Dusty plasmas: from Saturn’s rings to semiconductor processing devices

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ABSTRACT
Dusty plasmas are plasmas containing solid particles in the size range of about 10 nm—10 μm. The particles acquire an electrical charge by collecting electrons and ions from the plasma, or by photo-electron emission if they are exposed to UV radiation. The charged dust particles interact with the electrons and ions, forming a multi-component plasma. Dusty plasmas occur in a number of natural environments, including planetary rings, comet tails, and solar nebulae; as well as in technological devices used to manufacture semiconductor chips, and in magnetic fusion devices. This article focuses on the physics underlying dusty plasmas, which are studied by plasma physicists, aeronomists, space physicists, and astrophysicists. The article begins with an introduction explaining what we mean by a dusty plasma, where they are found, and a summary of their basic properties. The article then presents the fundamental physics of dust charging, forces on dust particles, a description of devices used to produce dusty plasmas, strongly coupled dusty plasmas, collective phenomenon (waves) in dusty plasmas, magnetized dusty plasmas, and the emerging technologies based on dusty plasmas. It concludes with a few perspective comments on how the field has developed historically and the prospects for future advances.
1. Introduction: what is a dusty plasma and where do you find them?

I began a talk at the Fourth International Conference of the Physics of Dusty Plasmas (Orléans, France, 2005) [1], with the comment that all plasmas are dusty plasmas\(^1\) – plasmas which contain charged micron-sized dust particles. This admittedly exaggerated statement\(^2\) was intended to emphasize the broad range of environments in which dusty plasmas are found, including:

(a) the Earth’s upper atmosphere (mesosphere, noctilucent clouds),
(b) the solar system (the Moon, comets, planetary rings),
(c) the solar dust corona,
(d) the interstellar medium,
(e) solar nebulae,
(f) volcanic clouds,
(g) semiconductor processing tools,
(h) magnetic fusion devices (tokamaks),
(i) rocket exhaust,
(j) flames,
(k) thermonuclear fireballs.

(a) – (f) are examples of naturally occurring dusty plasmas\(^3\), while (g) – (k) are examples of man-made systems in which dust particles are present in (at least partially) ionized media.\(^4\) Representative plasma and dust parameters for some of the examples mentioned above are given in Table 1. These examples reveal the interdisciplinary nature of dusty plasma research and the purview of diverse scientific communities such as astrophysics, space physics, plasma physics and applied physics. What is most fascinating is the degree to which phenomena occurring in a Q-machine uses contact ionization on a hot (2300 K) W plate to produce a Cs\(^+\) or K\(^+\) plasma. These very distinct environments are rooted in similar physical processes. Some

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**Table 1. Parameters for various dusty plasmas.**

|                  | Electron density \((\text{cm}^{-3})\) | Electron Temperature \(\text{(eV)}\) | Particle density \((\text{cm}^{-3})\) | Particle size \((\mu\text{m})\) |
|------------------|----------------------------------------|-------------------------------------|-------------------------------------|--------------------------------|
| Noctilucent clouds | \(10^3\) | 0.01 | 10 | 0.1 |
| Saturn’s F ring   | 10 | 10–100 | 10 | 1 |
| Halley’s Comet    | \(10^4 – 10^6\) | 0.1–1 | \(10^2 – 10^4\) | 0.01–10 |
| Flame             | \(10^{12}\) | 0.2 | \(10^1\) | 0.01–0.1 |
| Moon              | 500–1000 | 0.1–5 | 5000 | 0.3–0.7 |
| Rocket exhaust    | \(10^{13}\) | 0.3 | \(10^8\) | 0.5–1 |
| Semiconductor processing tool | \(10^9\) | 2–5 | \(10^7 – 10^8\) | 0.01–1 |
| Discharge dusty plasma | \(10^8 – 10^{11}\) | 1–4 | \(10^7 – 10^6\) | 0.5–10 |
| Q-machine dusty plasma | \(10^8 – 10^{12}\) | 0.2 | \(10^7 – 10^6\) | 1–5 |
| Thermonuclear fireball | \(10^{14}\) | 1 | \(10^8\) | 1 |
examples of ostensibly unrelated phenomena with some connection to dusty plasmas will be pointed out in this article.

The field of dusty plasmas emerged as a robust subdiscipline in 1990s due in part to the approximate confluence of observations in three separate disciplines – applied plasma physics (plasma processing [2])\(^5\), space physics (the discovery of the spokes in Saturn’s B ring\(^6\)), and magnetic fusion (dust in tokamaks\(^7\)).

Although a great deal of theoretical work on dusty plasmas had been performed prior to 1990, the last decade of the 20\(^{th}\) century saw the introduction of laboratory experiments dedicated to understanding dusty plasma physics. Various plasma devices were invented in that dust particles could be introduced into a plasma in order to investigate the characteristics and behavior of charged dust in a plasma. The growth in experimental work on dusty plasmas is reflected by the increasing number of such papers presented at international conferences on dusty plasmas. In one of the earliest workshops on dusty plasmas (Capri, Italy 1989), there were no experimental papers presented.\(^8\) Ten years later at the Second International Conference on the Physics of Dusty Plasmas (Hakone, Japan), over 40% of the papers were experimental. More recent conferences

\[\text{Figure 1. Schematic diagram of the GEC RF reference cell [3]. Here the device is operated in the symmetric mode, in which the rf power is applied symmetrically across the electrodes. Depending on the application, the device can also be operated in the unsymmetric mode, in which the upper electrode is grounded, and the rf is applied to the lower electrode through a blocking capacitor. The device can also be operated without the upper electrode, with the walls grounded and the power applied to the lower electrode.}\]
have seen a nearly even split between theory and experiment in dusty plasmas, and roughly tenfold increase in the number of participants compared with the Capri Workshop.

The mutual needs of the basic and applied plasma physics communities to understand the behavior of dusty plasmas led to the adoption of an experimental platform (the Gaseous Electronics Conference, GEC RF reference cell [3]) in which dusty plasmas could be produced and studied. The GEC reference cell, shown schematically in Figure 1, was modeled after devices used for plasma-based semiconductor processing. It consisted of two 10.2 cm diameter circular parallel plates separated by 2.54 cm and powered by a 13.56 MHz RF oscillator with power levels up to 100 W. This system was used to produce a plasma discharge using various gases in the pressure range of 1 – 100 Pa. The generic parallel plate RF discharge device is used by several groups around the world to investigate the properties of dusty plasmas, and many important dusty plasma discoveries were made in these devices; some of these will be discussed later in this paper.

The term dusty plasma generally applies to situations in which there is a relatively large density of dust grains in the plasma so that the dust interacts collectively with the plasma.9 This is in contrast to situations in which there are just a few dust grains in the plasma, so there would be no discernable effects on the plasma.10 The term dusty plasma implies that the plasma affects the dust and in turn, the dust affects the plasma. The plasma alters the dust by charging it, and as a result, the plasma electrons may be substantially depleted. For example, in astrophysical environments, the presence of charged dust can affect the conductivity of the plasma, which in turn can affect magnetic fields that are generated by plasma currents. Mestel and Spitzer [4] argued that dust plays a crucial role in star formation in magnetic clouds, since the magnetic pressure in the cloud inhibits gravitational condensation. The attachment of electrons to dust grains lowers the plasma density facilitating the slippage of plasma relative to the magnetic field, thereby lowering the magnetic energy and allowing the cloud to break up into stars. Cosmic dust grains may be physically altered due to electrostatic disruption, as first pointed out by Öpik [5] and further analyzed by Mendis.11

The extent to which the charged dust particles interact with each other depends on the value of the ratio \( d/\lambda_D \), where \( d \sim (3/4\pi n_d)^{1/3} \) is the inter-particle spacing, \( n_d \) is the dust number density, and \( \lambda_D \) is the Debye shielding distance.12 For \( d/\lambda_D > 1 \), the particles are effectively shielded by the plasma and act as isolated particles, while for \( d/\lambda_D < 1 \), the shielding is incomplete, so the particles see each other and behave collectively.

The mass and charge are the most important properties of a dust particle in a plasma, and both depend on its size, although in different ways.
Assuming spherical grains of radius $a$, its mass is $m_d = 4\pi \rho a^3 / 3$, where $\rho$ is the mass density of the dust material. For a 1 $\mu$m diameter silica dust grain, $m_d \approx 10^{-15}$ kg, roughly a trillion times higher than the proton mass. The gravitational force (weight) of the electrons and ions in a laboratory plasma is negligible compared to the electromagnetic forces. However, for a typical 1 $\mu$m diameter dust grain having an equilibrium charge $|q_{d,eq}| \approx 2000e$, the gravitational force $mg \approx 10^{-14}$ N, is comparable to the electric force $q_{d,eq}E$, for $E < 1$ V/cm. The negatively charged dust particles in a parallel-plate RF device are levitated in a few horizontal layers just above the lower (negative) electrode, where the downward time-averaged electric field is large enough to balance their weight. To produce extended 3D dusty plasmas, researchers have installed dusty plasma devices on board the International Space Station, taking advantage of the microgravity conditions afforded by an orbiting platform [6] or on aircraft executing parabolic trajectories that provide a few seconds of microgravity conditions.

As we will discuss in more detail in a subsequent section, a dust particle does not collect equal numbers of positive and negative charges from the plasma, so it has a net charge, which for a typical laboratory plasma will be negative. Of course, the fact that the grains get charged is what makes them an interesting system to study; the dust is now one component of the plasma. In a typical low-temperature (electron temperature $T_e \approx 1 - 3$ eV, and cold ions, $T_i \approx 0.03$ eV) argon plasma, a 1 $\mu$m diameter dust grain will have a negative charge corresponding to about 2000 elementary charges. The tendency for a plasma to remain neutral is maintained even in the presence of dust grains. However, since some of the electrons are now on the dust, the usual quasi-neutrality condition, $n_i \approx n_e$, where $n_i$ and $n_e$ are the electron and ion densities, is replaced by

$$n_i \approx n_e + Z_{d,eq} n_d$$  \hspace{1cm} (1)

in a dusty plasma, where $n_d$ is the dust density and $Z_{d,eq} = |q_{d,eq}/e|$ is the dust charge number. One gains an appreciation for the complexity of a dusty plasma by comparing the charge to mass ratios of a typical dust grain and an electron: $(q/m)_d < 1$ C/kg, while $(q/m)_e = 1.76 \times 10^{11}$ C/kg. To make matters worse, the dust charge is not necessarily constant.

The huge difference in the dynamical timescales of the dust and plasma components is a unique feature of a dusty plasma. For typical processes such as electron and ion plasma waves, it is possible to treat the dust as immobile (essentially having an infinite mass relative to the electrons and ions). In that case, the effect of the dust on the plasma occurs through the plasma neutrality condition, since in a typical laboratory dusty plasma, the electrons may be depleted to the point where the electron density is much smaller
than the ion density. On the other hand, the presence of the massive dust component gives rise to very low frequency phenomena such as dust acoustic waves. To get a sense for the difference in the timescales for electron, ion, and dust phenomena in a plasma, we can compare their respective inverse plasma frequencies \[\omega_{-1} = (n_e q^2 / \varepsilon_0 m_d)^{-1/2}, \alpha = (e, i, d).\] For \(n_e \approx n_i \approx 10^{15} m^{-3}, n_d \approx 10^{10} m^{-3}, |q_{d,eq}| \approx 2000e,\) we find that \(\omega_{-1}^e \approx 1 ns, \omega_{-1}^i \approx 1 \mu s, \omega_{-1}^d \approx 1 ms.\)

A unique characteristic of a dusty plasma is that you can see the dust particles with your eyes. Dust particles of sizes on the order of about half a micron size and larger can be imaged in visible light. Thus, the behavior of the dust grains in a dusty plasma can be observed and recorded in real time using laser illumination and digital video cameras. For example, in an ensemble of \(N\) dust grains, in a 2D layer, where \(N \approx 10,000,\) it is possible to track the position \(\vec{r}_i = (x_i, y_i)\) of each grain in a series of video frames and then determine their velocities \(\vec{v}_i = (v_{xi}, v_{yi}),\) thus providing a complete set of kinetic data \([\vec{r}_i(t), \vec{v}_i(t); i = 1],\) for the entire system. This has been made possible in the last 20 years by the availability of digital high speed, mega-pixel video cameras with hundreds of gigabytes of memory and sophisticated image analysis algorithms. This has allowed researchers to use dusty plasmas as model systems to study fluid-like phenomena at the individual particle level.

Over the last three decades, there has been a rapid growth in research on dusty plasmas covering the areas of basic plasma physics, space and astrophysical plasmas, applied plasma physics, and magnetic fusion. Initially, much of the work on dusty plasmas was theoretical, but gradually devices were introduced to produce dusty plasmas in the laboratory for controlled experiments. In addition, computer simulations in particular, molecular dynamics (MD) simulations have proven to be essential in understanding dusty plasma physics. There are now a number of textbooks [2, 7–13] and review articles [14–19] available in which various aspects of dusty plasmas are presented.\(^{14}\)

Recognizing the importance of dusty plasmas, several introductory plasma physics textbooks now include chapters on dusty plasmas [20–23].

The goal of this article is not to provide a comprehensive review of the entire field of dusty plasmas, as presented in references [7–19], but to focus on a few important and novel aspects of dusty plasma physics, including

- dust grain charging (Sec. 2)
- forces on dust grains in a plasma (Sec. 3)
- devices for producing dusty plasmas (Sec. 4)
- strongly coupled dusty plasmas (Sec. 5)
- waves and instabilities in dusty plasmas (Sec. 6)
- magnetized dusty plasmas (Sec. 7)
• dusty plasma technologies (Sec. 8).

A number of examples showing the commonality of the basic physical principles underlying dusty plasma phenomena occurring in diverse environments will be discussed. The reader who has reached this point in the article will realize that there are a number of footnotes intended to provide some historical context, as well as brief notes explaining specific jargon for non-plasma physicists. Wherever appropriate, comments related to published works have been included that I hope will provide useful direction for anyone seeking further information. Finally, the author has attempted to include sufficiently detailed discussions and clarifications of certain topics for the benefit of students who might be interested in pursuing research into this exciting state of matter that pervades most of the Universe.

2. The charge on dust grains in a plasma

In the absence of charge, dust dispersed in a neutral gas would behave as a gas of macroscopic particles subject to gravity and Brownian motion. When the particles are charged, they are also subjected to electric and magnetic forces due either to externally applied fields or self-consistently produced plasma fields. If the density of dust particles is sufficiently high so that the interparticle spacing is on the order of or less than a Debye length, the dust particles will interact strongly through their mutual Coulomb fields. Clearly, the charge on dust grains is central to any discussion of dusty plasmas, and the next few sections will present in some detail the basic physics of the dust charging process. Unlike the electrons and ions in a plasma with a fixed charge, the charge on a dust grain depends on its size and shape, the dust grain density, and the properties of the environment surrounding it in a complicated manner.

2.1 Electrically floating objects

What does an airplane flying through a thunderstorm [24,25] have in common with a dust particle in a plasma? They are both electrically floating objects in an environment containing positive and negative charges. Both objects collect electrical charges from the environment until an equilibrium is reached when the net current is zero. The potential of an isolated object relative to the local potential of its environment is its floating potential \( V_f \).\textsuperscript{15}

There are many examples of isolated (floating) objects that are electrically charged in this manner. There are a number of mechanisms, in addition to the collection of electrons and ions from the plasma, that affect the charge on a dust grain, including photoelectron emission, secondary electron emission, thermionic emission, field emission, radioactivity, triboelectric
effects, etc. An object, e.g. a spacecraft or dust particle exposed to UV radiation (e.g. sunlight), can emit photoelectrons and become positively charged. Charging by photoelectron emission is an important process for dust particles evaporated from comets, for ice crystals in the Earth’s mesosphere (~ 80–90 km) (associated with the Noctilucent clouds and the anomalous radar echoes known as the Polar Mesospheric Summer Echoes\textsuperscript{16}), for dust grains in the rings of Saturn, and on the Moon’s surface. In an environment containing energetic particles, currents due to secondary emission will also play a role in dust grain charging. Objects or particles containing radioactive elements may be charged by alpha or beta emission. For very small dust grains, the electric field at the grain surface can be large enough to cause field emission. The nature of the environment in which the object is located will determine which of these charging mechanisms must be taken into account.

