

DUSTY PLASMAS: ELEMENTARY PROCESSES, EXAMPLES AND POSSIBLE APPLICATIONS

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Abstract

This work presents an up-to-date account in dusty plasmas, a new field of current research's interest in applied physics and modern technology. These are complex systems containing nanometer or micrometer-sized particles suspended in plasma. Dust particles may be charged and the plasma and particles behave as plasma, following electromagnetic laws for particle up to about 10 nm or 100 nm if large charges are present. Dusty plasmas are interesting because presence of particles significantly alters the charged particle equilibrium leading to different phenomena. Electrostatic coupling between the grains can vary over a wide range so that the states of the dusty plasma can change from weakly coupled to crystalline. Such plasmas are of interest as a non-Hamiltonian system of interacting particles and as a means to study charging of dust particles in plasmas, electrostatic potential around a dust particle main forces acting on dust particles in plasmas, interaction between dust particles in plasmas, formation and growth of dust particles.

1. Introduction

Dusty plasmas are low-temperature multispecies ionized gases including electrons, ions, and negatively (or positively) charged dust grains typically micrometer or sub micrometer size. In such circumstances, the dust particles can be charged due to the collection of electron and ion currents from the background plasma. Therefore, the dust charge becomes another dynamical variable that distinguishes dusty plasma from ideal electron-ion plasma [1]. Dusty plasmas are found in various space environments as well as laboratory devices and industrial processes [2]. Dusty plasmas are interesting because presence of particles significantly alters the charged particle equilibrium leading to different phenomena. It is field of current research. Electrostatic coupling between the grains can vary over a wide range so that the states of the dusty plasma can

change from weakly coupled (gaseous) to crystalline [3]. Such plasmas are of interest as a non-Hamiltonian system of interacting particles and as a means to study generic fundamental physics of self-organization, pattern formation, phase transitions, and scaling [4, 5]. Dust particles may be charged and the plasma and particles behave as plasma, following electromagnetic laws for particle up to about 10 nm (or 100 nm if large charges are present). Dust particles may accrete into larger particles resulting in "grain plasmas"[5].

2. Theoretical considerations

Dusty plasma is loosely defined as normal electron–ion plasma with an additional charged component of micron- or submicron-sized particulates. This extra component of macro-particles increases the complexity of the system even further [3, 5]. Dusty plasmas are low-temperature fully or partially ionized electrically conducting gases whose constituents are electrons, ions, charged dust grains and neutral atoms. Dust grains are massive (billions times heavier than the protons) and their sizes range from nanometers to millimeters. Dust grains may be metallic, conducting, or made of ice particulates. The size and shape of dust grains will be different, unless they are man-made. However, when viewed from afar, they can be considered as point charges [5].

The motion of solid particles in plasma follows the momentum equation for ions and electrons:

$$m \frac{d\mathbf{v}}{dt} = m\mathbf{g} + q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - m\nu_c \mathbf{v} + \mathbf{f} \quad (1)$$

Where m , q are the mass and charge of the particle, \mathbf{g} is the gravitation acceleration, $m\nu_c \mathbf{v}$ is due to viscosity, and \mathbf{f} represents all other forces including radiation pressure. $q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$ is the Lorenz force, where \mathbf{E} is the electric field, \mathbf{v} is the velocity and \mathbf{B} is the magnetic field [4].

Then depending in the size of the particle, there are four categories:

- a. **Very small particles**, where $q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$ dominates over $m\mathbf{g}$.
- b. **Small grains**, where $q/m \approx \sqrt{G}$, and plasma still plays a major role in the dynamics.
- c. **Large grains**, where the electromagnetic term is negligible, and the particles are referred to as grains. Their motion is determined by gravity and viscosity, and the equation of motion becomes $m\nu_c \mathbf{v} = m\mathbf{g}$.

- d. **Large solid bodies.** In centimeter and meter-sized bodies, viscosity may cause significant perturbations that can change an orbit. In kilometer-sized (or more) bodies, gravity and inertia dominate the motion [4].

3. Dust charging processes

Different processes leading to the charging of dust particles immersed in plasmas are considered. Expressions for the ion and electron fluxes to (from) the particle surface, caused by different processes (collection of plasma electrons and ions, secondary, thermionic and photoelectric emission of electrons from the particle surface), are given. Problems such as stationary surface potential, kinetics of charging, changing of plasma charge composition in response to the presence of the dust, as well as dust particle charge fluctuations due to the stochastic nature of the charging process, are considered. Plasma with dust particles or grains can be termed as either ‘dust in plasma’ or ‘dusty plasma depending on the ordering of a number of characteristic lengths. These are the dust grain radius r_d , the average intergrain distance a , the plasma Debye radius λ_D and the dimension of the dusty plasma. The situation $r_d \leq \lambda_D < a$ (in which charged dust particles are considered as a collection of isolated screened grains) corresponds to ‘dust in a plasma’, while the situation $r_d \leq a < \lambda_D$ (in which charged dust particles participate in the collective behavior) corresponds to ‘a dusty plasma’. When consider plasma with isolated dust grains ($a \leq \lambda_D$), we should take into account the local plasma inhomogeneities [2].

