electrons will not produce secondaries. We assume a Maxwellian distribution of ambient plasma. Then secondary current for negatively charged grains ($\phi_s < 0$),

$$I_{sec} = 3.7\delta_M I_{oe} \exp\left(\frac{e \phi_s}{K T_e}\right) F_5\left(\frac{E_M}{4K T_e}\right)$$  \hspace{1cm} (1.5)

where

$$F_5(x) = x^2 \int_0^\infty u^5 e^{-(xu^2 + u)} du$$

For positively charged grains ($\phi_s > 0$),

$$I_{sec} = 3.7\delta_M I_{oe} \left(1 - \frac{e \phi_s}{K T_e}\right) \exp\left(\frac{e(\phi_s - \phi)}{K T_e}\right) F_{5,B}\left(\frac{E_M}{4K T_e}\right)$$  \hspace{1cm} (1.6)

where

$$F_{5,B}(x) = x^2 \int_B^\infty u^5 \exp\left[-(xu^2 + u)\right] du$$

and

$$B = \left(-\frac{x_c}{E_M/4KT_e}\right)^{1/2}$$

Photoelectron Currents:

Dust particles in space are exposed to UV-radiation. The incident high energetic photons generate photoelectrons. The escaping flux of photoelectrons
represents a positive current and is a function of the material properties of the dust particle. The photoelectric current is given as (\(\phi\) produced due to sun’s UV-radiation):

\[
I_{ph} = \begin{cases} 
\pi a^2 e f & \text{if } \phi_s < 0 \\
\pi a^2 e f \exp\left(-\frac{e\phi_s}{K T_e}\right) & \text{if } \phi_s \geq 0 
\end{cases}
\]

where

\(K T_e (\approx 1 - 3\text{eV})\) is the average energy of the photoelectrons

\(f \approx 2.5 \times 10^{10} \text{K/d}^2 \text{cm}^{-2} \text{s}^{-1}\)

\(K \rightarrow \text{efficiency factor } \sim \begin{cases} 
1 & \text{for conducting materials} \\
0.1 & \text{for dielectric materials}
\end{cases}\)

\(d \rightarrow \text{distance from the sun measured in AU.}\)

In deriving these charging currents, it is assumed that dust grains are at rest relative to the plasma, whereas in many cases, these particles have relative motion with respect to ambient plasma. For example, dust grains comprising planetary rings travel at approximately Keplerian speeds, immersed in a plasma that tends to co-rotate with the planet. In general, dust-to-plasma relative velocity is small compared to electron thermal speeds, but it might become comparable to or even exceed the ion thermal velocities so that the ion flux becomes anisotropic. A Maxwellian distribution in the plasma frame translates into a drifting Maxwellian distribution in frame fixed to the dust grain. In this case, current (ion) equation becomes:

For \(\phi_s < 0\)

\[
I_i = \frac{I_{oi}}{2} \left[(M^2 + \frac{1}{2} - \chi_i)\sqrt{\frac{\pi}{M}} \operatorname{erf}(M) + \exp(-M^2)\right]
\]
where

\[ \chi_i = \frac{e \phi}{K T_i} \]

\[ M = \frac{\omega}{\sqrt{2 K T_i / m_i}} \Rightarrow \text{relative Mach number} \]

\[ \omega = \text{dust-to-plasma relative velocity}. \]

For \( \phi_x > 0 \)

\[ I_i = \frac{I_{oi}}{2} \left[ \left( M^2 + \frac{1}{2} - \chi_i \right) \frac{\sqrt{\pi}}{M} \left[ \text{erf}(M + \sqrt{\chi_i}) + \text{erf}(M - \sqrt{\chi_i}) \right] + \left( \sqrt{\frac{\chi_i}{M}} + 1 \right) \exp \left[ - (M - \sqrt{\chi_i})^2 \right] - \left( \sqrt{\frac{\chi_i}{M}} - 1 \right) \exp \left[ - (M + \sqrt{\chi_i})^2 \right] \right] \]  

(1.9)

where

\[ I_{oi} = \pi a^2 n_i \left( \frac{8 T_i}{\pi m_i} \right)^{1/2} \]  

(1.10)

Thus, the ion current intercepted by the grains increases with \( \omega \). The charge on the moving grain tends to be more positive than on grain at rest with respect to the plasma. The electron current is not effected by the slow relative drift between the dust and the plasmas because \( \omega << v_{Te} \) where \( v_{Te} \) is the thermal speed of electrons.

**Charging of grain ensembles: Reduction of charge**

We have considered the case of a single isolated particle. This assumption is often not suitable for dusty laboratory plasmas, since they can have high particle concentrations. Several plasma physicists have shown that when dust number density is increased, the floating potential and charge of the particles get reduced, due to electron depletion on the particle [Goertz 198]. This electron depletion modifies the plasma potential. There are two competing effects
that lead to this result. One is that the capacitance of the grain increases, which tends to increase the charge and the other is that the magnitude of the grain surface potential relative to plasma potential decreases, which decreases the charge. The more important effect at high dust density arises from electron depletion, when the dust grains carry a significant fraction of the charge density in the plasma, so that much of the electron charge resides on the grain surfaces. In this case, the surface potential of the grain does not have to be as negative with respect to the plasma potential as in the isolated grain case to balance the electron and ion currents to the grain. This leads to decrease in the magnitude of the grain charge, since the charge is proportional to \((\phi_s - \phi)\).

