COLLECTIVE PARTICLE DYNAMICS IN A COMPLEX PLASMA

Sergey V. Vladimirov

School of Physics, The University of Sydney, NSW 2006, Australia

The dust-plasma system is an open system. Strong interactions of dust particles and the openness of the system lead to self-organization and `structurization' of initially homogeneous dust clouds into a complex aggregate of dissipative dust structures and dust voids, with sharp boundaries between them. These structures become quasi-stationary within short time scales and they are determined by a limited number of parameters controlling the structure. The quasi-stationary structures can be studied numerically and the limited ranges of the variations of the controlling parameters allow us to scan distributions of plasma and dust characteristics within them.

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1. INTRODUCTION

Dusty plasmas, i.e. plasmas containing solid "dust" particles, demonstrate unique properties. These properties allow us to consider a dusty plasma as an unusual strongly dissipative state of matter which is the mostly capable to self-organization and structure formation. The main physics of the dust structure self-organization can be summarized as follows [1].

The dust-plasma system is an open system; because of the floating charges on dust particles and their dependence on the local plasma environment it is a non-Hamiltonian system. Because of the openness of the system, the concept of free energy is generally not applicable to a dusty plasma. Moreover, dust particles with the same large charges can create strongly couples pairs. The physics of the processes is based on collective particle-particle and particle-plasma interactions in the presence of plasma flows because of the open and non-equilibrium character of the system. Strong interactions of dust particles and the openness of the system lead to self-organization and `structurization' of initially homogeneous dust clouds into a complex aggregate of dissipative dust structures and dust voids, with sharp boundaries between them. These structures become quasi-stationary within short time scales and they are determined by a limited number of parameters controlling the structure. The quasi-stationary structures can be studied numerically and the limited ranges of the variations of the controlling parameters allow us to scan distributions of plasma and dust characteristics within them.

Theory shows that a dust void generally results from the balance of the electrostatic and the plasma (such as the ion drag) forces acting on a dust particle. Here, the stability theory of a dust void is presented showing that sequences of stable and unstable void positions can exist [2]. The dynamics of dust in a plasma follows these stability characteristics leading to various stable and/or unstable dust void structures. A distinctive feature of the void is a sharp boundary between the dust and dust-free regions; this is manifested especially clear when dissipation in the plasma is small and discontinuity of the dust number density appears. The sharp boundary between the dust and void regions exists also in the presence of the ion diffusion on plasma neutral atoms; however, only derivatives of the dust density, dust charge, electron density and electric field are discontinuous at the void boundaries, while the functions themselves as well as derivatives of the ion drift velocity and the ion density are continuous [3]. Numerical calculations demonstrate various sorts of diffusive dust void structures as well as the possibility of singularities in the balance equations caused by the diffusion process inside the dust structures. These singularities can be responsible for a new type of shock-like structures while other structures are typically self-organized to eliminate the singularities.

The electrostatic force acting on dust particles is non-potential even in a potential electric field, and therefore a dusty plasma can create and support convective vortex structures [4,5]. The convection of dust particles in a plasma is related to the spatial gradients of dust charge distributions existing due to different plasma conditions in different parts of the dusty structure. For many experiments, the convection appears as a result of convective perturbations of basic nonlinear self-organized states of the dust structures. Here, the results of the study [5] is presented demonstrating solutions for the basic stationary dust cylindrical structures as well as their convective perturbations. There is the broad range of plasma and dust parameters where solutions of this set in the form of the self-organized static states exist. Perturbations of the cylindrical self-consistent dust structure states due to the dust convective motions are then treated linearly on the background of the basic nonlinear inhomogeneous distributions. For different basic states and boundary conditions various types of vortex structures can be created.

2. DUST VOIDS

In the theory of dust voids, the concepts of the virtual dust charge and virtual dust void boundary were recently introduced [2]. The virtual dust charge indicates that if a dust particle is placed in some region into a plasma, it will be charged up to the value corresponding to the virtual charge at that point. Forces acting on the dust grain will move it if the chosen position does not satisfy the equilibrium force balance condition. Similarly, the possible positions of dust void boundaries can be regarded as positions of ``virtual boundaries" in the absence of dust grains; the void boundaries can be realized at these positions depending on the boundary/initial conditions. These concepts are useful since they demonstrate various possibilities existing for the void's sizes and other properties; here, they will be used in the void's stability analysis.