A spacecraft in geosynchronous orbit is an example of a floating object that becomes electrically charged [26–28]. It has been known since the early days of space exploration that an orbiting spacecraft can acquire a substantial charge resulting in a spacecraft potential of several hundred volts in sunlight and several thousand volts when in Earth’s shadow. The changing polarity over the orbit points to the presence of two competing charging mechanisms – collection of electrons and ions when the spacecraft is in eclipse and photoelectron emission due to solar UV illumination when it is on the Earth’s dayside. Typically, when charging is due to the collection of plasma particles, the thermal speed of the electrons is considerably higher than that of the ions, and as a result, the spacecraft initially charges to a negative potential. This limits further collection of electrons and increases ion collection leading to the equilibrium charge. Emission of electrons, either by photoemission or secondary electron emission, increases the charge on the dust particle (makes it more positive) and under certain conditions can lead to dust with a positive charge. The charging of a spacecraft can wreak havoc on instruments designed to measure particle energies, since the potentials that are applied to the discriminating electrodes in a particle analyzer are referenced to the spacecraft potential, which can vary considerably depending on the location of the spacecraft. If any part of the spacecraft surface contains dielectric material (which also get charged), differential charging can produce unpredictable arcing which can damage sensitive electronics. A considerable effort has been invested in predicting the spacecraft potential (or on developing methods of controlling it) using theoretical and numerical modelling.\textsuperscript{17,18} Not surprisingly, some of the early theoretical analyses of dust charging were carried out by scientists who had worked on the spacecraft charging problem.
2.2 The floating potential of a dust grain

The various charging mechanisms mentioned above produce currents that cause charge to flow to or from a dust grain. The time evolution of the dust grain charge, \( q_d \) is determined by

\[
dq_d/dt = \sum_j I_j[V_f(t)],
\]

(2)

where \( I_j[V_f(t)] \) is the current due to charging process \( j \) evaluated at the value of the floating potential \( V_f \) at time \( t \). At equilibrium, the net current flowing to the floating dust grain surface must be zero, or

\[
\left[ dq_d/dt \right]_{V_f,eq} = \sum_j I_{j,eq} = 0,
\]

(3)

where \( I_{j,eq} = I_j(V_{f,eq}) \) are the charging currents at the equilibrium dust floating potential, \( V_{f,eq} \), which is obtained by solving equation (3) with all appropriate charging currents included that pertain to the particular environment in which the dust grains are immersed. Equation (3) is typically a non-linear transcendental equation which must be solved numerically for \( V_{f,eq} \).

2.3 The relation between the equilibrium floating potential and the equilibrium charge on a dust grain

The equilibrium dust charge \( q_{d,eq} \) is related to its floating potential, obtained from Equation (3), by the capacitance of the dust grain,

\[
q_{d,eq} = CV_{f,eq}.
\]

(4)

If we assume that the dust grains are conducting spheres of radius \( a \), then \( C \) is the capacitance of an isolated spherical conductor,

\[
C = 4\pi \varepsilon_0 a,
\]

(5)

so that the grain charge is

\[
q_{d,eq} = 4\pi \varepsilon_0 a V_{f,eq}.
\]

(6)

Equation (5) is a very good approximation when the dust grain radius is much smaller than the Debye length.\(^{20}\) For the case of a typical laboratory dusty plasma \( \lambda_D \approx 50 - 500 \ \mu m \), which is much greater than a typical micron-sized dust grain.
2.4 Charging of a dust grain in a plasma due to collection of electrons and ions: The orbital motion limited (OML) model

In typical laboratory devices used to study dusty plasmas, charging is due mainly to the collection of electrons and ions so that only these currents need be included in Equation (2). We will consider in detail the charging process for the case pertinent to laboratory dusty plasmas. We will assume that the electrons and ions experience no collisions while approaching a grain, that they stick to the grain when hitting it, and no secondary particles are emitted. We also assume that the grains are few and far between, so that interactions between the grains can be neglected, i.e. the grains are isolated.

The typical laboratory plasma is produced by an electrical discharge in a neutral gas, e.g., argon (neutral pressures on the order of 1–200 Pa), either by applying a DC or RF voltage source to an electrode. This produces a plasma with electrons with a temperature $T_e \approx 1 – 3 \text{ eV}$, and cold ions, $T_i \approx 0.03 \text{ eV}$. Thus, the thermal speed of the electrons is much greater than the thermal speed of the ions, and an uncharged grain in a plasma will initially acquire a negative charge due to the collection of the faster electrons. Since the net current to the grain must be zero, the grain will ultimately repel electrons and attract ions, as its potential approaches the equilibrium floating value $V_{f,eq}$.

The problem of determining the electron and ion currents to a small ($a < \lambda_D$) spherical dust grain in a plasma is very similar to the calculation of the currents to a small spherical floating probe in a plasma. This problem was first tackled by Mott-Smith and Langmuir in 1926 [29], Bohm, Burhop and Massey in 1949 [30]¹, Allen, Boyd, and Reynolds in 1957 [31], Bernstein and Rabinowitz in 1959 [32], Chen in 1965 [33], Laframboise in 1966 [34], and Hutchinson in 2002 [35].

When a dust grain in a plasma begins to become charged, it no longer collects electrons and ions that randomly hit it, since the currents now depend on the potential of the grain relative to the plasma. For the case in which $a < \lambda_D$ these currents can be described by the so-called orbital motion limited (OML) theory [7–12,30–32]². In the OML approach, the electrons and ions are assumed to proceed from infinity in a collisionless plasma toward the dust grain and under the influence of its electrostatic field. When the plasma particles enter the sphere of influence of the dust grain (the Debye sheath), they are deflected by its electric field by amounts that depend on their initial velocity and impact parameter, and the potential of the dust grain. Particles having trajectories that end on the dust grain are collected, particles having trajectories that miss the dust grain are not collected. The current is then limited by the trajectory of the particles that hit the dust grain tangentially, or at grazing incidence. This is the essence of
the OML theory, which applies conservation of energy and angular momentum (valid in a collisionless plasma) to obtain the effective cross-sections for collection of electrons and ions by the dust grain:

\[
\sigma_{e,\text{coll}}(v_e) = \begin{cases} 
\pi a^2 \left(1 + \frac{2eV_f}{m_e v_e^2}\right), & \frac{2eV_f}{m_e v_e^2} > -1, \\
0, & \frac{2eV_f}{m_e v_e^2} \leq -1,
\end{cases}
\]

(7)

\[
\sigma_{i,\text{coll}}(v_i) = \pi a^2 \left(1 - \frac{2eV_f}{m_i v_i^2}\right),
\]

(8)

where \(m_{i,e}\) is the (ion, electron) mass, \(v_{i,e}\) is the initial velocity of the (ion, electron), and we assume that the ions are singly charged. We see from Equations (7) and (8) that for negatively charged grains, i.e. \(V_f < 0\), ion collection is increased and electron collection is reduced, compared to the geometric cross-section of the dust grain. The cross-section in Equations (7) and (8) applies to monoenergetic, isotropic ions and electrons. Assuming that the ion and electron velocity distribution functions, \(f_{i,e}(v_{i,e})\) are Maxwellians, the charging currents are obtained from

\[
I_{i,e}(v_{i,e}) = \pm e \int_{v_{\text{min}(i,e)}}^{\infty} v_{i,e} \sigma_{i,\text{coll}}(v_i) f_{i,e}(v_{i,e}) dv_{i,e},
\]

(9)

where \(v_{\text{min}(i,e)} = \left[0, \left(-\frac{2eV_f}{m_e}\right)^{1/2}\right]\). Upon carrying out this integration, the ion and electron currents to the dust grain are

\[
I_i(V_f) = e n_i \pi a^2 \sqrt{\frac{8kT_i}{\pi m_i}} \left(1 - \frac{eV_f}{kT_i}\right),
\]

(10)

\[
I_e(V_f) = -e n_e \pi a^2 \sqrt{\frac{8kT_e}{\pi m_e}} \exp\left(\frac{eV_f}{kT_e}\right),
\]

(11)

where \(n_i, n_e, T_i, T_e,\) and \(k\) are the ion density, electron density, ion temperature, electron temperature, and Boltzmann’s constant, respectively.

### 2.5 The charging equation and evolution of the dust floating potential

Combining the charging currents, Equations (10) and (11), with Equations (3) and (6), we obtain a nonlinear differential equation for the evolution of the dust grain floating potential

\[
4\pi \varepsilon_0 a \frac{dV_f}{dt} = e \pi a^2 n_0 \left[ \sqrt{\frac{8kT_i}{\pi m_i}} \left(1 - \frac{eV_f}{kT_i}\right) - \sqrt{\frac{8kT_e}{\pi m_e}} \exp\left(\frac{eV_f}{kT_e}\right) \right],
\]

(12)
where the condition \( n_i = n_e = n_0 \) was used for the case of an isolated dust grain (or for dust densities, \( n_d < < n_{i,e} \)). In practice, it is not necessary to solve Equation (12) to obtain the equilibrium dust floating potential, \( V_{f,eq} \), rather one solves Equation (3) directly. However, it is instructive to illustrate the charging process in detail by providing an example of the solution to (12). Figure 2 shows the results of a numerical solution to Equation (12) using the parameters shown in Table 2.

The chosen parameters are typical for laboratory dusty plasmas. The dust floating potential, \( V_f \), is normalized to \( kT_e/e \) and is shown as the solid black curve. Also shown in Figure 2 are the ion (blue), electron (red), and total current (dashed black) to the dust grain. We see that initially, the electron current dominates and the dust begins to charge to a negative potential. As the ion current becomes comparable to the electron current at \( t > 5 \times 10^{-6}\) s, the total current and floating potential begin to decrease at a smaller rate. For \( t > 10^{-5}\) s, \( I_i \approx \left| I_e \right| \), the total current \( I_i + I_e \approx 0 \), and the normalized floating potential reaches an equilibrium value,

![Figure 2](image-url)

**Figure 2.** Electron current, ion current, total current, and floating potential vs. time for the parameters shown in Table 2.

| Parameter            | Symbol | Value          |
|----------------------|--------|----------------|
| Ion species          | \( \text{Ar}^+ \) |                |
| Plasma density       | \( n_0 \) | \( 1.0 \times 10^{15} \, \text{m}^{-3} \) |
| Electron temperature | \( kT_e \) | \( 2.5 \, \text{eV} \) |
| Ion temperature      | \( kT_i \) | \( 0.025 \, \text{eV} \) |
| Dust radius          | \( \alpha \) | \( 1.0 \, \mu\text{m} \) |

**Table 2.** Parameters used to obtain Figure 2.
$eV_{f,\text{eq}}/kT_e \approx -6$. For the parameters indicated in Table 2 the equilibrium dust charge $q_{d,\text{eq}} = 4\pi\varepsilon_0 aV_{f,\text{eq}} \approx -1.7 \times 10^{-15}$ C, corresponding to an equilibrium dust charge number $Z_{d,\text{eq}} = |q_{d,\text{eq}}|/e \approx 10^4$.

We note that in Figure 2, the dust grain attains full charge in a time $\sim 10 \mu s$, which is shorter than typical time scales over which appreciable changes in the plasma parameters might change, and also much shorter than the typical timescale for dust motion. Thus, it is reasonable to assume that the dust grain potential will be able to follow changes in the plasma parameters. The charging of a dust grain does not follow an exponential law since the current depends nonlinearly on the floating potential. Since the charging proceeds at a rate determined by the slower species, i.e, the ions, it is possible to define a charging time based on the ion current, which does depend linearly on the floating potential. While various definitions of the *dust charging time*, $\tau_{ch}$, have been discussed, e.g. [7,8,11,14,15,19], the scaling follows, $\tau_{ch} \propto a^{-1} n_0^{-1}$, so that small grains charge more slowly than large grains, and a grain attains its equilibrium charge faster when the plasma density $n_0$ is higher.

### 2.6 The equilibrium dust floating potential $V_{f,\text{eq}}$

It is not necessary to solve the differential Equation (11) to compute $V_{f,\text{eq}}$; this can be obtained by solving the equilibrium condition Equation (3) with the charging currents Equations (8) and (9). However, Equation (3) must be solved numerically for $V_f$. Defining the normalized equilibrium dust floating potential $\varphi_f = eV_{f,\text{eq}}/kT_e$, $\tau = T_e/T_i$, and $\mu = m_e/m_i$, Equation (3) can be written as

$$\sqrt{\mu} \left(1 - \tau \varphi_f\right) - \sqrt{\tau} \exp\left(\varphi_f\right) = 0,$$

(13)

showing that the normalized dust floating potential depends only on the electron to ion temperature and mass ratios. A bar plot showing $|\varphi_f| = |eV_{f,\text{eq}}/kT_e|$ obtained by solving Equation (13) numerically for various ion species and for three values of the temperature ratio is shown in Figure 3. The floating potential values are not extremely sensitive to either the ion mass or temperature ratio. As a *rule of thumb*, if one were to take $eV_{f,\text{eq}}/kT_e \approx -2.5$, for any of the parameters in Figure 3, the result would not be in error by more than a factor of two.

### 2.7 Other processes that affect dust charging

The OML theory of dust charging that has just been presented is quite restrictive, and depending on conditions, there are other effects that may
need to be considered. Here I will mention just a few of the other processes that affect the charge on dust grains.

2.7.1 Effect of collisions

Typical laboratory dusty plasmas are produced in weakly ionized gas discharges, in which collisions, particularly ion-neutral collisions, can strongly influence the charge on a dust grain. A basic premise of OML theory is that the electrons and ions do not incur collisions during their orbits to the dust particle. Typically, in weakly ionized plasmas, this is a more important effect for the ions, since their mean-free-paths due to collisions with neutral atoms tend to be considerably shorter than the electrons. For example, in a typical laboratory argon discharge plasma with electrons at $T_e = 2.5$ eV and ions with $T_i = 0.03$ eV, charge exchange is the dominant process in ion-neutral collisions, and the cross-section for charge exchange is roughly 20 times higher than the cross-section for electron-neutral momentum exchange. The effect of ion-neutral collisions is dependent on the parameter $a/\lambda_{in}$, where $\lambda_{in}$ is the ion-neutral mean free path. The self-consistent molecular dynamics simulations of Zobnin et al [36] showed that the absolute value of the dust surface potential first decreases with increasing

Figure 3. Bar plot of the equilibrium dust floating potential normalized to $kT_e$, for various positive ion species and electron to ion temperature ratios.
$a/\lambda_{in}$, reaches a minimum value and then increases. A collision between an ion and a neutral atom can cause an ion (which would not be collected if it did not have a collision) to be collected, thus reducing the magnitude of the negative charge. For larger values of $a/\lambda_{in}$, the mobility of the ions is decreased, so the (negative) charge on the grain increases. The effects of ion-neutral collisions on dust charging was also borne out in the analytic calculations of Lampe et al. [37], who showed that the increase in the ion current to the dust grain can be substantial even when $a/\lambda_{in} << 1$.

### 2.7.2 Effect of drifting ions

Gas discharge plasmas are sustained by electric fields that can accelerate ions to drift speeds $u_i$ comparable to or larger than their thermal speed $v_{Ti}$. This can be taken into account by modelling the ion distribution function as a shifted Maxwellian [18]. Fortov et al. [19] analyzed the behavior of the particle charge in the sheath above a negatively biased electrode in a discharge plasma. The ions are accelerated by the electric field in the sheath and can attain speeds of several times their thermal speed. For $u_i \leq v_{Ti}$, the charge was nearly constant, then increased with $u_i$, reaching a maximum at $u_i \approx (2 - 3)c_{IA}$ (where $c_{IA} = \sqrt{kT_e/m_i}$ is the ion-acoustic speed), and then decreased. The dust charge can even reach positive values sufficiently close to the electrode, where most electrons cannot penetrate.