Xu et al. has recently demonstrated experimentally the reduction the magnitude of the grain charge when the dust density is high.[Mendis 1994].

Electrostatic charging can change the physical characteristics of the dust grains. For example, the electrostatic tension might overcome the tensile strength of a grain. The growth of particles via nucleation and coagulation is generally handicapped between grains or droplets with like charges due to Coulomb repulsion. The small dust grains can be oppositely charged from the bigger ones due to the secondary and photo-electron currents that depend on plasma parameters, size or composition and hence result in enhanced growth rate.

In low-density region, photo and secondary electron production might become an important plasma source. Similarly, energetic enough plasma particles can sputter off atoms and molecules from dust grains, changing the density and composition of plasma environment.

When the Debye shielding distance in a plasma is comparable or smaller than the average inter grain distance \(\lambda_D \leq n_d^{-1/3}\), the dust particles no longer be treated as test particles, and the ensemble of electrons, ions and the dust become a real dusty plasma that exhibits unusual wave modes and instabilities. In the case of significant plasma depletion, the charge of dust particle in a cloud
of other dust particles become reduced.

The distribution of astrophysical plasma in general, is not uniform. The plasma composition, density and temperature might all exhibit spatial and temporal variations. Hence, the dust grains can have complicated charging histories. Their charge will not only depend on instantaneous plasma environment, but also on the previous charge states. In planetary magnetospheres, dust grain collect only a modest charge and the resulting electrodynamic forces acting on a centimeter-sized or bigger grains are negligible compared to gravity. However, towards the lower end of the mass distribution \( a \leq \text{few microns} \) the Lorentz force is the most important perturbation and result in significant deviation from Keplerian orbits. This range in size of dust particles is frequently represented in planetary rings, e.g. Saturn’s E-ring, Jovian ring, Neptune’s arcs are examples where significant portion of the optical path is attributed to micron-sized grains. Electrodynamic perturbations couple with other perturbations (oblateness, radiation pressure, plasma and neutral drag etc.) and can lead to unusual dynamics like transport, capture, ejection etc. [Horanyi 1996].

**Limitations of orbital motion - limited theory:**

The standard continuous charging model described above neglects the fact that the electron and ion currents collected by the particle actually consist of individual electrons and ions. The charge on the particle is an integer multiple of the electron charge, \( Q = Ne \) where \( N \) changes by \(-1\) when an electron is collected. Electrons and ions arrive at the particle’s surface at random intervals. The charge of the particle fluctuates in discrete steps (and at random times) about the steady state value \(< Q >\). [Goree 1994].

Effect of ion-trapping has been ignored in deriving the above charging theories. A particle’s negative charge creates a Debye sheath, which is an alternative potential well for positive ions. An ion can be trapped in this well when it...
suffers a collision within the particle's Debye sphere, loses energy and suffers a change in orbital angular momentum. It remains trapped there, in an orbit bound to the particle, until it is detrapped by another collision. These trapped ions shield the charged particle from external electric fields. These fields provide the particles levitation and confinement in the discharge. The effectiveness will vary with the number of trapped ions [Goree 1994].

OML theory of charging of dust grains has been derived under the condition that $a \ll \lambda_D \ll \lambda_{mfp}$ where $\lambda_{mfp}$ is the collisional mean free path between neutral gas atoms and either electrons or ions. The currents are calculated by assuming that the electrons and ions are collected if their collisionless orbits intersect in the grain's surface. The collision-effect has been completely neglected. OML theory fails if

$$\lambda_{mfp} < a \left( \frac{e\phi_s}{KT_i} \right)^{1/2}$$  \hspace{1cm} (1.11)

This provides a limitation to the use of OML theory in cases where collisional effect is not negligible. No plasma is entirely collision-free non-infinite in extent [Allen 1992].

1.3 Effect of charged dust grains on collective behavior of plasma:

Coagulation of dust grains in a dusty plasma

Coagulation is the process of sticking together of the grains that collide, in contrast to molecular condensation onto already existing grains. Horanyi and Goertz have done numerical simulation of the coagulation process in a plasma, with a model in which the grain charge is determined by plasma charging currents and secondary emissions [Horanyi et al. 1990]. Birmingham
and Northrop have included all electrostatic forces between two grains and plasma shielding. Coulomb force between the positively charged larger grains and negatively charged smaller grains enhance the coagulation rate.

Chow et al [1993] have shown that dust grains of different sizes can acquire opposite charges in warm plasmas even in the absence of changes in plasma environment. They have calculated the equilibrium potential for conducting and insulating grains immersed in both Maxwellian and generalized Lorentzian plasmas. Due to the effect of size of grains on secondary emission, they have found that insulating grains with diameters $0.01\mu m$ and $1\mu m$ have opposite polarity (the smaller one being positive) when the plasma temperature is in the range of 25-48 eV in Maxwellian plasma. Existence of different sized grains of opposite polarity - negatively charged large grains and positively charged small grains is possible in the interplanetary medium, local interstellar medium, supernova remnants etc. Both secondary emission and photo-emission may cause dust grains to acquire opposite charges in the same plasma and radiative environment, even if they have the same size, if their secondary emission and photo-emission yield vary widely. This leads to enhanced dust coagulation in certain region of the interstellar space [Mendis et al. 1994].

