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Dusty plasmas vs. multicomponent plasmas

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Abstract. Different approaches employed for dusty plasmas, ranging from single particle description (valid for low dust densities) to models appropriate in the presence of dense dusty clouds, are briefly reviewed. For environments with high dust density, a selection of examples is provided to elucidate phenomena arising in dusty plasmas when the effects of absorption of plasma particles on the dust surfaces and dust charge fluctuations are of importance and cannot be neglected.

Key words: dusty plasmas • electrostatic fluctuations • kinetic equations • multicomponent plasmas • strongly coupled systems

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Introduction

Dust is omnipresent in naturally occurring space [11] and astrophysical [8, 18, 39], as well as in industrial plasmas [2, 28]. The formation of dust in laboratory plasma is due to plasma-surface interaction and/or chemically active plasmas; either of two can be controlled (desirable) [2] or have an unwanted effect, such as "killer defects" on the silicon wafer in plasma etching reactors used in the microelectronics industry [28] or dust formed in fusion devices [9, 17, 25]. In addition, the so-called engineered dusty plasmas [10], i.e. when a controlled amount of precharacterized dust is injected in a plasma, typically of a micron or larger size for direct observations with CCD cameras, have been exploited starting from the discovery of the plasma crystal in 1994 [4, 30].

For a complete picture of dusty plasmas in a particular environment (space, fusion, laboratory), one can address the above cited review papers. Here, instead of a classification by environment, we briefly review different approaches used for dusty plasmas, which range from single particle description (valid for low dust densities) to models appropriate for dense dusty clouds. In the latter emphasis is on the difference of multicomponent plasmas where dust is treated as a massive species with fixed charge from dusty plasmas where absorption of plasma particles on the dust particles and dust charge fluctuations are of importance.

Single particle description

Isolated grains

The single particle description is appropriate for plasmas with low dust density, implying that dust does not affect plasma even the quasi-neutrality condition.

An example of such description is the modeling of dust dynamics in the scrape-off layer (SOL) plasmas of fusion devices. Motivation for such investigations is the understanding of dust dynamics and transport, which will eventually allow predicting and controlling dust – an operational and safety issue for the reactors [9]. It is expected that during the plasma discharge most of the dust particles concentrate in the region between the last closed magnetic surface and the chamber wall. There, a mixture of neutral gas, multi-species tenuous plasma and dust particles of various origins is present and it has proved useful to isolate dominant effects and to add simplified constraints to the motion of a test particle in given force fields and interaction with boundary.

Such an approach is appropriate for micron and larger size particles whose number density in SOL plasmas is low [17, 25]. We note that for nanosized dust, whose density can be relatively high, the regime can be different and it was shown that loss of plasma particles and their momenta on the grain surfaces can play a crucial role in dissipation of plasma structures [14].

In the models, see e.g. Refs. [7, 17, 21, 29], the equation of motion for dust grain is solved together with a charging equation (monitoring electron and ion fluxes to the dust surface) as well as energy balance (incoming bulk kinetic energy and outcoming radiative flux). In the environment of SOL plasmas, dust particle is typically subject to electrostatic force, friction force with ions and neutrals, gravity and other forces depending on the model and/or regime, e.g. rocket force during the dust ablation [17, 29], grad B force for ferromagnetic particles [21] or collisions with the wall [17, 21]. From these models, it emerges that the dynamics of dust particles is sensitive to geometry and profiles of specific machines.

An example of trajectory of two micron radius ferromagnetic particle in SOL of FTU tokamak is presented in Fig. 1 (after Ref. [21]). The mechanism responsible for such trajectory is the following; in the curved ion flow the effect of the ion drag, apart from dragging the dust particle in its toroidal motion, is to move the particle toward the wall (equivalent to a centrifugal force in a frame rotating with the ion flow) independently of the sign of the particle. Thus, any particle entering the hot zone, where the drag force is a maximum, will be pushed back into the cold plasma region and will hit the wall again.

The latter leads to questions which are still to be addressed; mobilization and sticking as well as inelastic collisions with the wall [25], whose nature depends on the impact velocity. Figure 1 of review [15] can serve as an indicator for the velocity ranges and the accompanying physical phenomena; (i) ~ 10 m/s for sticking/bouncing, (ii) ~ 1 km/s as a threshold for inelastic collisions, which imply wall destruction and formation of debris, see e.g. Fig. 6 of Ref. [17], (iii) ~ few km/s for the hypervelocity regime which is more damaging as the mass of excavated material of the wall/obstacle far exceeds mass of the projectile (dust) [15, 25].