The emerging negative charge on the particle leads to the repulsion of the electrons and the attraction of the ions. The stationary surface potential of the dust particle (connected to the particle charge) is defined (with the accuracy of a coefficient on the order of unity) as $\varphi_s = -\frac{T_e}{e}$ where T_e is the electron temperature in energy units. Physically, this can be explained by the requirement that in the stationary state most of the electrons should not have kinetic energies sufficient to overcome the potential barrier between the particle surface and surrounding plasma [6].

Consider an isolated spherical dust grain of radius a introduced into a plasma consisting of electrons of density n_e , as in figure 1. Once the dust surface potential is determined, the charge on the dust is computed using [7]:

$$Q = (4\pi\epsilon_0 a)V_s \quad (2)$$

When many dust particles are present with a number density n_d , the dust charge will be a function of the ratio of the interparticle spacing, to the plasma Debye length, λ_D .

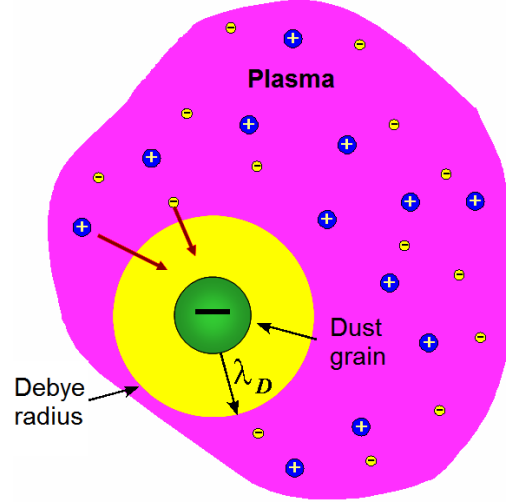


Figure 1. Spherical dust grain introduced into plasma.

The charging equation:
$$-\left(\frac{T_e}{T_i}\right)^{1/2} \left(\frac{m_i}{m_e}\right)^{1/2} \exp\left(\frac{e\phi_s}{kT_e}\right) + 1 - \frac{e\phi_s}{kT_i} = 0.$$

The electron and ion currents to the dust grain of radius a are given by:

$$I_e = en_e \sqrt{\frac{kT_e}{m_e}} \exp\left(\frac{eV_s}{kT_e}\right) \pi a^2$$

$$I_i = en_i \sqrt{\frac{kT_i}{m_i}} \left(1 - \frac{eV_s}{kT_i}\right) \pi a^2 \quad (3)$$

With V_s the potential of the dust grain relative to the plasma [7]. The grain surface potential is then obtained by requiring: $I_+ + I_e + I_- = 0 \rightarrow V_s \equiv V_f - V_p$.

For $V_s < 0$:

$$-n_- \left(\frac{kT_-}{2\pi m_-}\right)^{1/2} e^{eV_s/kT_-} + n_+ \left(\frac{kT_+}{2\pi m_+}\right)^{1/2} \left(1 - \frac{eV_s}{kT_+}\right) = 0. \quad (4)$$

For $V_s > 0$:

$$-n_e \left(\frac{kT_e}{2\pi m_e}\right)^{1/2} \left(1 + \frac{eV_s}{kT_e}\right) - n_- \left(\frac{kT_-}{2\pi m_-}\right)^{1/2} \left(1 + \frac{eV_s}{kT_-}\right) + n_+ \left(\frac{kT_+}{2\pi m_+}\right)^{1/2} e^{-eV_s/kT_+} = 0. \quad (5)$$

Examples of dusty plasmas include comets, planetary rings, exposed dusty surfaces, and the zodiacal dust cloud, and dust in interplanetary space, interstellar and circumstellar clouds, rockets exhaust, as in figure 2. The expanding water vapor condenses into ice, which becomes negatively charged by pickup of ionosphere electrons. The resulting dusty plasma acts as an enhanced backscatter target. Also, naturally occurring charged ice crystals are associated with noctilucent clouds which are confined to a geometrically thin layer (typically 1 to 3 km) and are often cirrus like in appearance, as in figure 2 (d).