The effect of ion streaming is particularly important in the case of spacecraft charging, since the spacecraft velocity typically exceeds the thermal speed of the ions [38,39].

### 2.7.3 Charging of dust in plasma sheaths

In the commonly used 13.56 MHz rf discharge device operated in the unsymmetric capacitively coupled mode, a negative self-bias is produced on the lower electrode. (This is discussed in more detail in Sect. 4.) Negatively charged dust grains are then levitated just above the lower electrode, by the downward electric field within the electrode sheath. Depending on the position of the dust particle in the sheath above the lower electrode, there can be a substantial reduction in the electron density, which reduces the magnitude of (negative) dust charge, since only the most energetic electrons can penetrate deep into the sheath.

### 2.7.4 Effect of high dust density – the close-packing effect

The charge on an isolated dust particle, or an ensemble of dust particles of density $n_d << n_i$, can be computed within the OML formalism using Equation (13). However, when the dust density becomes appreciable (i.e. close-packing), the plasma becomes depleted, and the charge available to charge the grains necessarily decreases. As a result, the equilibrium charge
on the grains must be reduced relative to the charge of an isolated grains. Simply put, when more grains share a fixed amount of charge, each grain gets less charge. This effect was investigated theoretically in a number of papers [39–42], and an instructive numerical illustration of the effect is shown in Figure 4 of the review article of Goertz [43].

The close-packing effect can be analyzed using Equation (13) by dropping the assumption of equal ion and electron densities and using the charge neutrality condition

\[ e n_i = e n_e - q_{d,eq} n_d. \]  

(14)

Defining \( \alpha = n_d/n_i \), the electron and ion densities can then be related using Equation (14) as

\[ n_e/n_i = 1 + \alpha \left( q_{d,eq}/e \right), \]

(15)

and using Equation (6) to relate the dust charge and floating potential

\[ \frac{n_e}{n_i} = 1 + \alpha \frac{4\pi e_0 a k T_e}{e^2} \left( \frac{e V_{f,eq}}{k T_e} \right). \]

(16)

Note that for isolated dust grains, \( n_d \approx 0, \alpha = 0 \). For \( \alpha \neq 0 \), the grain floating potential is now obtained by solving

**Figure 4.** The normalized equilibrium dust floating potential vs. the ratio \( n_d/n_i \) of the dust density to ion density, for ion mass number \( A = 40, \ a = 1 \mu m \), \( T_e \approx 100 T_i = 2.5 \ eV \).
\[ 0 = \sqrt{\mu (1 - \tau \varphi_f)} - \sqrt{\tau (1 + \alpha \beta \varphi_f)} e^{\varphi_f}, \]  

(17)

where the dimensionless parameter \( \beta \equiv (4\pi \varepsilon_0 akT_e/e^2) \). Solutions to Equation (17) are shown in Figure 4 as a function of \( \alpha \), for the parameters \( A = 40, \ a = 1.0 \ \mu m, \ T_e = 100T_i = 2.5 \ eV \). For \( \alpha \ll 1 \), the isolated grain value is obtained, but the normalized dust floating potential decreases (in absolute value) as \( \alpha \) increases, and approaches zero as \( \alpha \rightarrow 1 \).

This high-density dust effect has been observed experimentally in a Q-machine\textsuperscript{23} plasma in which variable amounts of dust grains were dispersed so that the ratio \( d/\lambda_D \) of the interparticle spacing to the Debye length was varied \textsuperscript{44,45}. The dust charge was found to decrease as the relative concentration of dust increased. High dust concentration effects were also observed experimentally in an RF discharge plasma in which dust particles were grown in-situ in an argon/silane plasma \textsuperscript{46}.

### 2.7.5 Dust charge fluctuations

The dust charging process is actually a sequence of discreet events at random times involving the collection of individual electrons and ions. This random process results in a fluctuation of the dust charge around its equilibrium value. The statistical nature of the charging process was studied in numerical simulations by Cui and Goree \textsuperscript{47} and analytically by Matsoukas and Russell \textsuperscript{48}. Dust charge fluctuations become particularly important for small grains in which the charge is small. For very small (nanometer size) grains, the discreteness of the charging process can also cause the charge to fluctuate in sign. The charge on a dust grain can also fluctuate if there are fluctuations in the plasma parameters. This leads to a unique phenomenon involving the interaction between dust and fluctuations due to plasma waves, particularly when the fluctuation timescale is comparable to the dust charging time. To the author’s knowledge, no direct experimental observations of the effect of dust charge fluctuations have been reported.

In addition to the variability of the dust charge due to the random nature of the charging process, the dust charge can also vary if the dust particle moves in an inhomogeneous plasma or in a plasma whose parameters fluctuate in time. This gives rise to a phenomenon known as the delayed charging effect (DCE). Due to the finite charging time of a dust grain, as the grain moves, its actual charge may be different from the equilibrium value. The delayed charging effect has been associated with a significant change in the damping rate of the oscillations of dust particles levitated in a plasma \textsuperscript{49}, and to the onset of self-excited vertical oscillations of dust particles in a Coulomb crystal \textsuperscript{50}. 
2.7.6 Effects of a dust size distribution
In most space and astrophysical dusty plasmas, the dust component contains particles of various sizes and shapes (non-monodisperse). The presence of a dust size distribution leads to a distribution of dust grain charges also. Theoretical progress in understanding the effects of non-monodisperse dust has been made by assuming either Gaussian or power law dust size distributions. Theoretical calculations of the capacitance of a dust grain immersed in a plasma containing a size distribution of dust particles was performed by Houpis and Whipple [51]. These calculations were specifically aimed at problems related to dust particles in the F ring of Saturn. Havnes et al. [52] extended these results to include charging due to the photoelectric effect. More recently, Soda et al. [53] analyzed the kinetics of a dusty plasma having spherical dust grains with a kappa distribution of dust sizes.

2.7.7 Effects of a magnetic field
The OML theory assumes that the electrons and ions approach the dust grains isotropically, which is not the case if a magnetic field is present. The problem of calculating the grain charge in a magnetized plasma is somewhat similar to the problem of calculating the currents to a Langmuir probe in a magnetized plasma. The relevant parameters that must be considered are the electron and ion gyroradii relative to the dust radius. The problem is most severe for the electrons, since for magnetic fields 1–2 T, a typical electron gyroradius in a discharge plasma is on the order or less than the dust radius. Under these conditions, the electron current to a dust grain (or small probe) may be significantly reduced. The effect of a magnetic field on the dust charge is of particular interest for understanding the dynamics of dust in magnetic fusion devices. A theoretical investigation of the effect of a magnetic field on dust charging was performed by Kodanova et al. [54] using particle-in-cell and Monte Carlo methods. Their calculations performed for dust having \( a = 3 \mu m \), and \( T_e = 19 \text{ eV} \), showed little effect on the dust charge for \( B \) up to about 4 T. For \( B = 10 \) T, there was a 25% reduction in the equilibrium dust charge. A significant increase in the charging time was also seen at higher magnetic fields.

Experiments on magnetized dusty plasmas have only recently begun [55] and will be discussed more fully in a later section of this article.

2.8 Experimental measurement of dust charge
The charge on a dust grain in a plasma is not only its most important property but also the most difficult one to measure. The OML theory predicts a negative charge on the dust grains, but what is the experimental evidence that this occurs? An indirect demonstration of dust grain charging can be obtained by using a Langmuir probe to observe the decrease in the
electron current to the probe when dust is injected into the plasma. When the dust is present, the negative current to a positively biased probe will be reduced relative to the current observed without dust, due to the fact that electrons, which become attached to dust grains of extremely low mobility, will not be collected by the probe. This is illustrated in Figure 5 which shows a Langmuir probe current-voltage characteristic taken without (upper curve) and with (lower curve) dust present in a dusty plasma device described in detail in [56]. Note that in this plot, the electron current is shown as the upper, positive current. A clear reduction in the electron current was observed when the dust was present. Also, as indicated by the arrow, the electron current returned to its no-dust value when the dust was turned off. The reduction in the electron current to a Langmuir probe in the presence of dust provides a method of estimating the quantity $q_{d,eq}n_d$ based on the assumption of charge neutrality, and if an independent measurement of the dust density $n_d$ is made, the dust charge can then be estimated [44,45].

Several methods have been employed to measure the charge on a dust grain in a plasma. The most direct measurements were made by allowing single dust grains to fall through a plasma where they were charged and then
The measurements reported in [57] established that the dust charge scaled with its radius and the absolute value agreed with the predictions of OML theory. Also, when energetic electrons were present in the plasma, a reduction in the (negative) charge was found due to secondary electron emission. In RF parallel plate devices, dust charge measurements were made by tracking the resonance oscillations of the particles due to application of a modulation voltage [58] or laser manipulation [59]. Other methods were based on the analysis of the equilibrium force balance condition of a dust particle under the influence of electric, gravitational, and/or neutral drag forces [60,61]. As we will discuss later in this article, dust density waves (DDWs) are often present in dusty plasmas. The dispersion properties of DDWs can be measured by video imaging techniques, and by comparing the measured wave properties, e.g. the phase speed, with theoretical dispersion relations, estimates of the dust charge have been made [62,63]. These measurements have been used to verify the reduction in dust charge due to ion-neutral collisions [62]. Plasma wave observations are often used as diagnostic tools for the measurement of the electron temperature in laboratory plasmas, and the plasma density in space plasmas.

3. Forces on dust particles

The forces on a dust grain in a plasma can be broken down into three major categories [64]:

1. forces due to externally applied electric, magnetic, and gravitational fields,
2. forces due to the interaction of dust grains with plasma electrons and ions, and neutral, gas atoms – ion and electron drag forces, neutral drag force, and thermophoretic force,
3. forces between dust grains – grain-grain interaction forces.

An comprehensive discussion of the forces on dust grains is given in the review article of Fortov et al [19].

3.1 External forces: gravity, electric and magnetic forces

3.1.1 Gravity

The force on a spherical dust grain of radius $a$ and mass $m_d$ due to the Earth’s gravitational field is

\[ \vec{F}_G = m_d \vec{g} = \frac{4}{3} \pi \rho_d a^3 \vec{g}, \]

where $g = 9.8 \text{ m/s}^2$, and $\rho_d$ is the mass density of the dust material.
3.1.2 Electric and magnetic forces

The electric force and magnetic forces are given by

\[ \overrightarrow{F_E} = q_d \overrightarrow{E}, \quad (19) \]
\[ \overrightarrow{F_M} = q_d \left( \overrightarrow{v_d} \times \overrightarrow{B} \right), \quad (20) \]

where \( q_d \) is the dust charge and \( \overrightarrow{v_d} \) is the dust grain velocity. An important consideration is how these forces scale with the dust radius. The gravitational force scales with the dust mass which scales as \( a^3 \), so \( F_G \propto a^3 \). The electric force scales as the dust charge, which scales as \( a \), so \( F_E \propto a \). The magnetic force \( F_M \propto q_d v_d \), and if the dust velocity is taken to be its thermal velocity, \( v_d \approx v_{T,d} = \sqrt{kT_d/m_d} \propto m_d^{-1/2} \propto (a^3)^{-1/2} \) so that, with \( q_d \propto a \), we have that \( F_M \propto a^{-1/2} \).

3.2 Forces due to collisions between dust and neutral atoms or molecules

Typically, in laboratory and industrial dusty plasmas, the plasma is weakly ionized so that the ionization fraction is very low. For example, at a neutral pressure \( \sim 10 \) Pa (75 millitorr) and plasma density \( \approx 10^{15} \, m^{-3} \), the ionization fraction is \( \approx 10^{-6} \).

3.2.1 Neutral drag force – Epstein drag

Neutral drag is the force on a dust particle that moves through a neutral gas. Since laboratory dusty plasmas are typically formed in weakly ionized discharges, the neutral drag force is very important. Under conditions in which the grain size is much less than the mean free path, and for particle speeds well below the thermal speed of the gas atoms, the neutral drag force (known as the Epstein drag force [65]) on a spherical dust grain of radius \( a \) is

\[ \overrightarrow{F_{dn}} = -\frac{4\pi \delta}{3} a^2 m_n v_{T,n} N \overrightarrow{v_d}, \quad (21) \]

where \( m_n \) is the mass of the neutral gas atoms, \( N = P/kT_n \) is the neutral gas density, \( P \) is the neutral gas pressure, \( v_{T,n} = \sqrt{8kT_n/\pi m_n} \) is the thermal speed of the neutral gas atoms, \( T_n \) is the neutral gas temperature, \( \overrightarrow{v_d} \) is the dust grain velocity, and \( \delta \) is a dimensionless parameter in the range of \( 1 - 1.5 \). Often the dust-neutral collision frequency, \( \nu_{dn} (= \nu_{Epstein}) \) is a more convenient parameter, which is defined in terms of the force in (21) by \( \overrightarrow{F_{dn}} = -m_d \nu_{dn} \overrightarrow{v_{dn}} \), so that
\[ \nu_{dn} = \frac{4\pi \delta a^2 m_n N v_{Tn}}{3m_d}. \]  

(22)

### 3.2.2 Thermophoretic force

The thermophoretic force occurs when there is a temperature gradient in the neutral gas, simply because the warmer gas atoms on one side of the dust grain transfer more momentum to it than the colder atoms on the other side. This effect has been used to levitate dust grains in parallel plate RF discharges by heating the lower electrode to produce a downward neutral gas temperature gradient [66].

### 3.3 Ion-dust and electron-dust forces

These *momentum-transfer* forces, which involve collisions of dust grains with ions, electrons, or other dust grains in relative motion, have been systematically analyzed by Khrapak, Ivlev, and Morfill [67]. Since these forces involve Coulomb interactions, they are analyzed by deriving appropriate collision cross-sections assuming a screened potential (Debye-Hückel or Yukawa) for the dust grains, \( \varphi(r) = (q_d/4\pi \varepsilon_o r) \exp(-r/\lambda_D) \).

Due to the larger ion mass, the ion-drag force is usually much larger than the electron drag force, so we will focus on the ion-drag force. The conditions under which the electron drag force was discussed by Khrapak and Morfill [68]. The ion drag force arises due to the relative motion of dust grains and ions. This force is quite important in discharge plasmas since the ions may acquire an appreciable drift speed in the electric field of the discharge. The dust grains then experience forces in opposite directions due to the electric field and ion flow, as well as gravity. The ion drag force is usually broken down into two parts: a *collection force* \( F_{id}^C \) due to momentum transfer to the grain by ions that are collected on the grain, and an *orbit force* \( F_{id}^O \) due to momentum transfer by ions that are deflected by the grain, \( F_{id} = F_{id}^C + F_{id}^O \). For example, for the case of monoenergetic ions of velocity \( v_i \), the collection term is \( F_{id}^C = \pi a^2 n_i m_i v_i^2 \), where \( n_i \) and \( m_i \) are the ion density and mass, respectively. The orbit term, on the other hand, is quite complicated due to the need to properly account for the Coulomb interaction between the shielded grain and the ions [69]. The orbit term, which also scales with the ion density, can be considerably larger than the collection term. A simple expression for the orbit force, which assumes that the force is zero for impact parameters larger than the Debye length, is provided in Equation (11) of [64]. Due to the large charge on a dust grain, the scattering of ions beyond the Debye sphere can significantly increase the strength of the ion drag force [67].
The need to consider the ion drag force on dust grains was recognized in the early 1990s, but a related problem of the drag exerted on an object moving through an ionized medium first arose in the latter half of the 1950s with the deployment of orbiting satellites. A satellite in orbit at an altitude of 500 km is subjected not only to drag due to neutral air molecules, but because it acquires an electrical charge, it is also subjected to drag due to collisions with charged particles. This was analyzed by Jastrow and Pearse [70], who in a manner identical to that used by Barnes et al. [64], divided the force into collection and orbit components. In the case of a satellite orbiting at an altitude of 500 km, the satellite size was much greater than the Debye shielding length in the ionospheric plasma, and thus, the orbit force was small compared to the collection force. However, the overall plasma drag force was comparable to the drag due to the neutral atmosphere.