Clusters of strongly coupled grains

Another example when an equation of motion of single particle proved to be successful is that of strongly coupled dusty plasma systems, where interaction energy exceeds the kinetic energy of the particles. Such systems are typically studied in the laboratory low-temperature discharges where variation of plasma parameters and neutral pressure allows to control the state of the system (gaseous, liquid, solid) as well as to observe

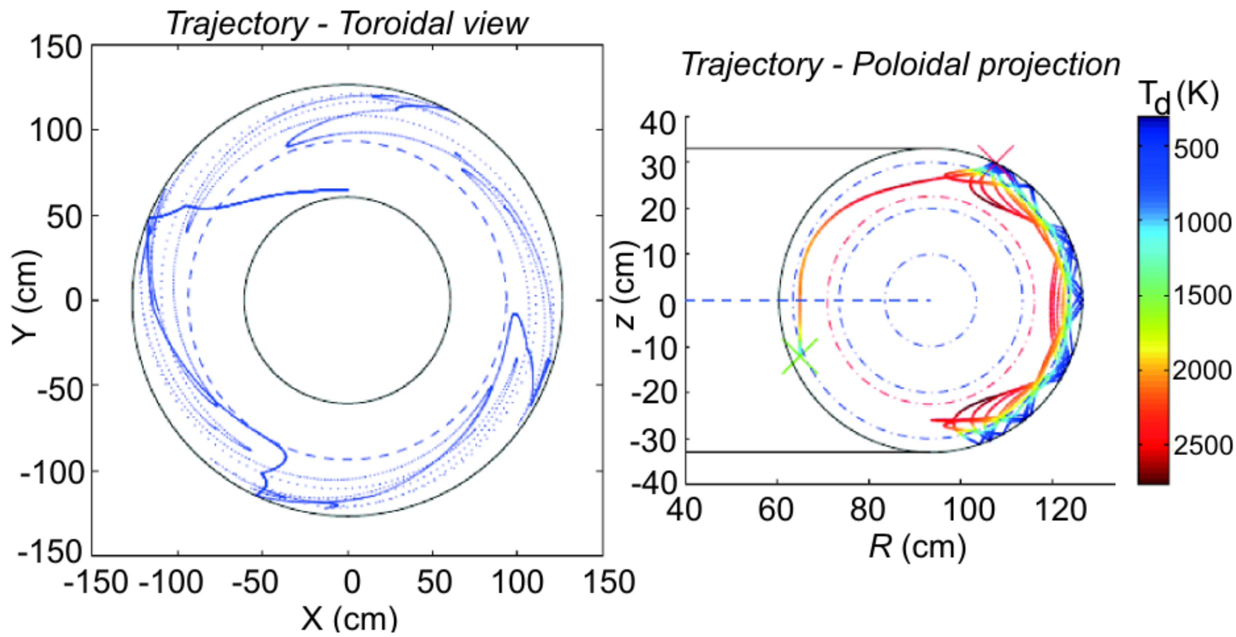

Fig. 1. After Ref. [21]. Trajectory of a Fe dust particle with 2 μm radius shown in a toroidal view of the FTU tokamak and in a poloidal projection. The green cross stands for the injection point, and the red cross is the end point. Dust temperature of the particle is indicated by the color code.

the transitions. For exhaustive reference list see, e.g. review [10].

Considering plasma as a media which provides dust (fixed) charge $Q = eZ_d$ and screening of the grain electrostatic potential, the following equations

$$(1) \quad m\frac{d^2\mathbf{r}_i}{dt^2} + m\nu_n\frac{d\mathbf{r}_i}{dt} = -Q\nabla\phi_c - Q\sum_{j\neq i}\nabla\phi(r_{ij}) + \mathbf{L}_i(t)$$

are solved for N particles of mass m embedded into a Langevin thermostat which simulates the effect of the collisions with the electrically neutral molecules of the background gas (see, e.g. [16]). Here $\nu_n = 1/\tau_n$ is the neutral gas friction, ϕ_c is the confinement potential, $r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$ and $\mathbf{L}_i(t)$ is the stochastic Langevin force (thermal noise induced by neutral gas particles). The pair interaction between the dust particles is described by the Debye-Hückel (Yukawa) potential: $\phi(r) = (Q/r)\exp(-r/\lambda_D)$, where λ_D is the plasma screening length.

Particle radius, mass and charge, mean inter-particle distance, neutral gas density and temperature are the parameters of the model. The interplay between the strength of the coupling and confinement vs. the stochastic term (which is the only energy source) results in the system's freezing or melting.