**Disruption**

When the dust particles acquire numerically very high potential, physical disruption of grains can occur, an opposite effect of coagulation. This is a consequence of electrostatic repulsion of like surface charges, which produce an electrostatic tension in the body. If the electrostatic tension exceeds the tensile strength of the body across any section, the body will break up across that section.

If $F_t \rightarrow$ sphere of uniform tensile strength ( obtained by integrating the component of Maxwell stress ($E^2 / 8 \pi$) normal to the plane section of one hemisphere over its surface ).
\[ F_e = \frac{q^2}{8\pi a^2} \rightarrow \text{electrostatic tension,} \]
then electrostatic distribution will occur across the section unless,

\[ F_t > F_e \quad (1.12) \]

For stability, this gives,

\[ a > a_0 \quad (1.13) \]

where \( a_0 = \frac{6.65 e|\phi|}{\sqrt{F_t}} \) (\( a_0 \) in \( \mu \text{m}, \phi \) in volts, \( F_t \) in dynes/cm\(^2\))

It is obvious from equation (1.12) that as \( a \) becomes smaller, the value of \( F_t \) required to prevent grain disruption increases rapidly. As the grain begins to disrupt electrostatically, it will continue to do so until reaching the smallest fragments for which the above macroscopic considerations apply. In that case, it can be a major obstacle for grain growth in a plasma. However, electric field emission of electrons from small grains may stop this runaway disruption. As the grain radius decreases, the surface electric field increases to such a value (\( \geq 10^7 \text{ V/cm} \)) that rapid electron emission occurs from negatively charged grains and the grain potential decreases (numerically) to a value that is no longer given by the plasma environment but rather by the size alone. Consequently, materials such as iron (\( F_t \sim 7 \times 10^{10} \text{ dynes/cm}^2 \)) are stabilized by this process against electrostatic disruption of grains, regardless of their size. Very fragile grains such as “cometary” grains (\( F_t \sim 10^6 \text{ dynes/cm}^2 \)) of very small radii (\( \sim 10\text{Å} \)) will be stable only if \( |\phi| \leq 0.15\text{V} \), which corresponds to \( T \leq 460 \text{ K} \) for a Maxwellian oxygen plasma and \( T \leq 230 \text{ K} \) for a Lorentzian oxygen plasma with \( K = 2 \).

Electric field emission effect will enable grain growth to take place in the above environments only if the grains are negatively charged. Hence, if there is sufficient UV radiation to make the grain charge positive due to photoemission, grain growth will not proceed even in low temperature plasmas.
Electrostatic disruption of dust grains may cause many interesting phenomena at comets. The discrete dust “packets” observed in the environment of comet Halley by the dust analyzers on the VEGA spacecrafts, peculiar spatial distribution of the VSG s \((10^{-20} \text{gm} \leq m_d \leq 10^{-17} \text{g})\) observed by VEGA spacecraft at comet Halley are some such examples arising due to the disruption of dust grains.

**Leviation:**

Electrostatic charging can also lead to the leviation of fine dust laying on charged surfaces. The charge \(q_d\) acquired by the grain is proportional to the projected surface area [Singer et al. 1962] and so,

\[
q_d = \pi a^2 \sigma = \pi a^2 (E_n/4\pi) = a^2 (\phi_s/4\lambda_D) = \left(\frac{a}{4\lambda_D}\right) (a\phi_s)
\]

Typically, \(a / \lambda_d << 1\), and so the charge on the grain is very much smaller than that it would acquire in free space. Mendis considered the charging of the bare cometary nucleus by the solar wind plasma and solar UV radiation at large heliocentric distances. They showed that while the subsolar point of cometary surface acquires a positive potential of \(\sim +5 \text{ V}\) due to dominance of photoemission, the nightside could acquire a negative potential. Hence, submicron-sized grains could overcome the gravitational attraction of the nucleus and levitate on the nightside of the comet, even when they had a deficit of just one electron charge. The nightside potential is highly modulated by the solar wind speed and hence, grains are more likely to be electrostatically levitated and subsequently blown off the dark surface when the comet intercepts a high speed solar wind stream. Flammer et. al. [1992] have shown that sporadic brightness variations of comet Halley observed inbound at large heliocentric distances \((\sim 8-11 \text{AU})\) is one of the examples of this effect. A large brightness increase of comet Halley at a heliocentric distance \(\approx 14.3\)
AU has been attributed to a solar-flare generated shock-wave moving at a speed $\sim 750$ Km/sec at that distance [Intrilligator et al. 1991].

1.4 Waves in dusty plasma:

Collective waves in plasma perturbate the process of dust charging, which in turn, affects the dielectric properties of dusty plasmas. The influence is mainly important for low-frequency waves (i.e. waves with frequencies much less than the so-called charging frequency). [Tsytovich et al. 1993].