The impact of the ion drag force has been somewhat of a surprising development in dusty plasmas and is responsible for the appearance of a peculiar phenomenon – void formation. A void is a region within a three-dimensional dust cloud that is free of dust grains. Voids tend to appear in RF parallel-plate discharge plasmas, in which very small dust grains are present so that the weight of the grains is not a significant factor, thus allowing large 3D clouds to be confined. Dust voids were observed in an early experiment by Praburam and Goree [71] in a dusty plasma in which dust grains (with a diameter \( \approx 100 \text{ nm} \)) were synthesized from carbon atoms sputtered from the lower graphite electrode. Two distinct void structures were observed, termed the filamentary and great void modes. The mechanism for void formation was clarified when dusty plasma experiments under microgravity conditions (either on parabolic flights or on the International Space Station) were performed. When the typically largest force-gravity (on earth) on the dust grains was effectively eliminated, the ion drag force on the micron-sized grains used in these experiments emerged in competition with the electric force, leading to the unexpected appearance of a void in the center of the plasma [72,73].

To understand the formation of a void in these plasmas, it must be pointed out that ambipolar diffusion leads to the presence of an electric field in the discharge directed from the center of the plasma outward. The center of the plasma is a region of highest plasma potential and highest ion density. The outward electric field in conjunction with ion-neutral collisions leads to an outward ion drift. A negatively charged dust grain in the center region then experiences an inward electric force and an outward ion drag force. The balance of these effects causes dust particles to be expelled from the center of the plasma forming the void.
3.4 Grain-grain interactions

The interactions between dust grains in a dusty plasma are usually modelled using the screened Coulomb potential \( \varphi(r) = \frac{q_d}{4\pi\varepsilon_o r} \exp(-r/\lambda_D) \). Konopka et al. [74] performed a detailed series of measurements of the interaction of two microspheres levitated in the sheath region of an rf argon discharge plasma. They found that their results were in excellent agreement with the assumption of a screened Coulomb interaction potential over the range of parameters of their experiment. Their measurements also provided values for the screening length and the effective charge on the dust particles.

The regimes of momentum exchange in grain-grain collisions are determined by the scattering parameter \( \beta_{dd} = q_d^2/(4\pi\varepsilon_o\lambda_D kT_d) \), which is the ratio of the unshielded Coulomb interaction energy evaluated at the screening length scale to the mean kinetic energy of the dust particles, \( kT_d \). Typically, \( \beta_{dd} \gtrsim 1 \), which is the regime in which the analogy to hard-sphere collisions can be used, and Khrapak et al. [67] have shown that the momentum exchange rate is then

\[
\nu_{dd} = \frac{4\sqrt{2\pi}}{3} n_d v_{Td} \lambda_D^2 (\ln 2\beta_{dd})^2. \tag{23}
\]

The binary collision analysis leading to Equation (23) holds under conditions in which the density of the dust grains is sufficiently low so that collective effects among the dust particles are not important. Generally speaking, the dust-dust interaction force is not important for laboratory dusty plasmas, since the relative velocity of dust grains is small.

The dust-dust interaction in a plasma is affected by ion flows past the dust particles. In the direction perpendicular to the ion drift, the screening due to the ions decreases with increasing drift velocity. There is an even more significant effect on grain-grain interactions for grains in multi-layer vertical dust suspensions. It was discovered that in RF dusty plasma discharges, dust grains are levitated just above the lower electrode, and in situations in which multiple layers are present, the dust grains tended to be vertically aligned [75–77]. This alignment was attributed to an ion wake effect produced by the interaction of ions drifting downward toward the lower electrode and the negatively charged dust grains. This effect is illustrated schematically in Figure 6. As the ions flow by a negatively charged grain, they are deflected slightly inward and converge to a region behind the grain producing a region of increased positive charge under the grain. Dust grains in the lower layer then tend to shift horizontally until they become vertically aligned with the grain in the upper layer. The presence of these nonreciprocal attractive forces between dust grains due to streaming ions was suggested by Schweigert, et al. [78], and Melzer et al. [79]. Vladimirov and Nambu [80]
demonstrated that charged dust particulates in plasmas with finite ion flows can attract each other due to collective interactions involving the ion oscillations in the flow.

4. Devices for investigating dusty plasmas

For about 30 years now, dusty plasmas have been produced and studied in devices specifically designed for that purpose. The devices that have been used in laboratory dusty plasma experiments have utilized a variety of plasma sources, including thermal ionization (Q machine), DC glow discharge plasmas, hot filament discharge plasmas, and RF discharge plasmas (capacitively or inductively coupled). Starting with a suitable plasma source, researchers then employed some mechanism for getting dust into the plasma. The simplest method was to use dust ‘salt shakers’ to sprinkle dust grains into the plasma. Dust particles were also grown directly in the plasma starting with atoms sputtered off of carbon electrodes or radicals chemically produced using reactive gas mixtures. The advantage of introducing dust externally is the one that has control over its size and material,
since spherical, monodisperse particles of various sizes and materials are commercially available. Dust grown in a plasma is not always either monodisperse or spherical, although the dust size can be controlled by the duration of the growth cycle duration (typically on the order of minutes), which can be terminated by shutting off the reactive gas. Combinations of argon with silane, methane, and acetylene have been employed to grow dust, in GEC-type devices [3].

Dust salt shakers are small receptacles containing dust particles, with either a small hole in the bottom or a fine mesh. Dust is added to the plasma by manually tapping on a rod that the shaker is attached to, and allowing gravity to do the work, or under microgravity conditions, some form of electro-mechanical oscillation device is used. To allow dust to fall through a magnetized plasma column as in a Q machine\textsuperscript{23}, we have surrounded a portion of the plasma column by a cylinder that was loaded with dust grains [81]. When the cylinder was rotated around the plasma using an external motor, the dust was carried upward, and at a point, this depended on the rotation rate detached from the inner wall and fell into the plasma\textsuperscript{24}.

The most commonly used dusty plasma device is the parallel plate, 13.56 MHz rf discharge, shown schematically in Figure 1. When the device is operated in the so-called unsymmetric mode, the upper electrode is grounded and the rf power is applied through a blocking capacitor (capacitively coupled) to the lower electrode. In this mode of operation, a negative DC self-bias develops on the lower electrode. The downward electric field associated with the sheath of the lower electrode then provides an upward force on negatively charged dust grains which balances their weight, allowing them to levitate above the lower electrode.

There have also been a number of devices that use a DC glow discharge as the plasma source. Due to ambipolar diffusion, the central region of a glow discharge will have a positive space potential relative to the walls, so an electric field of sufficient magnitude and direction will be present that naturally traps negatively charged dust grains. Schematic diagrams of three dusty plasma devices based on the DC glow discharge are shown in Figure 7. Figure 7(a) is a device in which a discharge (usually in argon gas) is formed below an anode whose normal is oriented vertically downward. The grounded chamber wall serves as the cathode, although a separate cathode electrode can also be used. Dust grains, loaded onto a tray below the anode, are spontaneously incorporated into the plasma when the discharge is struck. The dust grains are levitated by the downward electric field in the discharge [82–86].

A variation of this device, which uses an anode with its normal oriented along a weak, uniform, horizontal magnetic field, is shown in Figure 7(b). The magnetic field was of sufficient strength, $B \approx 10 \text{ mT}$, to magnetize the electrons, allowing the glow discharge to form along the horizontal direction.
The dust particles were also incorporated into the discharge from an electrically floating tray located below the anode [85]. A variation of the device in Figure 7(b) in which a dust cloud was trapped within an anode glow discharge formed within a magnetized Q machine plasma was discussed in [81]. A DC anodic glow discharge plasma produced within an RF plasma with a horizontal magnetic field of 20 mT was used by Trottenberg et al. [86], who also provided a detailed model to explain the dust confinement. Figure 7 (c) shows a schematic of a DC glow discharge device, in a U-shaped geometry that allows neutral gas to flow from one end to the other. The dust grains can be entrained in the gas flow allowing studies of the effects of flowing complex plasma behavior. This device (PK-4) was installed on the ISS in March 2019 and is being used to investigate the liquid state of complex plasmas on the kinetic level, the transition from laminar to turbulent flow, lane formation, and dust acoustic waves [87].
5. Strongly coupled dusty plasmas

In 1934, Eugene Wigner predicted the formation of a solid (crystalline) phase of electrons in a uniform neutralizing background, if the potential energy of the electrons was greater than their kinetic energy [88]. Some 50 years later, Hideo Ikezi predicted that dust grains in a plasma would, under certain conditions, form a Coulomb lattice or dust crystal [89]. A dust crystal is an ordered arrangement of dust grains, which is formed when the dust grains are in a strongly coupled state, i.e. when the Coulomb interaction potential energy (PE) between nearest neighbors greatly exceeds their average kinetic energy (KE). This is quantified by the Coulomb coupling parameter

$$\Gamma = \frac{PE}{KE} = \frac{q_d^2}{4\pi\epsilon_0 d} \frac{1}{kT_d}$$  \hspace{1cm} (24)

where \(d \approx n_d^{-1/3}\) is the average interparticle spacing and \(T_d\) is the dust kinetic temperature. Although garden variety plasmas tend to be in the weakly coupled state, \(\Gamma < 1\), the large charge on grains in a dusty plasma opens up the possibility that \(\Gamma > 1\), so that the dust crystals predicted by Ikezi\textsuperscript{25} can be formed. Because the charge on the dust grains is partially screened by plasma, the Coulomb coupling parameter in Equation (24) must be modified by the introduction of an additional parameter \(\kappa = d/\lambda_D\), where \(\lambda_D\) is the plasma screening length. If the grain-grain interaction is modelled as a Debye-Hückel (Yukawa) potential, the modified or screened coupling parameter is defined as

$$\Gamma_s = \Gamma \exp(-\kappa) = \frac{q_d^2}{4\pi\epsilon_0 d kT_d} \exp(-\kappa).$$  \hspace{1cm} (25)

The parameters that control the value of \(\Gamma_s\) are the dust charge, the dust density, which fixes the intergrain spacing \(d\), the ion density, which fixes the screening length \(\lambda_D\), and the thermal energy of the dust grain suspension, \(kT_d\). In practice, one chooses a grain radius \(a\) sufficient to provide a large charge \(q_d(\propto a)\) while still maintaining vertical equilibrium against gravity. The dust temperature \(T_d\) is maintained close to 300 K by operating at relatively high neutral gas pressures, so that the dust grains are cooled by collisions with the neutral gas atoms [90–92]. A plot of \(\Gamma_s\) vs. \(Z_d = |q_d/e|\) is shown in Figure 8, for various combinations of ion and dust densities and for \(kT_d = 0.025\, eV\). Clearly, dust charge numbers \(Z_d > 10^4\) are required to have \(\Gamma_s > 1\). If \(\Gamma_s \approx 1\), the dust is considered to be in a liquid-like state.

5.1 Theory of strongly coupled dusty plasmas

Ikezi based his prediction of the formation of a Coulomb lattice of dust particles [89] on calculations of a one-component plasma [92] showing that the fluid-
Solid transition would occur at a critical value of the coupling constant, $\Gamma_c \approx 170$, \cite{92,93}. Since these early works, theoretical progress has been made on understanding the strong correlations between charged dust particles in more realistic plasmas where screening is taken into account \cite{94}. To include Debye shielding, in addition to the coupling constant $\Gamma$, the parameter $\kappa = d/\lambda_D$, the ratio of the interparticle distance $d$, and the effective shielding length $\lambda_D$, must be taken into account. Farouki and Hamaguchi \cite{95} performed molecular dynamics simulations to study the equilibrium thermodynamics of strongly coupled systems interacting through a screened Coulomb potential. This enabled them to obtain an ‘equation of state’ for the screened Coulomb system in terms of the parameters, $\kappa$ and $\Gamma$. As expected, the critical value of the coupling constant for the formation of a solid increased with increasing $\kappa$.

One approach used in theoretical studies of dusty plasmas treats the dust particles as an additional heavy ion component of a multi-component fluid system. This approach is typically used to obtain linear dispersion relations for waves in dusty plasmas, see, e.g. \cite{7}. However, Tystovich and de Angelis \cite{96} have argued that since the dust particles are constantly absorbing...
electrons and ions from the plasma, a dusty plasma is inherently an open system which requires a plasma source to constantly replenish these losses. They stress that a dusty plasma cannot be properly treated as a multi-ion fluid and can only be investigated using kinetic theory, which takes into account plasma absorption on the dust particles. Various attempts have been made to formulate a kinetic theory of strongly coupled dusty plasmas starting from the BBGKY hierarchy and treating the dust charge as a dynamical variable [97–99]. These theories have been applied to understand the dynamical and structural properties of strongly coupled dusty plasmas, the formation of dust crystals, and phase transitions in dusty plasmas. A comprehensive kinetic theory of dusty plasmas was published in a series of five papers by Tsytovich and de Angelis [100–104].

Another interesting approach that has been applied in the theory of phase transitions in dusty plasmas is to derive a van der Waal’s equation of state for the dusty plasma [105]. At first glance, this seems counterintuitive since the Van der Waal’s force is an attractive force, and the force between like-charged dust grains is repulsive. However, the possible existence of a long range attractive component of the dust-dust interaction has been discussed [26]. It was shown that predicted value of the critical coupling parameter for the phase transition (to the crystalline state) was in qualitative agreement with experimental observations. It was also shown that phase transitions were not possible for a pure screened Coulomb interaction.

### 5.2 Observations of dust crystals in the laboratory

The discovery of a dust (Coulomb) crystal of charged dust particles was first reported in 1993 at the ICPIG meeting in Bochum, Germany [106]. The formation of a dust crystal was being pursued by a number of groups, and in the three-month period from June to August 1994 research teams in Germany, Taiwan, and Japan reported their discovery [75,76,107,108]. In somewhat of a stroke of good luck, the parallel-plate rf discharge plasma device adopted by many dusty plasma research groups turned out to be ideal for the formation of a two-dimensional dust crystal. Dust grains, which acquired very large charges (tens of thousands of electrons), could be levitated above the lower electrode in a single layer, and the typical neutral gas pressures (20–200 Pa) were adequate to maintain low dust temperatures. Horizontal dust confinement was also provided by the self-consistently produced radial electric fields in the plasma. A schematic of a typical setup used to form a two-dimensional dust crystal is shown in Figure 9(a). A single-frame video image of the dust crystal is shown in Figure 9(b). A summary of important contributions to dust crystal research has been given in [106,109,110].
The dust crystals reported in [76,107,108] were flat, two-dimensional structures, since the RF parallel plate devices used in these ground-based experiments can produce a single-layer dust suspension. In 2004, however, fully three-dimensional dust crystals – Coulomb balls, were formed in the same type of device, which included a novel dust vertical and horizontal confinement scheme that permitted the formation of extended three-dimensional dust clouds that evolved into a structure of nested crystalline shells [111]. Three-dimensional dust balls were also observed in a cloud of dust grains confined in an anode double layer [60].

Apart from the intrinsic interest in systems of like charges than from ordered states, dust crystals have been investigated as model systems exhibiting strong coupling behavior, phase transitions [90,112], structures [113], dislocations and lattice defects in crystals. Dust crystals are ideal for this purpose because of the ability to study their properties at the
microscopic level in real time. Almost from the time of their experimental
discovery, possible commercial applications of dust crystals have been
anticipated [114]. For example, dust crystals have been considered as pos-
sible photonic band gap structures [115], because the region where electro-
magnetic wave propagation is forbidden is in the range of typical Debye
length scales, \( \lambda_D \approx 100 \, \mu m \), which corresponds to the (commer-
cially interesting) THz frequency range. Moreover, since the Debye length is controlled
by the plasma density, the band gap could be adjustable.