Grain trajectories from the molecular dynamics simulations of the Yukawa-Langevin system of Ref. [26] are presented in Fig. 2. The similarity with the experimental data can be assessed, if compared with Fig. 2 of Ref. [27], and Figs. 2–8 of [26] and can be addressed for detailed comparison of the statistical properties of the such systems in the simulations and experiments.

Dense dust clouds

Let us now discuss phenomena arising in the dust cloud where particle density is sufficiently high for the dust to be treated as a distinct plasma species and for the following effects to be of importance [32];

i. continuous collection of electron and ion fluxes on the dust surface,
ii. thus a necessity to inclusion of a source to define a steady-state in such systems,

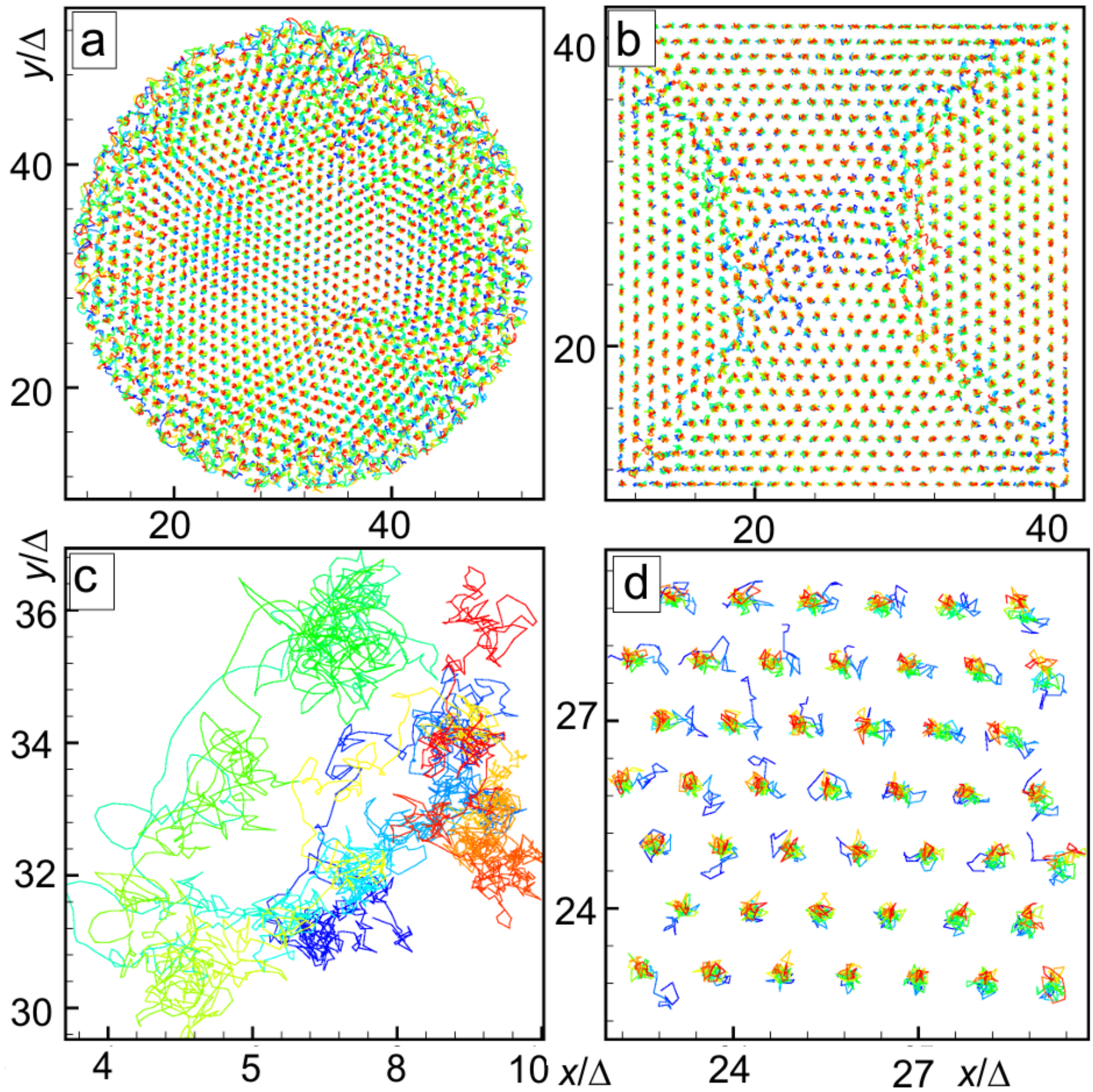

Fig. 2. After Ref. [26]. Grain trajectories from the molecular dynamics simulations of the Yukawa-Langevin system. The trajectories are color-coded by the time. Motion of particles during time 100 δt in the case of parabolic confinement (a) and the hard wall confinement (b). A typical trajectory from the outer region of panel (a) plotted for time 4000 δt (c). Close-up on stiff central region of panel (b), motion of particles is shown for 100 δt (d).