When $a << d << \lambda_D$ ('d' is the inter-grain distance), the charged dust grains may be considered as point particles, similar to multiply charged positive or negative ions. Dust particles can be considered as another component of plasma. However, it is different from negative ion or two-ion component plasmas in several aspects:

i) Charge to mass ratio of dust grain is generally smaller than that of ions. Typical frequencies associated with the dynamics of dust grains are very low compared with typical ion wave frequencies in standard electron-ion plasmas.

ii) The grain charge depends on both the properties of dust particles and the ambient plasma and radiative properties. Hence, the charge to mass ratio can differ in different environments even for a grain of fixed size and electrical properties.

iii) It has been observed that dust grain generally in space plasmas have a size distribution, with the number density of grains generally given by a power law: $n_d \, da \propto a^{-p} \, da$

where p varies from $\sim 0.9$ to 4.5 in various space and astrophysical environments. [Havnes et al. 1990]. Since the dust mass $m_d \propto a^3$ and the dust charge $q_d \propto a$, the frequencies associated with the dust grains, such as dust plasma frequency and gyrofrequency may be continuous variables.

The dynamics of three-component plasma comprising of electrons, ions
and charged dust particles is governed by the equations of continuity and
momentum coupled with Maxwell's equation as given by,

\[
\frac{\partial n_\alpha}{\partial t} = -\nabla \cdot (n_\alpha \vec{v}_\alpha) \quad (1.14)
\]

\[
n_\alpha m_\alpha \left( \frac{\partial}{\partial t} + \vec{v}_\alpha \cdot \nabla \right) \vec{v}_\alpha = -\nabla P_\alpha + q_\alpha n_\alpha \left( \vec{E} + \frac{\vec{v}_\alpha \times \vec{B}}{c} \right) \quad (1.15)
\]

For expressing overall charge neutrality in plasma, quasineutrality condi­
tion is used:

\[
Z_i n_i + \epsilon_d Z_d n_d = n_e \quad (1.16)
\]

Where \( \epsilon_d = 1, -1 \) for positively, negatively charged grains respectively. The charging equations given by Orbital Motion Limited theory is used when fluctuation of charge on dust grains of considered. In equation (1.14) and (1.15), \( n_\alpha, \vec{v}_\alpha, m_\alpha \) and \( P_\alpha \) are the density, fluid velocity, mass and pressure of each species \( \alpha \), where \( \alpha = e, i, d \) for electrons, ions and dust grain respectively. The dispersion relation for the propagation for a particular type of wave can be obtained by solving these equations.

The presence of dust grains modify the usual modes in an electron-ion
plasma. Several new modes may arise in low frequency and low phase velocity
regimes in presence of the dust grains. In presence of charged dust grains,
\( n_e \neq z_i n_i \). Ion modes can be modified due to this charge imbalance be­
tween electrons and ions in the equilibrium state. Dust particles contribute to
the dispersion relation through the charge neutrality condition. When dust dy­
namics are included in momentum and continuity equation, new low frequency
modes associated with the response of dust grains can arise.

The linear dispersion relation for ion-acoustic waves is modified due to the
presence of charged dust grains. In the phase velocity regime where electron
inertia is negligible i.e. \( v_{ta}, v_{ti} \ll v_{ph} \ll v_{te} \) where \( v_{ta} \) are thermal speed of the species \( \alpha (= e, i, d) \) and \( v_{ph} = \frac{\omega}{k} \) is phase velocity. In the limit of very large dust mass, the dispersion relation for dust-ion-acoustic waves in a plasma with electrons, singly charged ions and charged dust is

\[
\omega^2 = \delta \frac{k^2 c_s^2}{1 + k^2 \lambda_{De}^2}
\]

where \( \delta = n_{td} / n_{co} > 1 \) for negatively charged dust.

\( c_s = \left( \frac{kT_i}{m_i} \right)^{1/2} \) is ion-acoustic speed.

Since the phase velocity of this mode for long wavelengths (i.e. \( k\lambda_{De} \ll 1 \)) is \( v_{ph} = \left( \frac{4kT_i}{m_i} \right)^{1/2} \), the dust acoustic mode can exist as a normal mode of the system even for \( T_e = T_i \) as long as dust grains carry most of the negative charge in the dusty plasma, i.e. \( \delta \gg 1 \), because in that case Landau damping is very small. This is in contrast to the electron-ion plasma, where \( T_e \gg T_i \) is required for propagation of ion-sound waves. This mode may be relevant in astrophysical situations where the plasma is isothermal but where dust can carry much of the negligible charge, such as in the F-ring of Saturn.

In the lower phase velocity regime \( v_{td} \ll v_{ph} \ll v_{ti} \), the presence of dust can lead to a new dust-acoustic wave associated with the grain dynamics. [Rao et al., 1990]. Assuming that electron and ion inertia are negligible in this velocity regime and that the electrons and singly charged ions are in Boltzmann equilibrium, and considering dust fluid equation, the dispersion relation for the dust-acoustic wave is

\[
\omega^2 = Z_d \left( \delta - 1 \right) \frac{m_i}{m_d} \frac{k^2 c_s^2}{\left( 1 + k^2 \lambda_{De}^2 + \delta T_e/T_i \right)}
\]

for negatively charged dust grains with \( \delta > 1 \). The electrons and ions provide the pressure while the dust mass provides the inertia.