6. Waves in dusty plasmas

A large fraction of all the papers published on dusty plasmas deal with
waves. An eruption of theoretical papers on waves in dusty plasmas
occurred in the late 1980s, spurred on by observations of new phenomena
associated with charged dust in planetary rings, comet tails, and the Earth’s
mesosphere. A cottage industry soon sprung up to (a) analyze the effect of
charged dust on plasma waves and (b) derive the dispersion relations for
very low-frequency collective modes involving the dynamics of the dust
grains [116–124]. Both kinetic theory and fluid theory were used to derive
dispersion relations by treating the charged dust as part of a three-
component system along with the plasma electrons and ions, in a manner
analogous to the methods applied to multi-ion plasmas.28 The voluminous
literature on waves in dusty plasmas precludes the possibility of giving
a comprehensive summary, and this will not be attempted here. The reader
is referred to references [8,13–15,125,126] for more complete reviews.
Furthermore, in any discussion of waves in dusty plasmas, a distinction
must be made between dusty plasmas in the weakly to moderately coupled
state and dusty plasmas in the strongly coupled state. In keeping with the
inclinations of the author, the discussion here will focus on waves in non-
strongly coupled dusty plasmas.

The huge difference between the masses of the electrons and ions, on the
one hand, and the dust grains on the other hand, introduces some new
wrinkles, as well as possible simplifications in the analysis of wave phenom-
emon in dusty plasmas. As indicated above, there are two aspects of the
problem that can be considered separately. For the usual plasma waves, such
as, e.g. electron plasma waves, ion acoustic waves, and electrostatic ion
cyclotron waves, the dynamics of the dust grains can be ignored, and their
effect on the dispersion relations enters only through the dust charge
modification on the plasma neutrality condition (Equation 14). The plasma
waves occur at frequencies that are too high for the dust grains to respond.
However, since the dust is considered as a third component of the plasma
(in the fluid approach, the electrons, ions, and dust are treated as three
interpenetrating species coupled by electric fields), there is an additional
class of dust wave modes that involve the dynamics of the dust grains, i.e.
oscillations in the dust fluid. I will illustrate how these cases differ by
discussing two examples: 6.1 – the dust ion acoustic wave (DIA) and 6.2 –
the dust acoustic wave (DA), in a dusty plasma with dust grains having
a negative and constant charge, \( q_d = -eZ_d, \ Z_d > 0 \). The analysis will be
based on the plasma fluid continuity and momentum equations in one
dimension

\[
\frac{\partial n_j}{\partial t} + \frac{\partial}{\partial x} (n_j v_j) = 0,
\]

\( m_j n_j \left( \frac{\partial v_j}{\partial t} + v_j \frac{\partial v_j}{\partial x} \right) + kT_j \frac{\partial n_j}{\partial x} + q_j n_j \frac{\partial \phi}{\partial x} = 0,
\]

where \( j = (e, i, d) \), and Poisson’s equation for the electrostatic potential \( \phi \)

\[
\frac{\partial^2 \phi}{\partial x^2} = -\frac{1}{\varepsilon_0} \sum_{j=(e,i,d)} q_j n_j.
\]

### 6.1 The dust ion acoustic (DIA) wave

The DIA wave is an ion acoustic wave (a longitudinal, compressional ion
wave) in a dusty plasma, that is modified by the presence of the immobile
dust.\(^{29}\) It is a wave that occurs at frequencies well below both the electron
and ion plasma frequencies, \( f < < f_{pe}, f < < f_{pi} \), but well above the dust
plasma frequency, \( f > > f_{pd} \), where \( f_{pa} = \sqrt{q_e^2 n_e / \varepsilon_0 m_e} \), \( \alpha = (e,i,d) \), so that
the dust grains do not participate in the wave motion. Because of the
separation of the time scales, we can take the electrons as massless
\( (m_e \rightarrow 0) \) and the dust grains as infinitely massive \( (m_d \rightarrow \infty) \); for simplicity
we can take the ions to be cold, \( T_i = 0 \). The phase velocity for linear DIA
waves is obtained by linearizing the fluid equations around a zero order state
by expanding the fluid variables and electric potential in terms of zero-order
and first-order quantities as \( n_i = n_{i0} + n_{i1}, \ \ n_e = n_{e0} + n_{e1}, \ \ v_i = v_{i0} + v_{i1} \)
and \( \phi = \phi_0 + \phi_1 \), with no zero order drifts or electric fields,
\( v_{i0} = 0, \ \ \phi_0 = 0 \). For low-frequency ion waves (having wavelengths much
longer than the Debye length), we use the quasineutrality condition
\( \frac{\partial^2 \phi_1}{\partial x^2} \approx 0 \), \( \rightarrow \ n_{e1} = n_{i1} \), since dust motion is not considered, \( n_{d1} = 0 \). In the zero order state, \( n_{i0} = n_{i0} + Z_d n_{d0} \), so that \( n_{e0} = (1 - \varepsilon Z_d) n_{i0} \),
where \( \varepsilon = n_{d0} / n_{i0} \). The linearized fluid equations are then
\[
\frac{\partial n_{i1}}{\partial t} + n_{i0} \frac{\partial v_{i1}}{\partial x} = 0, \tag{29}
\]

\[
\frac{\partial v_{i1}}{\partial t} + \frac{e}{m_i} \frac{\partial \varphi_1}{\partial x} = 0, \tag{30}
\]

\[
kT_e \frac{\partial n_{i1}}{\partial x} - en_{e0} \frac{\partial \varphi_1}{\partial x} = 0, \text{ with } n_{e1} = n_{i1}. \tag{31}
\]

Equation (31) is used to eliminate \(\partial \varphi_1 / \partial x\) in Equation (30) giving

\[
\frac{\partial v_{i1}}{\partial t} = - \frac{kT_e}{m_i n_{e0}} \frac{\partial n_{i1}}{\partial x}, \tag{32}
\]

illustrating that the coupling between electrons and ions in the compressional wave is through the electric field. The linear wave equation for \(n_{i1}\) is obtained by taking \(\partial / \partial x\) on Equation (32) and \(\partial / \partial t\) on Equation (29) and equating the mixed partial derivatives of \(v_{i1}\)

\[
\frac{\partial^2 n_{i1}}{\partial x^2} = \frac{1}{c_{sd}^2} \frac{\partial^2 n_{i1}}{\partial t^2}, \tag{33}
\]

where

\[
c_{sd} = \sqrt{kT_e m_i (1 - \varepsilon Z_d)} \tag{34}
\]

is the dust modified ion acoustic speed, which can be expressed as \(c_{sd} = c_s / \sqrt{1 - \varepsilon Z_d}\), where \(c_s = \sqrt{kT_e / m_i}\) is the dust acoustic speed. Note that in the absence of dust, \(\varepsilon = n_{i0} / n_{i0} = 0\), and \(c_{sd} \rightarrow c_s\). The phase velocity increases as the quantity \(\varepsilon Z_d\) increases, which has an important effect on wave damping. The fluid theory provides no conclusions about the growth or damping of the DIA waves. However, an analysis based on the Vlasov equation (kinetic theory) shows that ion acoustic waves are subject to Landau damping, due to a wave-particle resonance when the phase velocity is on the order of the ion thermal velocity. In the presence of dust, the phase velocity is increased, which reduces the Landau damping lowering the threshold for excitation.\(^{30}\)

### 6.2 The dust acoustic (DA) wave

The DA wave is a very low frequency, \(f << f_{pe}, f << f_{pi}, f << f_{pd}\), longitudinal dust density wave.\(^{31}\) The phase velocity for this wave can be obtained using fluid theory using Equations (29) – (31) under certain simplifying conditions. The wave frequency is so low that, in this case, both the electrons and ions can be taken as massless, \((m_{i,e} \rightarrow 0)\), so the momentum equation, Equation (27) reduces, in first order, to
\[ n_{i/e,1} = (-/+) n_{i/e,0} \frac{e\phi_1}{kT_{i/e}}, \]  

(35)

which is the linearized Boltzmann condition. We can again assume quasi-neutrality in the zero-order state, \( n_{e0} = (1 - \varepsilon Z_d)n_{i0}, \) with \( \varepsilon = n_{d0}/n_{i0}. \) The same linearization procedure is used as in Section 6.1. The linearized continuity and momentum equations for the dust (taken, for simplicity, to be cold, \( T_d = 0) \) are

\[ \frac{\partial n_{d1}}{\partial t} + n_{d0} \frac{\partial v_{d1}}{\partial x} = 0 \]  

(36)

\[ \frac{\partial v_{d1}}{\partial t} - \frac{eZ_d}{m_d} \frac{\partial \phi_1}{\partial x} = 0 \]  

(37)

The fluid equations are closed with the addition of the quasineutrality condition

\[ n_{i1} = n_{e1} + Z_d n_{d1}. \]  

(38)

Equation (35) is then used in Equation (38) to relate \( n_{d1} \) to \( \phi_1, \) and when this is inserted in Equation (37) we obtain

\[ \frac{\partial v_{d1}}{\partial t} = - \frac{c_{DA}^2}{n_{d0}} \frac{\partial n_{d1}}{\partial x}, \]  

(39)

where

\[ c_{DA} = \sqrt{\frac{eZ_d^2 kT_i}{m_d [1 + (T_i/T_e)(1 - \varepsilon Z_d)]}}, \]  

(40)

is the dust acoustic speed. Performing the same process as in Sec. 6.1 of equating the mixed partial derivatives of \( v_{d1} \) formed by taking \( \partial/\partial t \) on Equation (36) and \( \partial/\partial x \) on Equation (39) we obtain the linear wave equation for \( n_{d1} \)

\[ \frac{\partial^2 n_{d1}}{\partial x^2} = \frac{1}{c_{DA}^2} \frac{\partial^2 n_{d1}}{\partial t^2}. \]  

(41)

In the theory of sound waves in a neutral gas, the wave inertia is due to the mass of the atoms, and the restoring force is due to the pressure imbalance which is transmitted to the gas atoms through collisions. In the DA wave, the inertia is provided by the dust grains, and the restoring force is provided by the plasma pressure gradient with the interaction mediated by the electric field due to the small imbalance in the plasma charge densities.

The dust acoustic speed Equation (40) is \( \propto m_d^{-1/2}, \) which accounts for the relatively low-phase speed of the DA waves. For example, with
\( \varepsilon = 10^{-4}, \ Z_d \approx 2000, \ m_d \approx 10^{-15} \text{ kg}, \ T_i/T_e = 10^{-2}, \ kT_i = 0.025 \text{ eV}, \ c_{\text{DA}} \approx 4 \text{ cm/s} \). For waves having a wavelength of 1 cm, the wave frequency is 4 Hz.

### 6.3 Dispersion relations for the dust ion acoustic and dust acoustic waves

The analyses of the DIA and DA waves in 6.1 and 6.2 were presented to highlight the differences between these two wave modes, and in particular, the fact that the DIA mode is a dust-modified wave in which the dust enters only through the quasineutrality condition, whereas the DA mode is a dust mode, which directly involves dust motion. A general dispersion relation including both wave modes could be obtained from the fluid equations by retaining the ion mass (inertial) term, while still assuming \( m_e = 0 \). The general dispersion relation for low-frequency electrostatic waves in a dusty plasmas was obtained in [119], a treatment that also included a zero-order magnetic field, allowing for wave propagation both parallel and transverse to \( \overrightarrow{B} \). The dispersion relation was obtained by linearizing the continuity and momentum equations for the electrons, ions, and dust components and assuming that all first-order quantities vary as \( e^{i(K_x x + K_z z - \omega t)} \), where \( z \) is the direction parallel to \( \overrightarrow{B} \) and \( x \) is the transverse direction. The acoustic modes are obtained by taking \( \overrightarrow{B} = 0 \), and \( K_x = 0 \), where \( K \) represents the wave number. This results in a fourth-order dispersion relation for \( \omega(K) \), (quadratic in \( \omega^2 \)) for DIA and DA wave propagation along \( \pm \overrightarrow{K} \). To illustrate the results, the dispersion relation was solved numerically with the following set of parameters:

\[
\begin{align*}
\text{Ar}^+ \text{ ions, } kT_i = kT_d = 0.025 \text{ eV, } kT_e = 2.5 \text{ eV, } m_d = 10^{-15} \text{ kg} \quad (42)
\end{align*}
\]

and the results are shown in Figure 10. The 3 upper curves correspond to the DIA wave, for \( Z_d = 2000 \) and for \( \varepsilon = 1 \times 10^{-4} \) (red) and \( \varepsilon = 4 \times 10^{-4} \) (green). For comparison, the ion acoustic wave dispersion relation (\( \varepsilon = 0 \)) is shown as the black line. For a fixed \( K \), \( \omega \) increases with increasing dust density, since the phase velocity increases with \( \varepsilon \), as indicated in Equation (34). The bottom curve (blue) is the lower frequency DA wave, for \( \varepsilon Z_d = 0.2 \).

### 6.4 Experimental observation of waves in dusty plasmas

#### 6.4.1 The effect of negatively charged dust on current-driven electrostatic ion-cyclotron waves

A considerable amount of theoretical work on waves in dusty plasmas was done in the late 80s, and early 90s, and experimental work followed a few
years later when devices to produce dusty plasmas were developed. One of the earliest experiments to study the effect of dust on a plasma wave was performed in the modified dusty Q machine described in [81]. This work investigated the effect of dust on the excitation of electrostatic ion-cyclotron waves (EIC) [127]. It was found that a substantial amount of negatively charged dust made the plasma more unstable to the EIC instability, i.e., it reduced the critical electron drift velocity for instability. This result was predicted theoretically by Chow and Rosenberg [124,128] using the Vlasov theory.

6.4.2 The dust ion-acoustic (DIA) wave
The dusty Q machine was also used to study the propagation of grid-launched ion acoustic waves (frequencies ~ tens of kHz) propagating through a dusty plasma column [129,130]. The results of the experiment are shown in Figure 11. Figure 11(a) shows that the DIA wave phase velocity increases with increasing $\varepsilon Z_d$ (the fraction of negative charge per unit volume on the dust). Figure 11(b) shows a plot of the spatial damping rate
$K_i$ of the waves normalized by the wavenumber $K_r$ vs. $\varepsilon Z_d$. As predicted by kinetic theory, the wave damping decreases with increasing, $\varepsilon Z_d$. The results in Figure 11 are an example of the modification of a plasma wave dispersion relation due to the effect of negative dust on the plasma neutrality condition. In this case, the dust does not participate in the wave motion because of its large mass. In fact, for this experiment, the dust merely fell through the plasma, residing in the plasma long enough to acquire a negative charge.

Figure 11. Experimentally measured DIA wave dispersion relation. (a) Phase velocity vs. $\varepsilon Z_d$. (b) Ratio of the imaginary to real wavenumber $K_i/K_r$ vs. $\varepsilon Z_d$, where the imaginary part of $K$ corresponds to the spatial damping rate. The solid lines in (a) and (b) are the theoretical dispersion curves computed using the Vlasov theory [129].
6.4.3 The dust-acoustic wave (DAW)

The DAW is a wave in which the dust particles participate in the wave motion and is thus a very low frequency (compared to the usual plasma waves) mode. It is in a true sense, a dust wave, since the dust particles jiggle back and forth in the wave just as air molecules do in a sound wave. The DAW is essentially a plasma sound wave propagating through the dust suspension.\textsuperscript{32} The DAW is unique in that with micron-sized particles, the wave is visible.

The appearance of the DAW occurs in a plasma in which the dust is confined within the plasma.