iii. fluctuations of the dust charge caused by the fluctuations in the collected fluxes.

Those can be taken into account in fluid description or, self-consistently in the framework of fluctuation approach. Below we outline both description using the standard plasma notations and define only the new terms compared to ordinary plasmas.

(I). In the presence of dense dust clouds the standard system of fluid equations for electron and ion components will be modified [10] ($\alpha = \{e,i\}$ and $\beta = \{e,i,d\} \neq \alpha$).

(2) $$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \mathbf{v}_\alpha) = Q_{I\alpha} - Q_{L\alpha} - \widetilde{I}_\alpha n_d$$

(3) $$\frac{\partial \mathbf{v}_\alpha}{\partial t} + (\mathbf{v}_\alpha \cdot \nabla)\,\mathbf{v}_\alpha = -\frac{e_\alpha}{m_\alpha}\nabla\phi - \frac{\nabla n_\alpha T_\alpha}{m_\alpha n_\alpha} - \sum_\beta \nu_{\alpha\beta}^{\mathrm{scat}}(\mathbf{v}_\alpha - \mathbf{v}_\beta) - \left(\frac{Q_{L\alpha}}{n_\alpha} + \nu_{\alpha d}^{abs}\right)\mathbf{v}_\alpha$$

to include;

- the term $-\widetilde{I}_\alpha n_d$ in the continuity equation due to particle absorption on dust,
- the momentum loss terms $-\sum_\beta \nu_{\alpha\beta}^{\mathrm{scat}}(\mathbf{v}_\alpha - \mathbf{v}_\beta)$ and $-\mathbf{v}_{ad}^{\mathrm{abs}} \cdot \mathbf{v}_\alpha$ (due to elastic and inelastic collisions with dust, respectively) in the momentum equation.

Note that the momentum transfer associated with ion absorption is much smaller than that due to scattering and often can be neglected. The fluid equations for dust will be [10]

(4) $$\frac{\partial n_d}{\partial t} + \nabla \cdot (n_d \mathbf{v}_d) = 0$$

(5) $$\frac{\partial \mathbf{v}_d}{\partial t} + (\mathbf{v}_d \cdot \nabla)\mathbf{v}_d = -\frac{q}{m_d}\nabla\phi - \frac{\nabla n_d T_d}{m_d n_d} - \sum_\beta \nu_{d\beta}(\mathbf{v}_d - \mathbf{v}_\beta)$$

(II). In the framework of the fluctuation approach [1], as suggested in Refs. [32–36], for the dust component the phase space $\{\mathbf{r},\mathbf{p}\}$ is extended to include the dust charge $\{\mathbf{r},\mathbf{p},q\}$. The additional phase space variable will also introduce an additional dynamic equation to complement Hamilton's equations for $\{\mathbf{r},\mathbf{p}\}$, that is the charging equation

(6) $$\frac{dq}{dt} = \sum_\alpha I_\alpha(q) + I_{ext}$$

where $I(q) = \sum_\alpha I_\alpha(q)$ are the plasma currents flowing to the grain and I_{ext} are the assumed non-fluctuating, currents emitted from the grain. In light of the above, the Liouville theorem will lead to the Klimontovich equation [32]

(7) $$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}} + q\mathbf{E}(\mathbf{r},t)\cdot\frac{\partial}{\partial \mathbf{p}}\right) f_{\mathbf{p}}^{d}(\mathbf{r},q,t) + \frac{\partial}{\partial q}\left\{\left(I_{ext}(\mathbf{r},t) + \sum_\alpha I_\alpha(\mathbf{r},q,t)\right) f_{\mathbf{p}}^{d}(\mathbf{r},q,t)\right\} = 0$$

For electrons and ions, the Klimontovich equations are also modified [32]