Thus, Rao et al. [1990], have studied the long-wavelength low-frequency
collective oscillations in a dusty plasma. They have considered modes in which
the dust particle dynamics is crucial, rather than modes which are simply af-
tected by the dust. They have considered the collective motion of the nega-
tively charged dust particles in the background of hot electrons and ions in
thermodynamic equilibrium. They have shown the existence of a new type of
sound wave, viz. the dust-acoustic waves. The phase velocity of linear waves
is approximately given by \((n_{d0} z T_e / n_{i0} m_d)^{1/2}\) where \(n_{d0}, z\) and \(m_d\) are
number density, charge and mass of the dust particle. \(T_e\) is the electron
temperature and \(n_{i0}\) is the ion density.

In a magnetized, homogeneous dusty plasma, the presence of charged dust
can similarly affect electrostatic waves such as acoustic waves, Electrostatic Ion
Cyclotron (EIC) waves and lower hybrid waves. There are two ion-acoustic
waves and two EIC waves associated with the positive ions and the negative
dust grains. For negatively charged dust, frequencies of both acoustic waves
increase with dust density as does the frequency of the positive ion EIC waves.
For positively charged grains, the frequency of the ion-acoustic mode decreases
with increasing dust density, while the frequency of ion EIC mode approaches
the ion gyrofrequency as \(n_d\) increases.

The dispersion relation of the lower hybrid mode in the frequency regime
\(\Omega_d, \Omega_i \ll \omega \ll \Omega_e\), is also modified by the presence of charged dust. In
the limit \(m_d \to \infty\) in a dense plasma with \(\omega_{pe}^2 / \Omega_e^2 \gg 1\), the lower
hybrid wave frequency is

\[
\omega^2 \approx \delta z_i \Omega_e \Omega_i
\]

which increases as the negative dust density increases.

The dispersion properties of a low frequency electromagnetic waves, viz.
Alfven waves, magnetosonic waves are also influenced by the presence of dust
grains. The Alfven wave spectrum in the cold plasma in very low-frequency
regime \(\omega \ll \Omega_d\) becomes
\[ \omega^2 = \frac{k^2 v_A^2}{1 + (v_A/C)^2 + \left(\frac{n_{d0} m_d}{n_{i0} m_i}\right)} \]

where the usual Alfven speed is

\[ v_A = \left( \frac{B^2}{4 \pi n_{i0} m_i} \right)^{1/2} \]

Shukla et al. [1992] studied the effect of negatively charged dust grains on electrostatic drift waves in homogeneous magnetizes low \( \beta - \text{plasma} \) using a multifluid analysis. The dynamics of negatively charged dust grains modify the dispersion property of the usual electrostatic drift waves, and lead to appearance of new low frequency dust drift waves in the regime \( \omega \ll \Omega_d \). [Mendis et al. 1994].

Thus an important consequence of the dynamical charging of dust particles is the appearance of new collective wave modes and modification of the plasma dielectric properties. The modes with frequencies much less than the characteristic dust charging frequency are substantially changed. For a dust density exceeding some critical value, drift modes can be actively affected by dust.

Till now, very few laboratory experiments have been done, where waves or modes in dusty plasma have been detected. Chu [1994] reported a very low frequency ( \( \sim 12 \text{ Hz} \) ) modes with a wavelength of about 0.5 cm, which they detected in the motion of their strongly coupled charged grains. Based on the apparent phase velocity of 6 cm/sec in that experiment, D' Angelo has suggested that the fluctuations were a dust-acoustic mode. Praburam and Goree [1996] have reported the experimental observations of very low-frequency macroscopic modes in a laboratory dusty plasma. They have observed a phase velocity which is comparable to the dust thermal speed, which is suggestive of an acoustic wave. The mode might also be an ionization wave. In their experiment, they saw that the glow was enhanced profoundly in a localized
region that rotated synchronously with the void in the dust cloud. Glow in a gas discharge is produced by electron-impact excitation of neutrals by the same fast electrons that produce ionization. The modulation in the glow indicates that the nonlinear dust void was linked to a time-varying fast electron component.

In dusty plasma, the surface recombination would be distributed throughout a cloud of dust in plasma. Local electric fields might be generated in non-neutral boundaries between the dusty and clean plasma regions, and these would push the dust cloud around. The electron temperature may increase with dust density, which leads to a higher ionization rate. Thus, a moving dust cloud would cause a propagating temperature and ionization wave. Such an ionization wave may be responsible for the great void mode observed.

Barkan et al. have observed the current driven electrostatic ion cyclotron (EIC) waves in a dusty plasma laboratory experiment [1995] which verifies the theoretical prediction made by D'Angelo in 1990, that EIC waves are possible plasma modes in dusty plasmas.