The analysis is done for a one-dimensional model (in the *x*-direction), with planar geometry that is symmetric about the center of the void, by numerical investigation of the stationary force balance equations for the void structure. The void boundary positions correspond to x_v. The dust region can appear at $x>x_v$ where the dust number density n_d will then be finite (and positive). We describe a structure which size is much larger than the ion-neutral mean free path, and use the dimensionless variables given by [2,3].

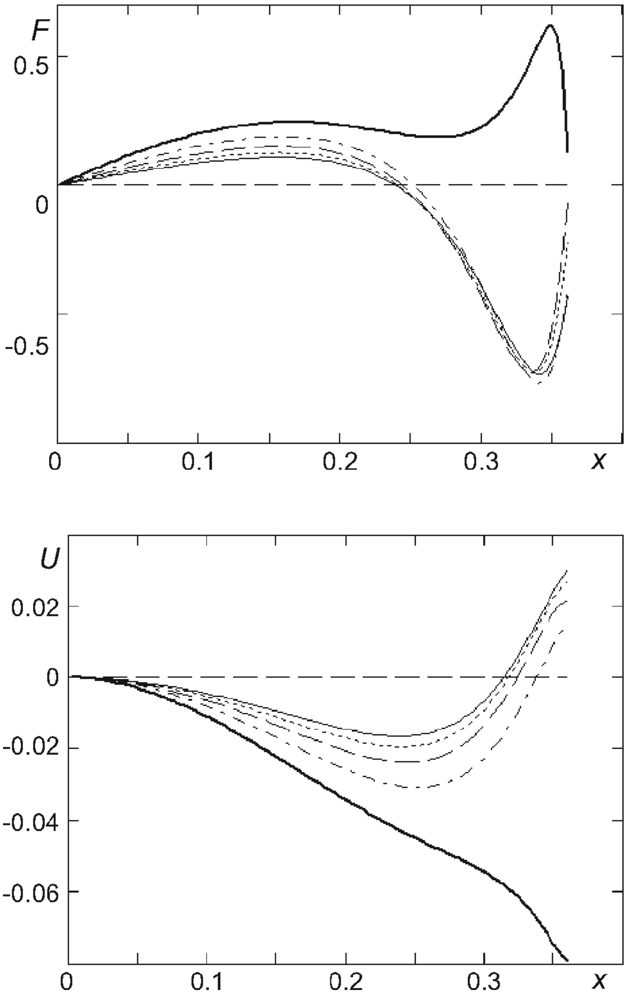

Fig. 1. The force (acting on the dust charge) and the potential energy curves for different ionization levels when the ion diffusion on neutral atoms is present and the ion flux at the void's center is entirely convective. Solid curve corresponds to $x_i=2$, dotted curve – to $x_i=5/3$, dashed curve – to $x_i=4/3$, dash-dotted curve – to $x_i=1$. The solid bold curve corresponds to $x_i=2/3$

The total system of balance equations is given by [2,3]: (1) the electron momentum equation for the electron pressure force balanced by the electric field force; (2) the ion momentum equation for the ion pressure force balanced by the electric field force, the friction on the dust force and the friction on the neutral atoms force, and containing the dust ion drag coefficient; (3) dust momentum equation balancing the dust pressure force by the electric field force and the ion drag force; (4) ion continuity equation determining the ion flow velocity and containing the ionization source x_i and the dissipation sink on the dust component (written as an equation for the ion flux); (5) the ion flux relation including the convective flux and the diffusion flux; (6) the dust charging equation obtained from the balance of charging currents on the dust grains; (7) the Poisson's equation. The boundary conditions determining the position x_v of the void boundary and the dust charge at this boundary are given by the continuity of the electric field equation and the charging equation for the dust charge.