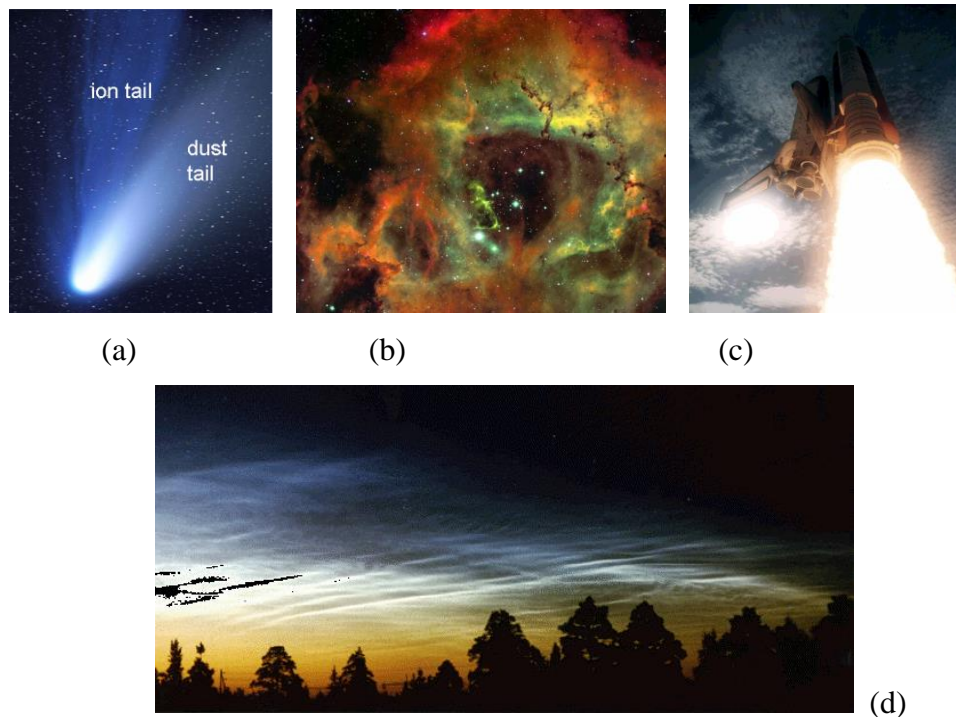


Figure 2. Examples of dusty plasmas: comets (a), dust in interplanetary space (b), rockets exhaust (c), noctilucent clouds (d).

4. Applications of dusty plasmas

Dusty plasmas have already been applied in industry for many decades, for example, in such technologies as precipitation of aerosol particles in combustion products of electric power stations, plasma spraying, and electrostatic painting, as well as in a number of other areas [8]. At present, the interest is mainly caused by applied research related to materials science and, recently, also with regard to plasma diagnostics. But powder formation has also been a critical concern for the microelectronics industry, because dust contamination can severely reduce the yield and performance of fabricated devices. Submicron particles deposited on the surface of

process wafers can obscure device regions, cause voids and dislocations, and reduce the adhesion of thin films. Nowadays, dust particles are not considered as unwanted pollutants any more. Positive aspects of dusty plasmas emerged, and they even turned into production goods. Powders produced using plasma technology have interesting and potentially useful properties, e.g., very small sizes (nanometer to micrometer range), uniform size distribution, and chemical activity. Size, structure, and composition can be tailored to the specific requirements dependent on the desired application. There are several links between dusty plasma physics and materials science [8-10]. The trend is similar to the well-established plasma surface modification technology, except that now the surface of dust particles is the subject of treatment. Here, deposition, etching, surface activation, modification, or separation of clustered grains in the plasma is considered. In these types of processing, particles are either grown in the plasma or are externally injected for subsequent treatment [8].

Various ways particle's treatments in process plasmas are presented in figure 3:

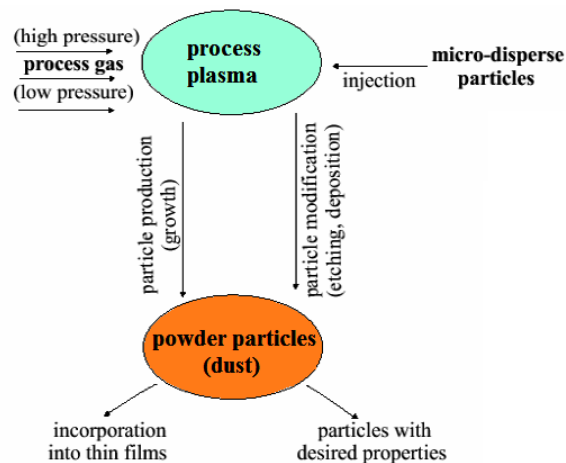


Figure 3. Particle's treatment in process plasmas.

Figure 4 presents a schematic of magnetized glow discharge dusty plasma. Dust particles are lifted up into the glow discharge when it is initiated by applying a DC voltage to an anode disk immersed in argon. The dust is confined (levitated) by strong electric fields within the anode glow [7].