A confined dust cloud was formed using a modified version of the device used in [81]. At the end of the plasma column opposite to the plasma source, a secondary anode glow discharge (referred to as a firerod) was formed, which electrostatically confined a cloud of micron-size dust grains. Under these conditions, a propagating wave was observed within the dust cloud,

![Figure 12](image.jpg)

**Figure 12.** A single frame video image of a dust acoustic wave taken from reference [131]. The bright vertical striped are the compressional zones of the dust acoustic wave which propagates from right to left in this image. The scattered light intensity is proportional to the dust density, and the lower plot shows the intensity profile taken along a line through the center of the upper image.
which could be imaged with a video camera, as shown in Figure 2 of [131]. The bright vertical stripes are the regions of enhanced dust density corresponding to the wave crests. The bottom plot shows the light intensity (proportional to the dust density) profile along a horizontal line through the wave, showing the sinusoidal fluctuation at a given time. The video images provide direct measurement of the wavelength, $\lambda \approx 0.6 \text{ cm}$, and phase velocity, $v_{ph} \approx 9 \text{ cm/s}$, from which a wave frequency $f = v_{ph}/\lambda \approx 15 \text{ Hz}$ is obtained. The measured phase velocity was in good agreement with the value calculated using Equation (40). The DA wave seen in Figure 12 was self-excited by an ion-dust streaming instability [132], and thus, neither the wave frequency nor wavelength could be varied.

Measurement of the DA wave dispersion relation, $K$ vs. $\omega$, was performed in a device described in [133], in which a dusty plasma was formed in a DC anode glow discharge of the type shown in Figure 6(b). To control the wave frequency, a sinusoidal voltage modulation was applied to the anode at frequencies in the range of 5–40 Hz. Dust acoustic waves, naturally excited by the relative drift of the ions through the dust suspension, were synchronized to the modulation frequency. For each value of the modulation frequency, the wavelength of the DA waves was measured and the dispersion relation is shown in Figure 13. The measured wave numbers agreed

![Figure 13](image-url)  
**Figure 13.** Experimentally measured dust acoustic wave dispersion relation, taken from reference [133]. The wave frequency was controlled by applying an AC modulation to the DC discharge voltage. The wave frequency spontaneously synchronized to the applied modulation, and the wavenumber $K$ was measured by analyzing the images obtained from a video camera.
well with the theoretical DA dispersion relation, including the effect of dust-neutral collisions.

The DA wave (or dust density wave) has been investigated theoretically and experimentally over a span of about 25 years. It has been observed in weakly coupled, moderately coupled, and strongly coupled dusty plasmas. DA waves are a rather ubiquitous feature of dusty plasmas formed in gas discharges [134]. It has been studied under microgravity conditions onboard the ISS. It has been predicted that it might be present in dusty plasmas near the Moon’s surface [135–138] and might be captured by the high-resolution cameras onboard the Rosetta spacecraft in its rendezvous with comet 67P/Churyumov-Gerasimenko [139]. However, to this day, there have been no reported observations of DA waves outside the laboratory. It has been speculated that the dust acoustic wave may be important in astrophysics as a possible mechanism for triggering dust grain condensation [140,141]. In a dusty plasma with like charged particles, Coulomb repulsion inhibits agglomeration of the grains into larger and larger objects. However, dust grains accelerated toward each other by a passing DA wave, might be able to overcome the Coulomb repulsion and coalesce. A contributing factor is the effect, pointed out in Section 2.7, that the charge on a dust grain is reduced if the interparticle separation is less than the Debye shielding distance. An experiment reported in 2012 showed that dust grain agglomeration was induced by self-excited dust density waves [142].

This author has given a summary of DA wave research up to 2014 [143]; however, interest in this topic has not waned, and new papers continue to appear regularly.

### 6.5 Nonlinear waves in dusty plasmas

The very low-frequency waves in a dusty plasma, e.g. the dust acoustic wave, are important because they provide a mechanism for organizing and structuring the dust. In a cosmic dusty plasma, the dust component accounts for the overwhelming fraction of the mass, so that any process that produces structurization of the dust essentially determines the structure of the cloud. If the dust waves grow to large amplitudes (i.e. become nonlinear), the structurization can completely alter the characteristics of the cloud. As mentioned in Sec. 6.4, a large amplitude dust acoustic wave or dust acoustic shock wave can induce agglomeration of dust grains, which is the first stage in the formation of larger objects. There are certain processes that are unique to a dusty plasma through which an unstable wave mode may saturate after attaining large amplitude. One such process is associated with the fluctuations in the charge on the dust grains. The nonlinearities can lead to localization of the waves and the formation of coherent structures such as solitons, shocks, and vortices [144,145]. The potential
importance of nonlinear dust acoustic waves was already recognized in the early work of Rao, Shukla and Yu [118] who carried the perturbation analysis beyond the linear level and obtained a generalized K-dV equation to show that the DAW can propagate as solitons.

In laboratory experiments, very large amplitude DAWs are commonly observed. This was also evident from the observation that the waveforms of the DAWs were non-sinusoidal with sharp wave crests and flat wave troughs [146,147]. In another experiment, the DAWs were observed to grow as they propagated through the plasma and harmonics were generated [148]. Nonlinear DAWs have been treated theoretically by development of a second-order perturbation theory [149], or by descriptions in terms of cnoidal wave functions [147]. These nonlinear theories were able to capture the non-sinusoidal features of the DA waveforms. Observations of the linear growth phase of the DAWs were accomplished in an rf discharge plasma operating at high neutral pressures (~ 0.4 Torr) so that the waves were highly damped by dust-neutral collisions [150] or in a quiescent drifting dusty plasma that flowed into a plasma region where the ion drift velocity was above a critical value for wave excitation [151].

There have been a number of experiments investigating nonlinear wave behavior in dusty plasmas. Bandyopadhyay et al. [152] observed the propagation of finite amplitude low frequency solitary waves in a DC discharge plasma. The product of the solitary wave amplitude and the square of the pulse width was constant as the Mach number was increased, in agreement with predictions of the KdV equation. Boruah et al. [153] observed that in the oblique collision of two solitons, the solitons preserve their identity, which is a characteristic property of solitons. Jaiswal et al. [154] observed precursor DA solitons ahead of a rapidly moving object in a flowing dusty plasma. Meyer et al. [155] observed the formation of a transient bow shock when a supersonically flowing dusty plasma impinged on a cylindrical object. Heinrich et al. [156] reported the observation of the steepening of self-excited DAWs into DA shock waves (DASWs) in a DC glow discharge dusty plasma. The development of the DASWs was consistent with numerical solutions to the fully nonlinear fluid equations obtained by Eliasson and Shukla [157]. Heinrich et al. [158] observed a structure-forming instability in a dusty plasma that produced a stationary region of high and low dust density in a dust suspension.

### 6.6 Waves in strongly coupled dusty plasmas

We have been discussing mostly waves in weakly dusty plasmas, in which $\Gamma < 1$. Both the DIA and DA modes are longitudinal, compressional waves that propagate in gas-like dusty plasmas. A dusty plasma in the strongly coupled state exhibits short range order and behaves more like a liquid or
a solid (Coulomb crystal) if $\Gamma > 1$, and can support, in addition to longitudinal, compressional modes, transverse or shear modes. Waves which propagate in dust crystals are called dust-lattice waves and can be analyzed using the equations of motion of the individual particles with a Yukawa-like screened Coulomb potential. The development of the theory of waves in strongly coupled dusty plasmas is an ongoing process and a number of different theoretical approaches have been proposed, including the quasi-localized charge approximation of Rosenberg and Kalman [159], the multi-component kinetic approach of Murillo [160], and the generalized hydrodynamic approach of Wang and Bhattacharjee [161] and Kaw and Sen [162], and numerical (PIC) simulations by Winske et al. [163].

There have been a large number of laboratory investigations of waves in strongly coupled dusty plasmas. Piper and Goree [164] excited low frequency compressional waves in a planar (2D) dust crystal by applying a sinusoidal voltage signal to a wire at the edge of the dust crystal. The frequency of the applied signal was varied and the real and imaginary parts of the wavenumber of the resulting perturbation were measured. The results appeared to be in good agreement with the theory of dust acoustic waves for a continuum system. Homan et al. [165] used a laser to excite dust lattice waves in a linear chain of dust particles. The measured dispersion relation was compared with a model of one-dimensional dust lattice waves to obtain the shielding length. In this case, the experimentally determined dispersion relation was not in agreement with the dispersion relation for the (continuum) dust acoustic waves. Nonomura et al. [166] used the laser excitation method to investigate transverse waves in a 2D dust crystal. The measured dispersion relation exhibited a nondispersive characteristic ($\omega \propto K$) over a wide range of $K$ values. Misawa, et al. [167] used a hot filament dc argon discharge plasma to form a linear dust chain of strongly coupled dust particles. The transverse dust lattice wave was excited by applying a sinusoidal voltage to a pin electrode near the edge of the dust chain. Pramanik et al. [168] reported the experimental observation of a spontaneously excited transverse shear wave in a 3D strongly coupled DC glow discharge dusty plasma in the fluid regime. Liu et al. [169] studied the excitation of a transverse optical mode (in analogy with the optical mode in ionic crystals) in a one-dimensional chain of dust particles confined in a groove in the lower electrode of an rf discharge plasma. The mode was excited by applying a perturbation to a single particle in the chain using two counterpropagating laser beams. The measured dispersion relation was compared with a theoretical dispersion relation and a molecular dynamics simulation, which were both presented in the paper. Meyer et al. [170] used a large plasma chamber with an rf powered electrode of 85 cm diameter to form a large 2D dust crystal having an unprecedented diameter of 27 cm (the largest ever produced). This set-up was used to observe the coupling of the transverse vertical and longitudinal in-plane dust-lattice wave modes in the absence of mode crossing. The results were in good
agreement with molecular dynamics simulations. Finally, we mention the observation of a Mach cone in a 2D Coulomb lattice of dust particles created by the disturbance induced by the supersonic motion of an errant dust particle in a partial dust layer beneath the main layer [171]. The measured Mach cone angle corresponded to a particle Mach number of 1.8. Mach cones in dusty plasma were predicted theoretically by Havnes et al. [172], who suggested that their potential observation in Saturn’s rings and the measurement of their opening angles could be used as a diagnostic for the dusty plasma conditions in Saturn’s rings.

7. Magnetized dusty plasmas

This article has focused mainly on laboratory dusty plasmas without externally applied magnetic fields. However, space and astrophysical environments [16,173] or controlled fusion devices include magnetic fields, which can affect the dynamics of dust particles [43,174–176]. For example, the ITER-controlled fusion device under construction in France has a toroidal magnetic field up to 5 T in strength in a vacuum vessel of 2 m minor radius. Recognizing the need to study dusty plasmas in strong magnetic fields, the dusty plasma community roughly ten years ago began discussing the possibility of building a magnetized dusty plasma device.

7.1. Dust magnetization

What does magnetized mean in this context? A dusty plasma contains at least three charged particle species: electrons, ions, and dust, whose dynamics can, to a lesser or greater extent, be influenced by magnetic fields. A magnetized collisionless plasma is defined as one in which the gyroradius (or cyclotron radius) of both the electrons and the ions, \( r_g = m_j v_j / q_j B \), \( j = (e, i) \), is much smaller than the size of the device. For example, in a cylindrical plasma, \( r_g \ll R \), where \( R \) is the radius of the plasma. For a low-temperature plasma \( T_{(e,i)} \leq 1 \) eV), a magnetic field < 0.1 T is usually sufficient to magnetize both electrons and ions (say Ar\(^+\)) in a plasma column of 10 cm diameter. The task of magnetizing a dust particle having a charge to mass ratio some twelve orders of magnitude smaller than \( e/m_e \) is considerably more challenging, but not impossible. Recall that the dust charge \( q_d \propto a \) and \( m_d \propto a^3 \), if \( v_d \approx v_{Td} \approx \sqrt{kT_{d}/m_d} \), then the dust gyroradius scales as \( r_{cd} \propto a^2 B^{-1} \), so that \( r_{cd} \) can be made small by using very small dust grains. One needs to keep in mind, however, that to be able to image individual dust grains in visible laser light, the particle size cannot be much smaller than the laser wavelength, which places a practical lower limit on the dust size.\(^{35}\) Figure 14(a) shows a plot of the gyroradius of a dust particle vs. B for various combinations of dust sizes and
dust temperatures. For a plasma scale size on the order of 10 cm, the gyroradius should be less than say 1 cm, which requires magnetic fields $\geq 1$ T. For steady state operation with magnetic fields $\geq 1$ T, superconducting magnet coils must be used. To place a typical dusty plasma device in such a magnetic field, a solenoid with a relatively large bore is required. Superconducting magnet systems that can produce magnetic fields up to a few Teslas are commercially available, with a cost in the range of about 1 M USD.

Having the dust gyroradius small relative to the plasma size is not the only parameter that must be considered, however. Almost all plasma sources in which dust grains are suspended are weakly ionized so that the effects of collisions between the dust grains and the neutral atoms must be taken into account. When a gyrating charged particle collides with another particle, its guiding center effectively jumps from one magnetic field line to another by a step size on the order of its gyroradius. To minimize the motion of a particle across the magnetic field lines, the collision frequency should be much less than the gyrofrequency of the particle, i.e. $\nu_{dn} \ll \omega_{cd} = q_d B/m_d$, a condition that is equivalent to requiring that particle gyroradius is much smaller than the collision mean free path, $r_{cd} \ll \lambda_{dn}$. If the dust-neutral collision frequency is computed using the Epstein formula [Equation (22)], the ratio $\omega_{cd}/\nu_{dn} \propto B/P$, where $P$ is the neutral pressure. A plot of $\omega_{cd}/\nu_{dn}$ vs. $B/P$ for dust radii of $a = 0.25 \mu m$ and $1.0 \mu m$ is shown in Figure 14(b). Very small dust grains and very large magnetic field strengths are required to have $\omega_{cd}/\nu_{dn} > 1$. Even with $a = 0.25 \mu m$, the dust grains are only marginally magnetized; however, under these conditions, the magnetic field may still affect the dynamics of the dust particles.

![Figure 14](image)

**Figure 14.** (a) The gyroradius of a dust particle vs. applied magnetic field, for various dust radii and temperatures. (b) Ratio of the dust gyrofrequency to the dust-neutral collision frequency, $\omega_{cd}/\nu_{dn}$ for $a = 1.0 \mu m$ and $a = 0.2 \mu m$, vs. $B/P$. Dust magnetization requires $\omega_{cd}/\nu_{dn} > 1$. ...
Even though the dust grains may not be magnetized, if the plasma electrons and ions are magnetized, there can be a significant influence on the dust because the collection of ions and electrons by the dust grains will be affected by the magnetic field. A magnetic field makes the plasma anisotropic because the ions and electrons move primarily along the field lines. This may completely change the nature of the charging processes, and the OML charging theory, which assumed that the plasma was isotropic, no longer applies. A plot of ion and electron gyroradii vs. B for argon ions at $T_i = 0.025 \text{ eV}$ and electrons at $T_e = 2.5 \text{ eV}$ is shown in Figure 15. For micron-size dust grains, the electron gyroradius $r_{ce} \leq a$ while $r_{ci} > a$ for $B \geq 1 \text{ T}$. This means that the electron collection will be greatly affected by the magnetic field but much less of an effect for the ions. This problem is very similar to the case of current collection by a Langmuir probe in a plasma – the electron current to the probe tends to be significantly reduced when the electrons are magnetized. For the dust grains, a reduction in electron current implies that the charge on the dust will be reduced in a magnetic field. The theory of dust grain charging in a magnetic field has only recently begun to receive attention in theory and numerical simulations [177].