The expression for the force acting on the dust charge is obtained from the dust momentum equation; the point(s) on the *x*-axis where the force acting on the dust particle is zero, correspond to the position(s) of the void boundary. It is also instructive to introduce the “potential energy'” *U* according to

$$U(x) = -2\int_0^x F(x')\,dx'.$$

Note that the dust charge $Z_d=Z_d(x)$ and therefore the dependence of the function *U* on the electrostatic potential ϕ conventionally defined as $E(x)=-d\phi(x)/dx$ is not that straightforward as in the case of a constant charge.

Figure 1 presents the force (acting on the dust) and the potential energy curves for the different ionization lengths. For increasing ionization level, the position of the stable void moves away from the center of the void (i.e. the void size increases). Note the qualitative change of behavior for larger ionization level (solid bold curves in Fig. 1): the stable void position characteristic for larger ionization distances disappears (although it may reappear at a significantly larger distance from the void's center). The depth of the potential energy increases, and the derivative of the force is increased. Thus the stability of the void first increases with the increased ionization and then disappears for a significantly larger ionization level. The ion density starts to decrease at a higher ionization level. For even higher levels, it becomes significantly lesser, finally leading to the disappearance of the associated stable void position as shown in Fig. 1 (the solid bold curve). Note the decrease of the dust charge at the boundary associated with the increased ion density and decreased electron density. The electric field at the void boundary is also increased with the increased ionization level in this case.

Figure 2 presents the force and the potential energy curves for the different ionization lengths at the unstable and metastable positions. For lower ionization levels (as compared to the case shown by the bold solid line in Fig. 2), the shallow stable position disappears (see inlets showing the magnified dependencies in the corresponding region of small distances in Fig. 2). For the increased ionization level, the positions of the unstable and metastable voids move closer to the center and the height of the potential barrier as well as the depth of the metastable void position decrease. Thus the unstable positions and the metastable positions show the tendency to appear at shorter distances from the void's center. The dust charge is decreasing for the unstable void position and is increasing for the metastable void position.

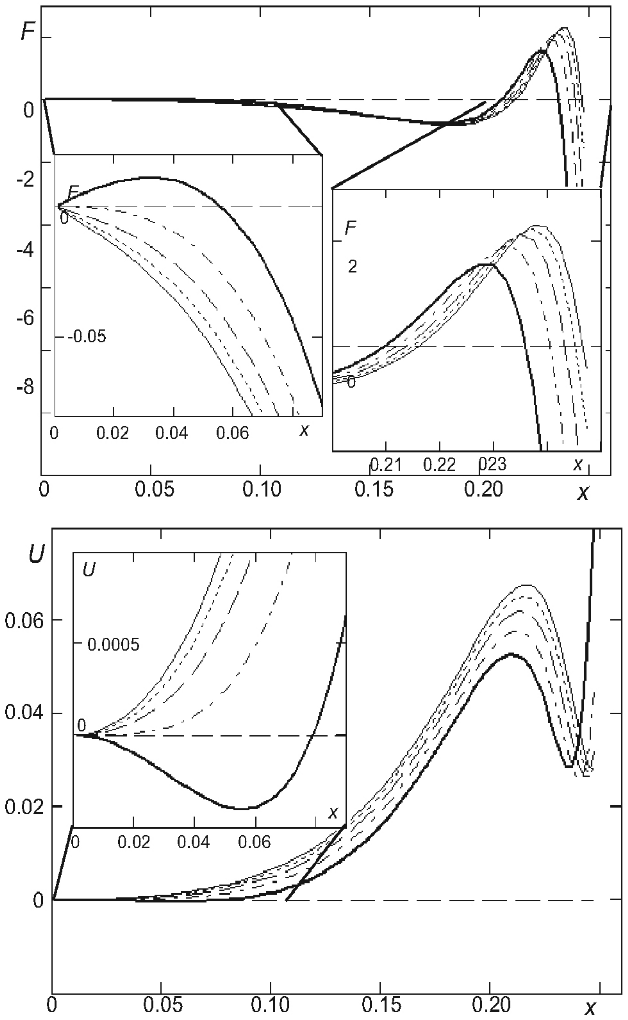

Fig. 2. The force and the potential energy at the unstable and metastable positions. The curves correspond to the same ionization levels as in Fig. 1. The inlets show details of the behavior of the force and the potential energy in the regions near the center of the void x=0 and near the unstable/metastable void positions