Thus the presence of static charged dust grains modifies the existing plasma wave spectra. Bliokh and Yaroshenko [1985] studied electrostatic waves in dusty plasma and applied their results in interpreting spoke-like structures in Saturn's rings. It has been shown both theoretically and experimentally that the charge dynamics of dust grains introduces new eigen modes. The dust-acoustic mode, where dust particle mass provides the inertia and the pressure of electrons and ions give rise to the restoring force, is one of them. Rao et al. have first reported theoretically the existence of extremely low phase velocity (in comparison with the electron and ion thermal velocities) dust-acoustic waves in dusty plasma. The laboratory experiments of Barkan et al. and D'Angelo have conclusively verified this theoretical prediction of Rao et al. and reported some nonlinear features of dust-acoustic waves.

Motivated by experimental observations [Barkan et al. 1995; D'Angelo 1995]
of these low-phase velocity dust-acoustic waves, a number of investigations have been made to study nonlinear properties of these dust-acoustic waves. Bharuthram et al. [1992] investigated the formation of large amplitude ion-acoustic solitons in a dusty unmagnetized plasma with negatively charged grains, cold ions and Boltzmann distributed electrons. The presence of dust grains was found to lead to appearance of (negative potential) solitons. Nonlinear ion-acoustic waves may be relevant to the formation of an electrostatic shock inside the ionopause at comet Halley. Rao et al. [1990] showed that dust-acoustic waves could also propagate nonlinearly as solitons of either negative or positive potential in a three component plasma with electrons, ions and negatively charged cold dust grains. Verheest [1992] extended the latter analysis to a multispecies dusty plasma, allowing for both hot and cold electrons and a number of cold dust grains species, and found also that both refractive and compressive solutions could propagate. Meuris and Verheest have studied [1992] nonlinear magnetosonic waves propagating perpendicular to an external magnetic field in a warm dusty plasma with polytropic pressure.

1.5 Instabilities in plasma in presence of dust grains

The presence of charged dust grains in plasma can both modify the behavior of usual plasma instabilities and lead to the appearance of new instabilities. Dust-grains are subject to non-electromagnetic force such as gravity, friction or radiation pressure and hence new source of free energy may arise that drive instabilities, including relative drifts between the charged dust and the lighter plasma particles in cosmic dusty plasma environment. The dust grains in planetary rings move azimuthally around the planet with a speed between the Kepler and corotation speeds, while the plasma ions and electrons tend to corotate with the planet; this leads to a relative azimuthal drift between dust
grains and plasma.

Different types of instabilities in dusty plasma have been widely studied. Havens [1988] used a kinetic analysis to study streaming instabilities in a cometary environment where there is a relative drift between the cometary dust and the solar wind plasma flow, with flow speed in the range $v_{te} > u > v_{di}$. It was found that an instability driven by streaming dust in a three-component unmagnetized dusty plasma require small dust velocity dispersion and that the presence of a sufficiently high neutral density could quench the instability due to ion-neutral or electron-neutral collisions. The conditions for growth were found to be more probable for comets at large distances from the sun. Two stream instabilities driven by either ion or dust beams in an unmagnetized dusty plasma have also been studied by Bharuthram et al. [1992], who found that the dust grains affect both growth rates and ranges of drift speeds for which instability occurs.

The Kelvin-Helmholtz instability can occur in a plasma when there is a gradient in the fluid flow speed between adjacent fluid layers, as happens in the cometary environment [Ershkovich et al. 1986]. D' Angelo and Song considered [1990] the effect of either negatively or positively charged dust on the Kelvin-Helmholtz instability in a magnetized, low $\beta$ plasma with shear in the ion field-aligned flow, using a multifluid analysis. The dust was assumed to be immobile and of uniform mass and charge. The charged dust grains change the critical shear for the onset of instability from that in an electron-ion plasma, where the relative speed between adjacent flows of the order of the ion sound speed is required for instability. The critical shear increases with dust charge density in a plasma with negatively charged grains and decreases with dust charge density in a plasma with positively charged grains. D' Angelo first considered [1965] K-H instability due to transverse shear in the field-aligned flow in a fully ionized plasma. Bharuthram and Shukla have examined the K-H instability in a magnetized dusty plasma and found that the nonlinear
stationary state of the K-H instability in dusty plasmas can be represented as coherent dipolar vortex structures [Bharuthram et al. 1992]. Rewat and Rao [1993] investigated K-H instability in magnetized dusty plasma driven by shear flow in dust fluid. It is found that the relative velocity between adjacent layers of dust fluid should be of the order of the dust-acoustic wave phase speed in order to excite the K-H instability. Singh et al. [1998] have examined K-H instability by considering the effect of the dust charge fluctuations in the dusty plasma. The transverse shear in the flow parallel to the magnetic field is considered. The instability is found to grow for limiting wave numbers for a particular value of shear velocity. The effect of adiabatic dust plasma pressure enhances the growth rate of instability. For dense plasma, it is found that growth rate of the instability is affected by the presence of dust charge fluctuations.