(8) $$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}} + e_\alpha\mathbf{E}(\mathbf{r},t)\cdot\frac{\partial}{\partial \mathbf{p}}\right) f_{\mathbf{p}}^{\alpha}(\mathbf{r},t) = S_\alpha(\mathbf{r},t) - \left(\int \sigma_\alpha(q,v) v f_{\mathbf{p}'}^{d}(\mathbf{r},q,t)\frac{dq\,d\mathbf{p}'}{(2\pi)^3}\right) f_{\mathbf{p}}^{\alpha}(\mathbf{r},t)$$

to include a sink term

$$-\left(\int \sigma_\alpha(q,v) v f_{\mathbf{p}'}^{d}(\mathbf{r},q,t)\frac{dq\,d\mathbf{p}'}{(2\pi)^3}\right) f_{\mathbf{p}}^{a}(\mathbf{r},t)$$

due to plasma absorption on dust and an arbitrary source term $S_\alpha(\mathbf{r},t)$, necessary to sustain the plasma. The source can be considered as a constant – relevant, e.g., for plasma production by photo-ionization, or as proportional to the plasma density – relevant for electron impact ionization [32] (for the effects of neutrals see, e.g., Refs. [31, 37]).

Below we present three examples that highlight new effects arising from taking into account differences from multicomponent plasmas.

Screening of dust particles

In weakly ionized dense dust clouds, collective effects and ion-neutral collisions play an important role in determining the shape of the potential distribution around a dust particle, e.g. [3, 6, 24, 38].

The non-linearity parameter $\beta = [|U_{\mathrm{coul}}(\lambda_{Di})|]/T_i$ [10], defined as the ratio between the unscreened Coulomb potential at the ion Debye length and the average ion kinetic energy, provides an estimate of the strength of plasma-grain coupling. For typical laboratory dusty plasmas $\beta > 1$, implying that the vicinity of a test grain can be divided: (i) in a nonlinear region $r < R_{NL}$ where potential perturbations are large and hence the Poisson equation should be solved for the ion and electron density distributions around the grain, (ii) in a region $r > R_{NL}$ where the linear approach is valid and the potential can be found by a perturbative solution of either the hydrodynamic or kinetic models presented above. The non-linearity radius is defined by the condition $|U(R_{NL})| = T_i$ and the two solutions should be matched in $r = R_{NL}$ by the continuity of the electric field and electrostatic potential.

Several simplifications can be evoked for solution of the Poisson equation in the nonlinear region. For electrons, due to $T_i >> T_{\mathrm{ion}}$ the Boltzmann relation can be used in its linearized form, i.e $n_e(r) = n_{e0}\{1 + [e\phi(r)]/T_e\}$ or even be omitted when compared to the ion density. For ions, in an attempt to include the effects of (i) absorption on dust, (ii) reflection of ions from the effective potential energy barrier, (iii) ion trapping , (iv) collisions with neutrals and other non-linearities it was proposed in Ref. [38] to use $n_i(r) = n_{i0}[|e\phi(r)/T_i|^{\nu}]$. Here ν is a non-linearity index that can vary from 0 to 1. For $\nu = 1$ the density acquires the linearized Boltzmann form (Yukawa form), while for $\nu = ½$ one recovers the leading term in the Gurevich distribution which is the exact distribution when taking into account only the effect of ion absorption on dust.

In these models, [3, 6, 24, 38], the existence of an attractive well in the dust-dust interaction potential has been demonstrated. A typical shape of the interaction potential for experimentally accessible conditions is

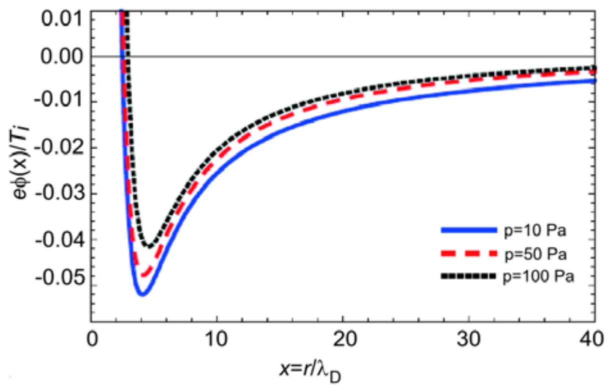

Fig. 3. After Ref. [6]. Normalized potentials for pressures p = 10, 50, and 100 Pa, density factor P_0 = 0.1, dust radius a = 3 μm and ν = 0.3.

shown in Fig. 3. In simple liquids the existence of gas-liquid transition requires the presence of an attractive well in the pair interaction potential [12]. In the dense dust clouds the appearance of long-range screening is a direct consequence of ion collection by the dust particles (charging collisions).