### 7.2. The Magnetized Dusty Plasma Experiment (MDPX)

A device designed for the investigation of magnetized dusty plasmas was constructed at Auburn University in Auburn, Alabama, under the direction
of Professor Edward Thomas, Jr. This device, known as the Magnetized Dusty Plasma EXperiment (MDPX) was commissioned in May 2014, and is operated as a user facility for the international dusty plasma community.\textsuperscript{38} The MDPX has been described in detail in a number of publications [178–182] and is shown schematically in Figure 16. The central component of the device is the superconducting magnet system composed of two sets of coils in separate cryostats, capable of producing a uniform magnetic field up to 4 T. The magnet system was designed to have a large open bore (50 cm) to accommodate an octagonal vacuum vessel with large ports for diagnostic access. The plasma source is a pair of 30 cm diameter parallel plate electrodes energized by a 13.56 MHz RF generator with 1–20 W of power. A unique feature of the MDPX device is the ability to rotate the entire system so that dusty plasmas can be investigated with $\vec{g} \parallel \vec{B}$ or $\vec{g} \perp \vec{B}$, where $\vec{g}$ is the Earth’s gravitational acceleration. There are presently two other high magnetic field dusty plasma devices in operation.\textsuperscript{39}

### 7.3. Observation of imposed order

One of the first and unexpected results in the MDPX device was the observation of a new form of imposed order that was directly linked to the presence of the high magnetic field [182]. These ordered structures formed in the dust suspension when a titanium mesh was used to cover a circular hole in the upper electrode to allow imaging the dust particles from above. The dust particles were suspended in the plasma approximately 20 to 30 mm above the lower, powered electrode and 30 to 40 mm below the upper, floating electrode. Figure 17 shows

![Figure 16. Schematic drawing of the Magnetized Dusty Plasma Experiment (MDPX) at Auburn University [178–182]. The device consists of a 4 superconducting magnet coils capable of a maximum field strength of 4 T, and an RF parallel plate plasma discharge.](image)
two images of the maximum intensity sum of a sequence of 100 video images of 2 \( \mu m \) diameter silica microspheres suspended in the plasma at a neutral argon pressure of 20 Pa. In Figure 17(a) with \( B = 1.0 \) T, the particles exhibited a continuous circular flowing motion caused by an azimuthal ion \( \overrightarrow{E} \times \overrightarrow{B} \) drift. However, when the magnetic field was increased to \( B = 2.0 \) T, although some circular motion is still present, the most prominent feature in the image is the apparent grid structure in the suspended microparticles. Further analysis of the images revealed that the structure in the particle suspension mimicked exactly the structure of the titanium wire grid located a few centimeters above the dust. Measurements of the particle spacing in the grid structure showed that it was identical to the spacing of the mesh wires. The structure of the wire mesh appears to have been imprinted on the dust suspension. We believe this is connected to a mapping of the wire mesh potential distribution along the magnetic field lines. We note that this effect occurs only at high magnetic fields and relatively low neutral pressures and is thus clearly related to the magnetization of the electrons and ions in the plasma.\(^{40}\)

### 7.4. The \( g \times B \) Force on Dust Particles

The dust gridding effect (imposed order) is connected to the magnetization of the electrons and ions and does not require that the dust particles be magnetized. An experiment was performed in MDPX to demonstrate the effect of the magnetic field on dust particle dynamics, by exploiting the capability of operating the device with the magnetic field perpendicular to \( \overrightarrow{g} \). A charged particle of mass \( m \) and charge \( q \) executes a drift motion in the presence of a gravitational and magnetic field, with a drift velocity \( \overrightarrow{v}_{g \times B} = m \left( \overrightarrow{g} \times \overrightarrow{B} \right) / qB^2 \), which for \( \overrightarrow{g} \perp \overrightarrow{B} \), has the magnitude \( v_{g \times B} = mg/qB \).\(^{41}\) Observation of the \( \overrightarrow{g} \times \overrightarrow{B} \) drift is a demonstration of the fact that the dust grains are at least partially magnetized, in the sense that the magnetic force has a direct (measurable) influence on the particle dynamics. This experiment was performed in MDPX [183] by dropping individual dust grains (\( a = 0.25 \mu m \)) into the plasma with the device rotated so that the axis of the solenoid was horizontal. The particles were illuminated by a sheet of 532 nm laser light and their trajectories were recorded using a video camera. The net effect of \( \overrightarrow{g} \times \overrightarrow{B} \) drift and the neutral drag force on the particles is to produce a deflection of the particle from the vertical direction. Deflections were measured for several thousand falling dust particles at a fixed neutral pressure (0.67 Pa) and for magnetic fields in the range of 0.5–2.25 T. Since the deflection angle is directly proportional to the dust gyrofrequency, \( \omega_{cd} = q_d/m_d B \propto q_d/m_d \), and since \( m_d \) is known from the dust radius, the measurement provides a direct estimate for the dust charge [184]. The dust grain charge deduced from this measurement was significantly less than the
value predicted from OML theory, which of course does not take the magnetic field into account. Also, the results indicated that the estimated charge decreased with increasing magnetic field. The large discrepancy between the measured dust charge and the OML value is believed to be due to the fact that in
the high magnetic field cases, the electron gyroradius becomes comparable to the dust size.

7.5. The electrostatic dust cyclotron wave (EDC)

In a plasma containing magnetized dust particles, a fundamental dust mode is the electrostatic dust cyclotron wave (EDC). The EDC mode has a frequency near the dust cyclotron frequency, \( f_{cd} = \frac{\omega_{cd}}{2\pi} = \frac{q_d B}{2\pi m_d} \), and propagates nearly perpendicular to \( \vec{B} \). For \( a = 0.25 \, \mu m \), \( q_d \approx 103 \, C \), \( m_d \approx 10^{-16} \, kg \), and \( B = 1 \, T \), \( f_{cd} \approx 0.25 \, Hz \). Observation of the EDC mode in a dusty plasma would provide convincing evidence of dust magnetization and is one of the experiments that is on the near-term agenda of the MDPX device. Note that a measurement of the mode frequency provides another method of estimating the dust charge. The excitation conditions for the EDC mode have been studied by M. Rosenberg using kinetic theory, including the effects of collisions [185], who showed that the mode could be excited by ions drifting along the magnetic field. The growth of the instability occurs for wave numbers in the range \( K_\perp r_{cd} \approx 1 \), and for ion drift speeds \( v_{id} \approx v_{Ti} \), the ion thermal speed. For the parameters given above, a \( K_\perp r_{cd} \approx 1 \) implies a perpendicular wavelength, \( \lambda_\perp \approx \) a few cm. Rosenberg also noted that the critical ion drift for the excitation of the EDC mode was smaller than that for exciting DA waves. The corresponding EIC (electrostatic ion cyclotron wave) in an electron/ion plasma, which occurs at a frequency slightly above the ion cyclotron frequency \( \omega_{ci} = eB/m_i \), is excited by a relatively moderate drift of the electrons with respect to the ions (i.e. it is a current-driven instability) and is well known to produce ion heating. In a magnetized dusty plasma, it is possible that excitation of the EDC instability could be a mechanism for heating the dust component.

8. Dusty plasma applications: a double-edged sword

The appearance of dust in plasma processing devices was initially met with distress and bewilderment [186]. For more than 40 years, one of the main methods of producing semiconductor integrated circuits involved plasma processing for etching, deposition, sputtering, and surface modification. Particulate contamination of the semiconductor surfaces was found to be a major problem, resulting in device loss rates of up to 50%. Initially, it was thought that the contamination was environmental in nature and occurred during the handling of the devices. However, even with the use of state-of-the-art clean rooms, contamination was still a major issue. Investigations into this problem revealed that the contamination was occurring during the processing itself and was due to plasma-generated particulates [187–189]. The particulates were a by-product
of the etching/sputtering processes in which significant amounts of particulates were formed which eventually fell onto the substrates causing in-situ contamination. This was shown by Gary Selwyn and his colleagues at the IBM Watson Research Center, who published dramatic photographs of structured dust clouds hovering over semiconductor wafers in a plasma processing tool [190,191]. Similar observations of the formation of silicon-containing particulates in silane plasmas used for producing thin films of hydrogenated amorphous silicon were reported by Roth et al. [192]. The formation of dust in silane discharges is now understood to occur in phases starting with anion nucleation followed by coagulation, and then surface growth to tens of nm sizes over periods of tens of seconds [193]. As feature sizes of the semiconductor chips decreased, contamination was recognized by the (hundreds of billion dollar) semiconductor industry as a potentially show-stopping problem that needed to be addressed by investing in basic and applied research [194]. Clean processing technologies are discussed in a 2002 review paper by Läifà Boufendi and André Bouchoule [195]. One interesting approach makes use of the ion drag force in a pulsed plasma jet for dust expulsion [196].

Investigations into the dust contamination problem and the development of dust mitigation processes soon led to the realization that new technologies based on dust formation in plasmas should be pursued – this is the other side of the sword, for example, the production of nanoparticles for the formation of nanostructured materials, carbon nanotubes [197], material coatings to reduce corrosion and increase wear-resistance or reduce friction, and most recently in MEMS processing (microelectron-mechanical devices) and microfluidic devices. The use of plasma processing devices for VLSI has been able to continue down to the ULSI for the production of ICs having 25 million transistors per mm².

In the area of magnetic fusion, there has also been a realization of the potential uses of dust for injection into the divertor regions for wall conditioning or for emergency quenching of the discharge to prevent a disruption. Dust injection is also under consideration as a diagnostic for magnetic fields or plasma flows [198,199]. The trajectories of injected dust particles, which become quickly charged, could be imaged and analyzed to obtain plasma parameters that might not be measurable by other means.

An exciting (and exotic) new application of dusty plasmas is as the working substance of a Dusty Plasma Based Fission Fragment Nuclear Reactor (DPFFR) [200,201]. This is an advanced propulsion device that would enable manned travel to the distant planets. The reactor material is radioactive dust, which emits energetic particles that could be used either directly as a rocket engine or indirectly as an electrical power generating system. Although the concept of a fission fragment nuclear reactor has been considered previously, a major problem was in heat removal of the nuclear core. The use of dispersed dust particles allows for the efficient removal of heat by radiation (due to the
large surface to volume ratio of the dust suspension) and the fact that the dust is charged allows for control using electric and magnetic fields.

The development (mentioned in Sec. 5.2) of possible applications of dust crystals has only begun to be considered. It seems reasonable to speculate that applications of a system of nano- to micron-sized particles, of a chosen material, and arranged in a regular lattice structure with a variable lattice spacing will be found.

9. Summary, outlook, and perspectives

In this article, I have tried to discuss some of the more critical physics and technological issues in the field of dusty plasmas. The field has progressed steadily, given that 40 years ago, the work was nearly 100% theoretical, since there were essentially no laboratory devices in which controlled experiments on dusty plasmas could be performed.

This article has focused on 5 major topics:

- charging of dust grains in a plasma,
- forces on dust grains,
- dusty plasmas in the strongly coupled state,
- waves in dusty plasmas, and
- magnetized dusty plasmas.

Many other important topics and discoveries have not been addressed, and admittedly, this choice of topics reflects to a large degree, my own experiences with ground-based laboratory experiments.

To a considerable extent, the field of dusty plasmas has been driven by discovery – dust formation in semiconductor manufacturing processes, the observation of transient radial spoke structures in Saturn’s B ring, the presence of dust particles in magnetic fusion devices, the laboratory realization of dust Coulomb crystals, the observation of dust streams emanating from the most massive planet in the solar system, the formation of voids in dusty plasmas under microgravity, the appearance of dust density waves in dust-laden gas discharges, and the amazing Hubble Space Telescope images of star forming regions. The discovery-driven phase of dusty plasma research has now shifted to a more systematic and goal-oriented phase of research. In their article in Reviews of Modern Physics, Morfill and Ivlev attribute the continuous growth in interest in the field (following the discovery-driven boost) as resting on three main pillars [15]:

(I) Investigations into the basic properties of the complex (dusty) plasma state as a new state of soft matter;
(II) The study of complex (dusty) plasmas as a model platform for investigation of the physics of strongly coupled plasmas;
(III) Possible technological applications of complex (dusty) plasmas.

These pillars continue to serve as a roadmap for future work in dusty plasmas.

The use of dusty plasmas as a model system to study generic processes of relevance in other physical contexts is due in part to (a) the ability to obtain individual particle-level data, fully resolved in space and time; and (b) the versatility of controlling the degree of interaction between the particles, which allows for investigating both crystalline and liquid-like behavior.43

Dusty plasmas have been used to investigate fluid-like behavior such as studies of bubble and blob formation in liquids [202], vortices [203], Taylor instability [204], laminar dust fluid flows [205], shear flows [206,207], and viscoelasticity [208]. A fruitful line of investigation being pursued by John Goree’s group is the use of a dusty plasma to test predictions of non-equilibrium statistical mechanics, such as the Green-Kubo relation [209], superdiffusion [210], and the autocorrelation function [211].

The study of plasma waves and instabilities continues to be a major area of interest for plasma physicists. With the exception of ionization waves in DC glow discharges, which are visible as luminous moving or stationary striations,44 plasma waves involving fluctuations in the ion and electron densities cannot be studied by visual techniques. The unique ability to image and record individual particle motion has enabled us to literally go inside a plasma wave and observe the motion of particles as the wave passes by, thus providing a deeper understanding of wave-particle interactions, which is one of the most important concepts in plasma physics [212–215]. Studies of nonlinear dust waves [145,147], solitons [152–154], and shocks [156,157] have also been performed, as well as experiments probing the transition from linear waves to non-linear waves to wave turbulence [216,217] considered to be one of the most important and unsolved problems in classical physics.

As this article was being written, members of the U. S. dusty plasma community were discussing possible future directions for the field. There was a consensus for the need to address the fundamental issue of dust charging in particular, to develop methods for controlling the charge on dust grains. The importance of the dust charging process cannot be overstated – roughly a third of this article has been devoted to it. This is due to the fact that it is an entirely new situation in plasma physics not known to a priori the charge on the particles. We know of course that the electron charge is – e, and most laboratory plasmas will have singly charged positive ions.45 Not knowing the charge on a dust particle, either by calculating it from theory under all circumstances or measuring it directly is a serious impediment to further progress and must be addressed. Most of the experimental work on dusty plasmas has concentrated
on monodisperse dust, since having all the same size particles simplifies the analysis. However, it is becoming clear that to make ‘real-world’ connections, investigations of polydisperse dust clouds should also be performed. Studies of polydisperse systems are revealing interesting phenomena such as segregation and de-mixing, and fundamental advances in the thermodynamic properties of binary dust mixtures are possible [218].

I will close with the following observation. Having participated in dusty plasma research since the early 90s, I have witnessed the tremendous growth that has taken place, particularly on the experimental side. Most of the early researchers in this field, including myself, had to learn dusty plasma physics on the fly, either from publications, or if we were lucky, through conversations with some of the pioneers in the field. The situation has changed considerably, since most of the basic material is now in textbooks and new students entering this field are taught the basics as part of the introductory plasma physics course. At the University of Iowa, we have now introduced dusty plasma experiments into our advanced lab course for physics and astronomy majors. This gives students exposure not only to basic plasma physics but also to the methods of video imaging and analysis. It has been a particularly pleasant experience for me to interact with many young students who now regularly attend the international conferences and workshops on dusty plasmas. This influx of enthusiastic young scientists is a sure indication that the field will remain vibrant in the future, and that more significant discoveries will be made.

Notes

1. The terms used to describe a system of solid microparticles dispersed in a plasma seem to vary geographically. The term dusty plasmas is generally preferred by US researchers. European scientists use the term complex plasmas to emphasize connections to complex fluids and colloidal systems – micron-sized particles (charged or uncharged) immersed in a fluid solution. Japanese scientists use the term fine-particle plasma. Regardless of the nomenclature, these systems fall under the general category of soft condensed matter.

2. My comment, which was intended only to attract the attention of a sympathetic audience, and not controversy, was met with the immediate retort of Vadim Tsytovich – ‘Not at the center of a neutron star.’

3. The importance of dusty plasmas in the evolution of the solar system (and more generally the universe) was pointed out by Nobel Laureate Hannes Alfvén who argued that ‘... most of the universe is likely a dusty plasma...’ [219].