Rosenberg [1993] investigated ion-acoustic and dust-acoustic instabilities, using a standard Vlasov analysis for a dusty unmagnetized plasma with electrons, ion and dust of uniform mass and charge. When the electrons have a weak drift \( u \) in a range \( v_{th} < u < v_{te} \), dust ion-acoustic waves can be excited under suitable condition if . For example, it has been shown that this instability is particularly relevant to cosmic plasmas, where generally it is assumed that \( T_e \sim T_i \), in environments where dust carries much of the negative charge. The ion-acoustic instability has often been invoked to provide anomalous resistivity in both laboratory and space plasmas. Since the electron and ion temperatures may be comparable in various cosmic environments, the standard ion-acoustic instability would not be applicable for such environments. However, in dusty plasma, if the dust carries much of the negative charges in the plasma, dust ion-acoustic modes could be driven unstable by electron drift even in an isothermal plasma. One such example is the evolution of very weakly ionized proto-stellar clouds. Dust-acoustic instability may be realized in planetary rings beyond the corotation radius where the electrons
and the ions corotate with the planet, while the dust grains move with a slower speed intermediate between the Keplar and corotation speed.

Low frequency drift instabilities in dusty magnetized plasma were investigated by Krall and Rosenberg [1996], with negatively charged grains in which there is a local electron density gradient which is opposite in sign to the dust density gradient. Frequencies less than the ion gyrofrequency but much longer than the dust gyrofrequency are considered. They have considered the application of these instabilities to spoke regions in the B-ring of Saturn in the vicinity of the synchronous orbit. The ring edges in the spoke region appear to be unstable to this instability. Another possible application may include future artificial dusty plasma experiments in the earth’s ionosphere using space shuttle exhaust [Burnhadt et al. 1995].

Ballooning modes are known in the magnetic fusion literatures as pressure driven instabilities. Such modes may be responsible for the plasma depletions [Horanyi et al. 1991] observed by Voyager II in the Javian magnetosphere. Shukla et al. [1998] have recently studied about the linear and nonlinear properties of drift-ballooning modes in the presence of an equilibrium electric field and stationary charged dust grains. It is found that the presence of these two contribute to the stability of the ballooning mode. It is shown that the nonlinear coupling between finite amplitude drift-ballooning modes give rise to different types of coherent vortex structures, which can affect the transport properties of an inhomogeneous magnetized plasma.

Tsytovich et al. have studied about influence of dust on drift instability in edge tokamak plasma. They have shown that the new type of drift instability is generated in presence of dust grains. The growth rate of this instability is found to be comparable or much larger than the usual drift instability, even for low dust density. This new instability may be a cause for increase of anomalous diffusion. The phase shift between the charge density on the dust and particle density variation in the drift modes lead to onset of this new type
of instability. It has a very low critical value of characteristic dust charge parameter. Whether this critical value is really exceeded in the tokamak SOL plasma is an experimental question.

Compared to theoretical progress, very few experiments have been done on instabilities in dusty plasma. Barkan et al. [1995] have observed in a laboratory dusty plasma, the current driven electrostatic ion cyclotron (EIC) instability. D'Angelo [1990], Chow and Rosenberg [1995] predicted that presence of negatively charged dust in plasma makes it more unstable to the EIC instability, lowering the critical drift of electrons along the magnetic field lines. The observations made by Barkan et al. agree with the theoretical predictions of Chow and Rosenberg concerning the enhancement of instability of the dust.

Merlino et al. [1998] have reported about the theoretical and experimental studies on low frequency electrostatic waves in plasmas containing negatively charged dust grains that they have done: Laboratory experiments on ion-acoustic waves and electrostatic ion-cyclotron waves confirm that these modes are more easily excited in a dusty plasma with negatively charged grains. The dust-acoustic (DA) mode was observed in a dusty plasma in which the charged grains were levitated by an electric field. The measured (experimental) dispersion relation agreed well with the theoretical relation taking into account the effect of dust-neutral collisions. Recently a current driven electrostatic dust cyclotron instability in a collisional plasma was analyzed by D'Angelo using a four-fluid model. The conditions for excitation of the EDC mode in both laboratory plasmas and in cometary dusty plasma environments were obtained.

### 1.6 Formation of dust plasma crystals

Plasma crystals represent a unique bridge connecting the fields of plasma and condensed matter physics. Plasma crystals consist of micrometer sized
particles trapped in the space charge sheath of magnetron or parallel plate rf-discharges, where the particles form flat, nearly two-dimensional ordered structures. Dust particles in plasmas can form a coulomb lattice. Colloidal particles become charged when placed in a low-temperature radio frequency plasma, and under certain conditions, group together in the form of stable hexagonal lattices several layers thick, with well defined intergrain separations. Dust plasma crystals have recently been produced in experiments in a number of laboratories [Goertz et al. 1998]. For dust crystallization to occur, there should exist an efficient mechanism for cooling of the dust plasma component. It is found that the excitation of collective plasma modes during collisions between the grains may serve as the required cooling mechanism [Lee et al. 1997]. The excitation of dust sound waves is found to be most efficient. The cooling of dust grains via the excitation of collective plasma modes be even more efficient than that due to collisions with neutral particles. Dust grains acquire a considerable charge (upto $10^4 - 10^5$ electron charges) in a plasma, and the intensity of their interaction can be higher than the intensity of the interaction between atoms and ions by many orders of magnitude. For this reason, dust grains can be involved (instead of atoms) in the crystallization processes in a plasma, in which a considerable grain charge is maintained by ion fluxes on the grain surfaces.