Effects of dust on electrostatic plasma responses

The simplest kinetic description treats dusty plasmas as multicomponent; charge fluctuations and absorption of plasma particles on dust are neglected, implying that dust is an additional charged species. In this approach the total permittivity is a sum of contributions of each species, where the electron and ion susceptibilities are as in dust-free plasmas [1].

The above-mentioned kinetic approach, developed in Refs. [32–36], allows to treat the problem self-consistently. Depending on the electron and ion time scales of interest, the electrons and ions can be treated as continuous or discrete [22, 34] as well as dust induced fluctuations may be neglected [31]. Generally such models show that inclusion of the dust effects modifies not only the dust response, but also the electron and ion responses (susceptibilities) and the fluctuating parts of their densities [33]. In some parameter regimes the two approaches coincide [24, 31, 34].

The dust particle "footprint" on the plasma responses can provide a basis for novel dust diagnostics. Modification of the plasma density and electric field fluctuations implies changes in the amplitude and spectrum of their respective correlators. These can be measured in both laboratory [23] and space plasmas [20] and hence are of particular interest. Changes of the plasma permittivity $\varepsilon_{\mathbf{k},\omega}$ imply modifications of the plasma modes which can be used to detect dust. Modification of the Boltzmann equation and the collisional integrals (see next subsection) yields modified transport coefficients for the plasma species [36] which are, generally, feasible to determine experimentally. Particle absorption on dust and the need for plasma source introduces new friction forces and collision frequencies in the Boltzmann equation, also altering the Fokker-Planck diffusion coefficient due to inelasticity of the binary collisions [32]. Especially, in the regime $P_eZ_d > 1$ with $P_e = n_dZ_d/n_e$, plasma-dust collisions dominate with respect to plasma Coulomb collisions and hence the effect in the hydrodynamic collision frequencies and therefore the transport coefficients (mobility, diffusion) will be even more dramatic.

Stochastic heating

Stochastic heating is one of the phenomena arising from dust charge fluctuations. To understand its mechanism one should address the Boltzmann equation for the dust component of the self-consistent kinetic model, where the collision integral can be decomposed in two terms; one of the typical Landau-Balescu form expressing energy conservation in Coulomb collisions that provides temporal relaxation to equilibrium, one non-conservative expressing the effect of inelastic charging collisions and resulting in a small evolution of the average distribution in time. From the second moment of the kinetic equation, the evolution equation for the particle energy can be found, where one can see that charge fluctuations produce an instability, which can lead to stochastic heating of dust particles mainly under astrophysical conditions [5]. The same growth rate for this process has been independently found from other very different theoretical approaches: from a Fokker-Planck type calculation [13] and from the theory of a harmonic oscillator with fluctuating frequency.

Stochastic heating has recently been used to address acceleration of small grains in the Interstellar Medium (ISM) [13], where it is particularly important for the process of shattering and coagulation of dust, thus determining the population of ISM dust. In a totally different parameter regime, the presence of hyper-velocity particles in tokamak edge plasmas can be possibly explained by the same mechanism: stochastic heating of a cloud of nanosized particles to very high energies in short time and acceleration to hyper-velocities of a micron-sized particle via collisions [19].

Conclusions

Above, different approaches employed in the description of dusty plasmas have been overviewed. (i) The single particle approach, appropriate for environments with low dust density, can be applied for both isolated grains as well as clusters of strongly coupled dust particles. In the latter case a Langevin description, where stochastic force simulates the effect of the dust collisions with the neutral molecules of the background gas and plasma is considered only as media providing dust charge and screening, is used to study the phase transitions and the thermodynamic state of system. (ii) When dense dust clouds are present, not only dust have to be treated as an additional component, but also the effects of plasma particle absorption on the dust surfaces and dust charge fluctuations cannot be neglected and lead to modifications of electron and ion equations. For dust clouds in a weakly-coupled (gaseous) state, the following applications have been discussed. Solutions of the problem of dust charge screening in such plasmas revealed the appearance of long-range screening which is a direct consequence of ion collection by the dust particles (charging collisions).

Kinetic models, where the above-mentioned effects are taken into account self-consistently enable one to study the modifications of the electrostatic plasma responses due to the presence of dust and explore their potential for dust diagnostics. Finally, stochastic heating, arising from dust charge fluctuations, has also been treated in the framework of self-consistent kinetic models and used for study of dust grains acceleration in both astrophysical and laboratory environments.

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