4. One might find it surprising to see items (i) – (k) included in this list. A solid rocket engine exhaust is an ionized gas which contains aluminum oxide particles (added to boost thrust). It is well known that communications to and from a spacecraft are disrupted when the rocket engines are used. An ordinary flame is an example of a thermally ionized plasma having a very low degree of ionized particles. Flames also contain solid (carbon soot) particles, which, when heated, emit thermonionic electrons which significantly enhance the degree of ionization. A thermonuclear explosion
releases enough energy in the form of energetic particles, ultraviolet, x-ray, and gamma radiation to ionize the air; it also contains weapons debris aerosols as well as entrained soil. A number of other example of environments which do not qualify as plasmas, but which do involve particles which acquire an electrical charge, could be mentioned. These include charged granular materials (sand), fog, automobile engine exhaust, and even snow. The charging mechanism in most of these cases is related to friction (triboelectric effect) due to particle-particle interactions or particle-object interactions. Blowing snow gets charged during a hoping motion called saltation, with the result that electric fields in blizzards are often several orders of magnitude higher that without drifting [220]. Processing tools are plasma-based devices that are used in the production of semiconductor integrated circuits. These plasmas use reactive chemicals (e.g., silane) to change the surface characteristics of silicon by reactive ion etching. They also turned out to be incubators in which dust particles are grown and eventually fall onto the product and contaminate them. The realization of this problem in the mid-1980s lead to a substantial increase in dedicated experimental and theoretical studies aimed at understanding the physics of dusty plasmas. Dust in a plasma is not always a problem however. By a stroke of good fortune particle growth in plasmas is also used for thin film deposition, which is one of the major processes involved in the production of solar cells. An excellent presentation of the physics of nanoparticle growth in dusty plasmas (and dustyplasmas in general!) can be found in the Ph.D. thesis of Kathleen De Bleecker, *Modelling of the formation and behavior of nanoparticles in dusty plasmas*, University of Antwerp, 2006, which can be downloaded from [https://www.uantwerpen.be/en/researchgroups/plasmant/research/phd-dissertations](https://www.uantwerpen.be/en/researchgroups/plasmant/research/phd-dissertations). See also [221].

5. **Plasma processing** is the term used to describe the plasma technologies that have been developed to manufacture semiconductor chips. The devices in which the semiconductor chips are actually made are referred to as tools. A book which provides an overview of dusty plasma research relevant to plasma discharges used for semiconductor processing is given in [2].

6. The first article I usually give to a graduate student interested in working on dusty plasmas is the one by my late colleague Chris Goertz [43]. This review article focusses on the observation and interpretation of the spokes in Saturn’s B ring observed by the Voyager 2 spacecraft. (They have also been observed by the Cassini spacecraft and by the Hubble space telescope. A movie made from separate images of the B ring can be viewed at [http://www.planetary.org/blogs/emily-lakdawalla/2009/2174.html](http://www.planetary.org/blogs/emily-lakdawalla/2009/2174.html)). The Goertz article gives a concise introduction to the problem of dust charging and provides a compelling argument for the need to include electromagnetic forces, as well as gravitational forces, on charged dust in the solar system or gravito-electrodynamics.

7. In thermonuclear magnetic fusion devices, the interaction of hot plasmas with material surfaces causes erosion due to sputtering and blistering, forming dust particles which can seriously degrade the performance of the plasma. In addition, the particles could absorb tritium fuel, leading to a potentially dangerous and uncontrolled inventory of tritium in the device. See, e.g. [222].

8. The Capri Workshop had 17 participants; the last International Conference on Dusty Plasmas held in Prague in 2017 had 135 participants. There are two major conferences in which dusty plasma researchers convene to present recent results – the International Conference on the Physics of Dusty Plasmas (ICPDP), and the U. S. Workshop on Dusty Plasmas. These conferences alternate and are each held every three years. Other major venues which hold sessions of dusty plasmas are the
APS Division of Plasma Physics (APS DPP), The European Physical Society (EPS), the International Conference on Plasma Physics (ICPP), the IEEE Plasma Science Meeting, and the Gaseous Electronics Conference (GEC).

9. The so-called ‘Havnes parameter’ \( P_H = \frac{Z_{d,eq} n_d}{n_i} \) is used to quantify the effect of charged dust in a plasma, where \( Z_{d,eq} = \frac{|q_{d,eq}|}{e} \) is the number of elementary charges on the dust, \( n_d \) is the number density of dust grains, and \( n_i \) is the ion density. \( P_{H,i} \) is the ratio of the charge residing on dust particles in the plasma to that of the ion component. \( P_H < 1 \) indicates that the electrons are not significantly depleted by the dust, while \( P_H > 1 \) indicates that a large fraction of the electrons in the plasma are attached to dust grains. (Caution: There are various definitions in the literature for the Havnes parameter, and these may not be the same as the one introduced originally by Havnes [223].

10. The situation in which there are a few isolated grains in a plasma is usually referred to as dust in plasma. The dust is affected by the plasma since it is the source of its charge, and the particle dynamics are influenced by the plasma, but in this situation, there is a negligible effect of the dust on the plasma.

11. Mendis [224] argues that electrostatic disruption of small dust grains may be overcome by electric field emission.

12. The electrons, ions, and charged dust grains in a dusty plasma are each surrounded by a dynamic shielding cloud that forms self consistently, limiting the range of the Coulomb interaction. The electric potential surrounding a particle will then vary with the radial distance as \( e^{-r/\lambda_D} / r \), where \( \lambda_D \) is the characteristic shielding length given by \( \lambda_D = \left( e_0 k T_a / e^2 n_a \right)^{1/2} \), where \( T_a \) and \( n_a \) are respectively the temperature and density of species \( a \). The shielding is never 100% effective due to the thermal motion of the electrons and ions.

13. The concept of quasi-neutrality is basically used to delineate the macroscopic property of a plasma to contain, to a very high degree, equal densities of positive and negative charge, from the micro-scale in which small charge imbalances produce electric fields. The Debye length is the largest scale length over which charge neutrality is violated. The corresponding time scale for a charge neutrality to be restored after a fluctuation is the inverse plasma frequency. The plasma frequency is defined for each species in a plasma as \( \omega_{pa} = \nu_{Ta} / \lambda_D = (n_a q_a^2 / e_0 m_a)^{1/2} \), where \( \nu_{Ta} \) is the thermal velocity.

14. To direct readers interested in further details, the following comments are provided: The textbook by P. K. Shukla and A. A. Mamun [7], which covers the basic physics of dusty plasmas, is the standard reference that will be found on the bookshelf of all dusty plasma researchers. The book by A. Ivlev, H. Löwen, G. Morfill, and C. P. Royall [12] focusses on the overlap between two branches of soft condensed matter physics, viz. complex plasmas and colloidal dispersions. The book by Frank Verheest [13] presents a comprehensive treatment of waves in dusty plasmas, including nonlinear waves, and also discusses the problem of self-gravitation of dust, which is of fundamental importance for the question of the evolution of astrophysical bodies.

15. The potential of a point in a plasma is called the plasma potential or space potential. The potential of an isolated (floating) object in the plasma is called its floating potential. Sounding probes (now called Langmuir probes) were first used at the turn of the 19th century to measure the anode drop in mercury arc discharges. At that time the distinction between the space potential of the plasma and the floating potential of the probe was not entirely appreciated, and researchers erroneously mistook the potential of a floating probe as the plasma potential. This error was
later pointed out by Langmuir [225], who with Mott-Smith developed the method for determining the plasma potential [29].

16. Perhaps no region of the Earth’s atmosphere has garnered more scientific attention \textit{per km} than the region between 80-90 km in altitude. A concise summary of the interesting phenomena happening in this region of the upper atmosphere was given by Ove Havnes, who has devoted a large portion of his research to studying processes driven by charged dust [226].

17. The standard reference work on ‘Potentials of surfaces in space’ is the review by Eldon C. Whipple [227]. This article considers charging not only of spacecraft but also any object in the solar system or interstellar space, ranging in size from planets to dust grains.

18. A historical perspective of spacecraft charging and a fairly detailed review of spacecraft charging observations up until about 1980 is given in [228]. This article also discusses the effects of spacecraft charging on measurements made using instrumentation onboard the spacecraft.

19. Not every dust grain is made of a conducting material or is spherical. However, if a dielectric grain is in an isotropic plasma, its surface will be charged symmetrically and will be an equipotential, so the use of Equation (4) is still justified. If the grains are not spherical, the charge may need to be calculated by numerical methods. If one is dealing with a dust cloud composed of irregularly shaped grains with a distribution of sizes, the problem becomes even more complicated. In practice, controlled dusty plasma experiments generally use spherical grains of a known size (so-called mono-disperse grains), which nonetheless are made of dielectric material, often silica or melamine formaldehyde, and Equation (4) is used to compute the dust charge.

20. The capacitance of a spherical dust grain of radius \(a\) in a plasma is given by \(C = 4 \pi \varepsilon_0 a (1 + a / \lambda_D)\), where \(\lambda_D\) is the Debye shielding distance [39,42].

21. This book contains a partial record of the technical efforts connected with the problem of electromagnetic separation of uranium isotopes for the Manhattan project. In addition to probe theory, it contains articles on ‘Bohm diffusion’, and the ‘Bohm sheath criterion’.

22. The chapter by Delzanno and Tang [177] provides an in-depth examination of the regime of applicability of OML charging theory. Their conclusions are supported by PIC simulations of the dust-plasma interaction. They show that the range of applicability of the OML theory includes not only the situation in which \(a / \lambda_D < 1\), but is also sufficiently accurate when \(a / \lambda_D \geq 1\) for negatively charged dust.

23. A Q-machine is a device that produces a nearly fully ionized, collisionless, magnetized plasma by surface ionization of alkali metal atoms (K or Cs) on a thermionically emitting hot plate (Ta or W) [229].

24. The rotating dust cylinder (once referred to by a colleague as based on the principle of the clothes dryer) does not trap dust in a plasma, but merely allows it to reside in the plasma for a sufficient time to acquire the full charge. The main purpose for this device was to study how the dust affected the plasma properties, and in particular how plasma waves are modified by the dust.

25. The dust crystals predicted by Ikezi [89] are classical systems in which the inter-particle spacing is much, much greater than the relevant deBroglie wavelength. This is in contrast to Wigner crystals of electrons in the milli-Kelvin temperature range in which quantum effects must be considered [230].

26. A clear elementary discussion of the possibility of a long range attractive component of the dust-dust interaction is given in Sec. 8.4 of the textbook of Shukla and Mamum [7]. Attractive forces due to collective interactions of dust particles in a plasma are
also discussed in reference [10]. Tsytovich et al [231] discuss the possibility of the formation of a dust molecule due to an attractive dust-dust interaction.

27. The melting transition of a dust crystal induced by lowering the gas pressure (decreasing the cooling effect due to dust-neutral collisions) has been investigated by H. M. Thomas and G. E. Morfill [90], and Melzer et. al. [112].

28. A multi-ion plasma is a plasma containing electrons and two or more species of positive ions or positive ions, negative ions and electrons. Multi-ion plasmas are commonly found in the ionosphere. Weakly ionized plasmas also contain neutral gas atoms or molecules, but other than including the effects of electron-neutral and ion-neutral collisions, the motion of the neutral atoms is not generally included in the analysis.

29. The dispersion relation for the dust ion-acoustic (DIA) wave was derived by P. K. Shukla and V. P. Silin [120] while they were attending the 1991 Spring School on Plasma Physics at the International Center for Theoretical Physics in Trieste. Although the authors properly describe the wave as a dust ion-acoustic wave, there are two places in the second column of the paper where it is called the dust acoustic wave, which has led to some confusion. The dispersion relation (Eq. 4) obtained by Shukla and Silin is clearly the DIA wave as seen by the fact that the mass of the dust grains does not appear in the dispersion relation. The DIA wave is a plasma ion wave with a dispersion relation that is modified by the dust, through its effect on the charge neutrality condition.

30. In addition to collisional damping, plasma waves are also subject to collisionless Landau damping, which is a kinetic effect in which energy is transferred from the waves to the particles, resulting in wave damping. The severity of this damping depends on the relation between the wave phase velocity and the electron and ion thermal velocities. In a plasma in which the electron and ion temperatures are comparable, $T_e \approx T_i$. Landau damping of ion acoustic waves is so strong that the waves are damped over a distance on the order of the wavelength of the waves. For this reason, it is often stated that ion-acoustic waves do not exist in a plasma where $T_e \approx T_i$. This statement has led to considerable confusion in the literature. This means that for the ion acoustic waves to propagate over large distances compared to the wavelength, a source of free energy to counter the Landau damping must be present. In a dusty plasma, however, it is seen from equation (34) that the effect of the dust is to increase the phase velocity to a value above the ion thermal speed.

31. The linear dispersion relation for the dust acoustic wave was derived by Rao, Shukla, and Yu [118] (Eqn. 8) and was published in 1990. The genesis of the DA wave, however, goes back to May of 1989 at the First Capri Workshop on Dusty Plasmas, where Padma Shukla discussed with Umberto DeAngelis the possibility of a very low frequency mode involving the motion of the dust particles. This was told to the author in a private communication with Umberto DeAngelis.

32. In a sound wave, the pressure or density disturbances are communicated from one layer of air to the next via collisions between the air molecules. In a DAW, the coupling is through an electric field created by small charge imbalances in the plasma.

33. The presence of a permanent, asymmetric dust cloud around the Moon has been reported based on in-situ measurements of the LADEE spacecraft [136]. Exploratory missions to the Moon are in progress or being planned by eight countries.

34. Comprehensive discussions of waves in strongly coupled dusty plasmas are given in references [19] and [126].

35. The scattering of light by small particles having a diameter similar to the wavelength of light is known as Mie scattering.
36. This is certainly the case for the most frequently used RF discharge device, which operate at neutral pressures in the range of 0.1 – 100 Pa.

37. The criterion for magnetization follows directly from the requirement that the Lorentz force term in the fluid momentum equation  is much larger than the collisional drag term, . It follows then that . The mean-free-path for dust-neutral collisions is, so that implies for dust magnetization.

38. The MDPX device is part of the Magnetized Plasma Research Laboratory (MPRL) at Auburn University. Further information about this facility, including information on how to apply to perform an experiment as a user can be found at: http://webhome.auburn.edu/~thomaed/mprl/index.html.

39. Both devices are located in Germany, one at the Justus-Liebig University Giessen [232], and one at the University of Greifswald [233,234].

40. The observation that imposed order in the dust suspension occurs at low neutral pressures is in direct contrast to the conditions required for the formation of a dust crystal, since the strong coupling which results in crystal formation occurs at high neutral pressures where the dust particles are cooled by gas friction.

41. The drift is negligible for the electrons and ions.

42. As an experimentalist who was lucky to get into dusty plasmas early in the game, I will admit that even though we knew that dust grains should acquire a charge in a plasma (a negative charge in most laboratory plasmas), it was still an exciting experience for us in 1994 to see with our eyes, dust grains suspended in a plasma. Even more striking was the observation [60] that the suspended dust ball (this was the term my student Adrian Barkan used to describe the spherical cluster of levitating dust particles) exploded when the plasma was suddenly turned off, due to the mutual Coulomb repulsion of the like-charged particles. About ten months later, I had another exciting experience when Adrian called me down to the lab just before lunch because as he put it, something interesting was going on in the plasma. We saw bright vertical dust bands moving away from the anode, which was unmistakably a dust acoustic wave (Figure 2 in [131]).

43. The screened Coulomb coupling parameter can be varied to some extent by the experimenters’ control over the RF power and neutral gas pressure. Recently, methods have been developed to heat the dust particles using laser irradiation and induce a melting transition, see. e.g. [235].

44. A photo of striations in a positive column can be found at: https://en.wikipedia.org/wiki/Glow_discharge#/media/File:Glow_discharge_regions.jpg See also [236].

45. The ionization state of the ions in a plasma is controlled by the electron energy when the ionization is due to electron impact, which is the usual case in laboratory plasmas. Doubly ionized ions can be avoided by setting the discharge voltage, which controls the electron energy, sufficient for single ionization but not high enough for double ionization. There may be some electrons energetic enough to produce doubly ionized ions, but the cross-sections for second ionization are generally at least a factor of 10 lower than the cross sections for first ionization. Thus, in low-temperature laboratory plasmas, we usually can be confident that the ions are singly charged.

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