Under varying conditions the crystal sometimes appears as deformed and oriented three-dimensional close-packed lattices of bcc, fcc or hcp type, but mostly as a triangular array of vertical chain of particles. Lee et al. [1997] have established the stability of the lattices against excitations due to compression (i.e. aspect ratio variations) and vibration (i.e. phonons or charge density waves).

It is generally recognized that charged dust grains in stationary gas discharges attract Debye clouds of opposite charge, and, therefore interact via a screened coulomb potential. Lattice structures can form when the particle's
electrostatic interaction potential energy exceeds the thermal kinetic energy. [Ikezi 1986].

The necessary condition for coulomb lattice to form is that the ratio between the coulomb energy and the kinetic energy of a charged particle system, \( \Gamma = (q_d^2/d)/T \) exceeds a critical value, \( \Gamma_c \approx 170 \) i.e. \( \Gamma > \Gamma_c \) where \( q_d \) is the charge on the particle and ‘d’ is the interparticle distance, \( T \) is temperature. Like the colloidal lattice, this type of particle crystal can be observed in the laboratory plasmas using both optical microscopy and light scattering [Ikezi et al.1998].

The experiments on the formation of artificial dust crystals are drawing much interest because of the possibility that new artificial materials can be produced whose properties are easy to control externally. New materials can be treated in which the binding energy is much larger than that in ordinary materials. Complex self-organization processes accompanying dust crystallization can be observed directly with the help of optical techniques [Goree et al.1998].

1.7 About the thesis

It has already been mentioned that dusty plasma is emerging as an important field of research in plasma physics. Theoretical and experimental studies are going on to explore various phenomena in plasma enriched by the presence of dust grains. The characteristic that distinguishes dusty plasma from other multi-component plasma is the charge fluctuation of dust grains. It is this charge-fluctuation accompanied by heavy mass on dust grain that causes modification of normal plasma mode, transport properties as well as give rise to various instabilities. Dusty plasma being ubiquitous in nature, it is quite important to study various properties and new phenomena arising in plasma.

In this thesis, our objective is to study some fundamental properties like diffusion, relaxation process in dusty plasma and charging mechanism of dust
grains via random motion of ion and electrons in plasma in various environments. A study has also been made on the effect of grain charge on the collective behavior of plasma viz. wave propagation, new plasma modes and instabilities. In chapter 2 of this thesis, we present theoretical study of transport properties of dusty plasma. Calculation of transport co-efficients of dusty plasma is critical for the understanding of plasma processing, plasma etching, synthesis of submicron particles etc. For calculating the transport co-efficients we have followed usual approach for calculating transport co-efficient outside the debye sphere i.e. in the region \( e\Phi/T < n_0^{-1/3} < \lambda_D \). Even in this region, there is modification to the usual transport co-efficient. Inside the debye sphere \( n_0^{-1/3} < e\Phi/T < \lambda_D \), the electric field becomes very strong and in this region, we have followed the strong field approximation of Chapman and Enskog (Smirnov, 1981) for calculating the transport co-efficients. We have discussed the latter method in Chapter 3. In the same chapter, we present a theoretical model of charging of dust grains in plasma where ionization rate is very low. This theory may be applicable in the region where collisional mean free path is comparable or smaller than the Debye length. In the last decade, stress has been mainly given in investigating collective modes of dusty plasma and little attention has been paid on the formulation of kinetic equation for charging of dust grains in plasma. Our theoretical model may give some light in this regard. The fluctuation of charge of dust grains affects the collective behavior of plasma.

In chapter 4, we present a study on the propagation of shock wave associated with ion- acoustic like mode in dusty plasma. Using the reductive perturbation method, we investigate the existence of shock wave in presence of dust charge fluctuation in dusty plasma. The charge fluctuation is found to play a major role in observing the shock wave in this case [Das et al. 1997]. Parametric decay instability is considered to be an important topic because of its role in anomalous heating of plasma, such as lower hybrid wave reso-
nance heating, laser heating etc. There has been considerable interest in the rf heating of tokamak plasmas with pump frequency near the lower hybrid frequency. In this frequency range, ions are directly heated by the pump through a nonlinear Landau damping and indirectly through the excitation of parametric instabilities, which in turn give rise to anomalous heating of ions. In chapter 5, we investigate the parametric decay of lower hybrid waves into ion-cyclotron and dust-acoustic waves. The physical mechanism underlying this nonlinear instability is the usual resonant three wave interaction, in which a constant amplitude wave couples to a low frequency wave and generates a high frequency mode. The high frequency waves again beat together and give rise to low frequency mode. Study of parametric instability in dusty plasma may play a major role in cloud heating.

In chapter 6 of this thesis [Schamel et al.2000], we consider the effect of trapped dust particles on the propagation of electrostatic dust modes in the dust thermal speed range, and show that there exists a new class of stationary, nonlinear modes over a wide range of dust fugacity. It is shown that these modes exist due to a distorted distribution of dust particles trapped in the wave field. They are a consequence of nonlinearity and lie outside the realm of standard linearized wave theory and it is true even in the infinitesimal amplitude limit.