3. DUST CONVECTION

Convection of dust particles in a low-temperature gas discharge plasma is a spectacular phenomenon observed for various conditions in dusty plasma experiments (see in [4,5]). The first theoretical explanation relates the dust convection to the process of dust charging by the ambient plasma particles (electrons and ions) and, consequently, to an inhomogeneity of the grain charge distributions appearing due to different plasma conditions. This distinguishes the dust convection from the common convection in gases and liquids related to the presence of the temperature gradients, such as Rayleigh-Benard convection: the convection of dust particles, which is the result of the gradients of the dust charges, is driven by ∇Z_d, where Z_d is the dimensionless dust charge such that $Q_d = - Z_d e$, and e is the (positive) absolute value of the electron charge. Here, an important phenomenon is that the electrostatic force acting on dust grains is not potential even for a potential electric field **E**, i.e. with $\nabla \mathbf{E} = 0$ since $\nabla \times (Z_d \mathbf{E}) = (\nabla Z_d) \times \mathbf{E} \neq 0$ because of the non-zero dust charge space gradients in the direction, perpendicular to the direction of the electric field. On the basis of this knowledge, a number of numerical models of the dust convection for various phenomenologically chosen gradients of the dust charges were constructed.

Here, a theoretical self-consistent model is presented for the dust convection in the case when it is induced by an external modulation of the ionization rate [4,5]. The main idea of the model is to proceed as far as possible with the analytic description taking into account the self-consistent dust charge distribution. The cylindrically-symmetric geometry is considered, and it is assumed that the external modulation of the ionization rate acts along the axis of a cylindrical dusty plasma. The collision-dominated case is studied where the size of the structure is larger than the ion-neutral mean-free path. In the model, the radial cylindrical coordinate perpendicular to the cylindrical axis is ρ and the coordinate along the cylindrical axis is x. In the basic nonlinear state, the convection is absent and all parameters of the structure depend only on ρ.

Similarly to the case of the dust void studies, the set of general nonlinear equations where the system (plasma and dust) parameters are not yet separated into the basic state stationary distributions and the (convective) perturbations is given by: (1) the electron momentum equation for the electron pressure force balanced by the electric field force; (2) the ion momentum equation for the ion pressure force balanced by the electric field force, the friction on the dust force and the friction on the neutral atoms force, and containing the dust ion drag coefficient; (3) the dust momentum equation balancing the dust pressure force by the electric field force and the ion drag force; (4) the ion continuity equation determining the ion flow velocity and containing the ionization source x_i and the dissipation sink on the dust component (written as an equation for the ion flux); (5) the ion flux relation including the convective flux and the diffusion flux; (6) the dust continuity equations; (7) the dust charging equation obtained from the balance of charging currents on the dust grains.

In the basic state, the velocity of dust grains is zero, and the perturbation of this state by the dust convection is related to the development of non-zero grain velocities accompanied by disturbances of the dust particles number density, the plasma ion/electron number densities, and the ion drift velocity caused by the convective motions. It is important that characteristics of these basic structures are determined by a limited number of the controlling parameters, internal (such as the ion number density in the center of the structures) and external (such as the ionization level).

Once the basic self-consistent state is obtained, sinusoidal perturbations of the ionization rate along the cylindrical axis of the structure are introduced; their period corresponds to the size of convective cells observed in the experiments. While in the basic state the dust grains are not moving, in the presence of the perturbations along the axis the grains acquire the both velocity components, i.e., the component along the cylindrical axis as well as the component along the radius. The convection thus appears as a result of the external perturbation of the ionization rate. In this convective motion, a grain moves in a way to substitute another grain, not changing the mean dust density substantially. This is the main argument to consider the perturbations (caused by the dust convection) of the self-consistent dust number density distributions to be small.