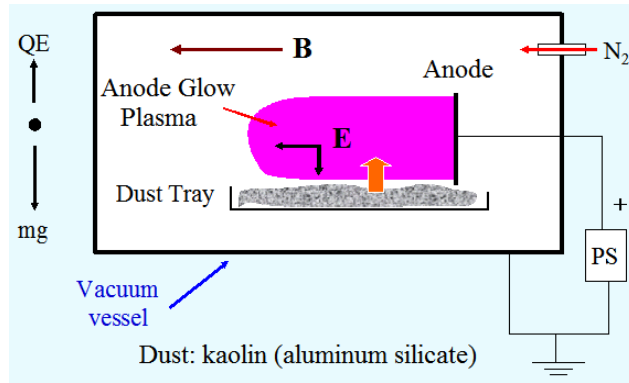


Figure 4. Schematic of a magnetized glow discharge dusty plasma.

Highly charged dust grains in plasma might form an ordered structure or Coulomb Crystal, as a new state of matter. Unlike colloidal systems, the dust structures form on rapid timescales and are easily imaged [6]. A two-dimensional Coulomb crystal with hexagonal structure schematic diagram is presented in figure 5:

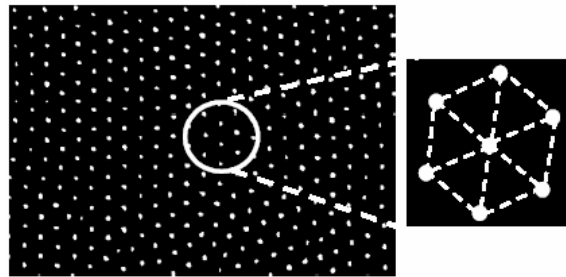


Figure 5. Two-dimensional Coulomb crystal with hexagonal structure

Another example is the lunar surface charging. The lunar surface is charged positive on the dayside via photoemission and negative on the night side due to plasma currents. On the night side the low density and elevated electron temperature of the lunar wake makes this region charge even more strongly negative (figure 6) [6].

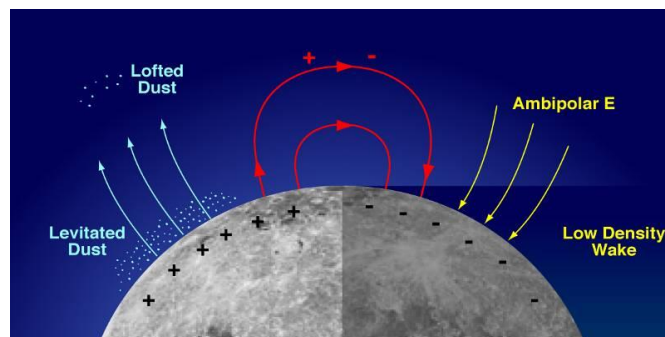


Figure 6. Lunar surface charging.

Dust acquires a positive charge due to solar UV and some grains are lifted off of the moon's surface by the electrostatic force. Some fraction of charged surface dust will be levitated and lofted, as shown in figure 7:

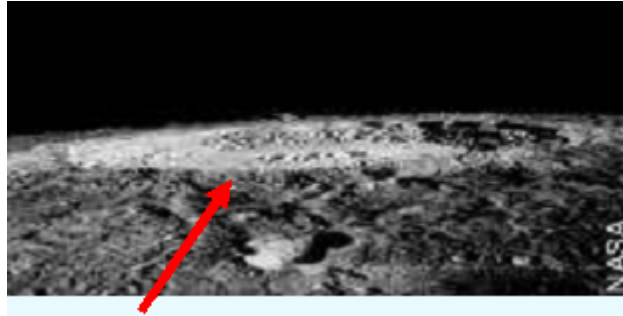


Figure 7. Electrostatically levitated dust on Moon's surface

Conclusions

The investigation of dusty plasmas has acquired particular attention only during the last decade, after the experimental discovery of the crystallization of the dust component. Due to their unique properties dusty plasmas are successfully used in solving fundamental and applied problems [1]. The simplicity of visualization permits measurements (of the dust component) at the kinetic level. A detailed analysis of thermodynamic and kinetic properties of dislocations and other defects of the dust lattices becomes possible. The latter have much in common with the usual crystalline lattice of solid bodies [2].

Only recently have we begun to explore the behavior of dusty plasmas in the laboratory for charging mechanisms, waves. Technological applications of dusty plasmas are now being exploited ceramic deposition – composites, growth of nanosize particles, diamond growth and deposition on metals and the dusty plasmas in space are usually embedded in magnetic fields. This aspect of dusty plasmas has yet to be studied in the laboratory [3].

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