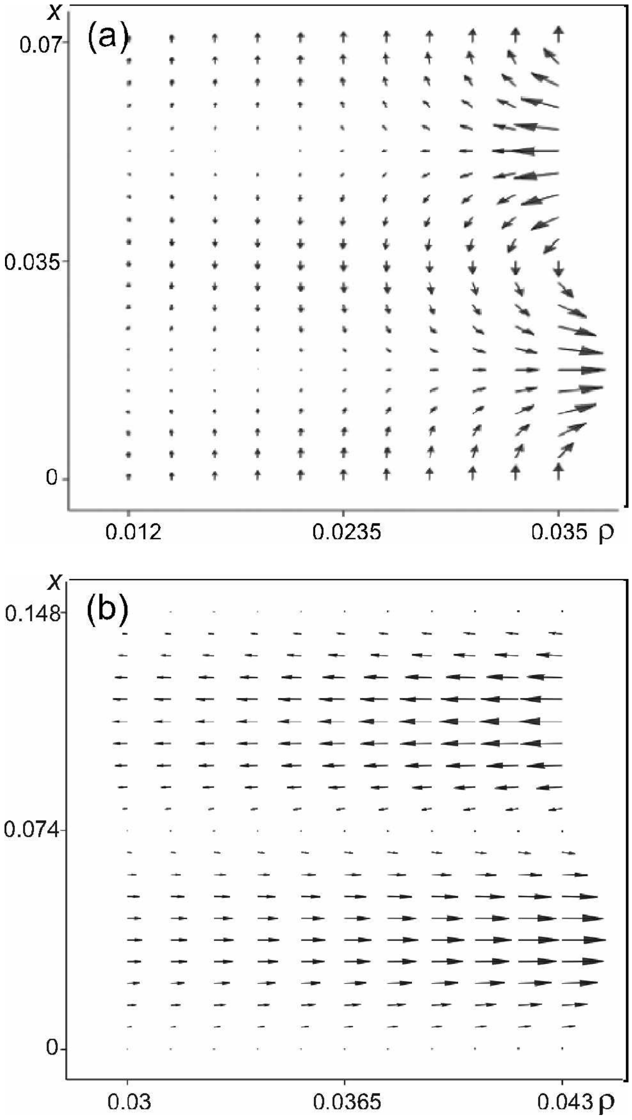

Fig. 3. The dust convective cells; the vector fields of the convective dust velocities are shown, the vertical axis is along the cylindrical axis and the radial axis is ρ.
(a) The dust convective pattern for the size of the basic structure ρ_P*=0.035; (b) the vector field distribution of the dust convective velocities closer to the axis for* ρ_P*=0.076*

The procedure consists in solution of the equations for the modulations related to the emerging dust convection and calculated on the basis of the known basic state. In this way, a set of the self-consistent nonlinear equations for the dust convection containing additional two parameters, the amplitude and the modulation period of the perturbation of the ionization factor, is derived. After simplifications, the final set of nonlinear equations for the perturbations of the variables is solved numerically using as boundary conditions the asymptotic properties of the corresponding variables (and the system parameters) at the axis of the cylinder.

The calculations start from some distance from the center and show different type of convective patterns. Figure 3(a) shows the vector field of the convective dust velocities; here, the dust drift velocity close to the axis is parallel to the axis and changing its sign; the convective velocity is increasing with the radius. Figure 3(b) demonstrates the vector field distribution of the dust convective velocities for ρ_P=0.076 (the physical size corresponding to this dimensionless value is about 1.5 mm). The dust velocities that are directed to the surface should be deviated and returned from the surface, and the surface of the structure will be then be curved in this case. Figure 4 demonstrates that some convective patterns are in the form of vertical flows (parallel to the cylindrical axis): the dust velocities close to the surface of the basic structure are along the surface and the radial size of the structure is not modified by the dust convection. Figure 4(b) demonstrates the whole convective cell in this case.

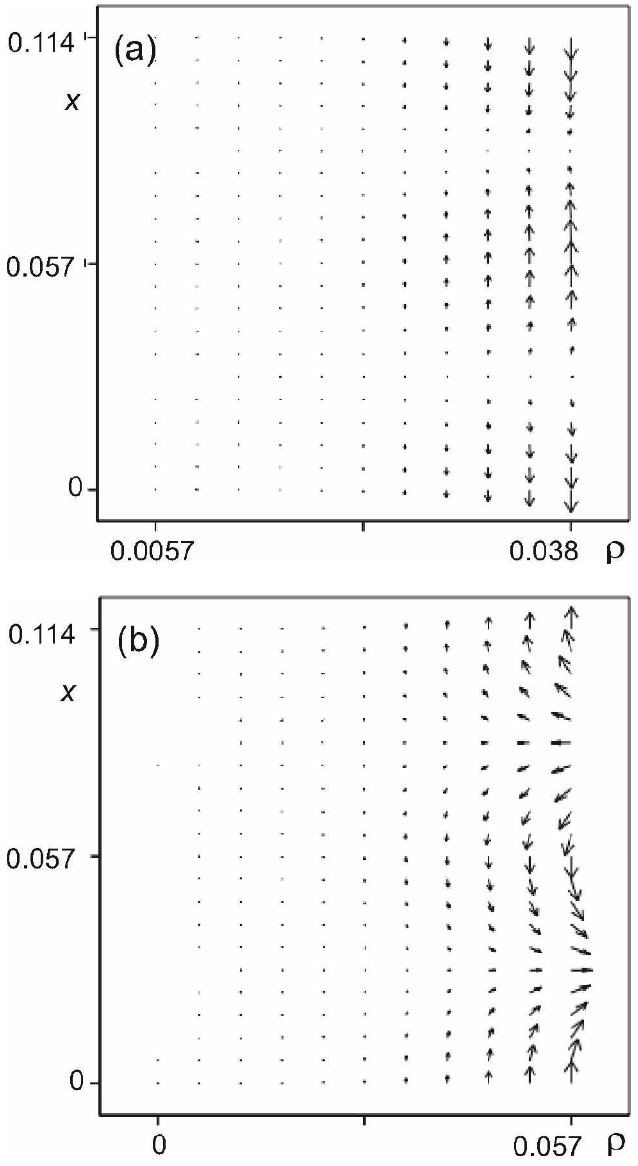

Fig. 4. The dust convective cells: (a) the convective patterns in the form of vertical flows (parallel to the cylindrical axis); (b) the whole convective cell in this case

The considered here convective cells are the limiting examples and in between there exist the convective cells with the almost circular convection. The general feature is that the convective velocities increase from the center of the cylindrical structure and in the most places are directed perpendicular to the cylindrical axis close to the surface of the basic structure, i.e., the surface of the basic nonlinear dust structure is modified by the dust convection.

ACKNOWLEDGEMENT

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КОЛЛЕКТИВНАЯ ДИНАМИКА ЧАСТИЦ В КОМПЛЕКСНОЙ ПЛАЗМЕ

С.В. Владимиров

Плазменно-пылевая система является открытой системой. Сильное взаимодействие пылевых частиц и открытость системы приводят к самоорганизации и структуризации первоначально однородных пылевых облаков в сложный конгломерат диссипативных пылевых структур и пустот (войдов), с резкими границами между ними. Эти структуры становятся квазистационарными за короткие промежутки времени; они при этом определяются ограниченным числом параметров, контролирующих структуры. Квазистационарные структуры могут исследоваться численно, причем ограниченные области вариаций контролирующих параметров позволяют получить и просканировать распределения плазменных и пылевых характеристик внутри этих структур.

КОЛЕКТИВНА ДИНАМІКА ЧАСТОК У КОМПЛЕКСНІЙ ПЛАЗМІ

С.В. Владимиров

Плазменно-пилова система є відкритою системою. Сильна взаємодія пилових часток і відкритість системи призводять до самоорганізації і структуризації спочатку однорідних пилових хмар у складний конгломерат дисипативних пилових структур і порожнеч (войдів), з різкими границями між ними. Ці структури стають квазістаціонарними за короткі проміжки часу; вони при цьому визначаються обмеженим числом параметрів, що контролюють структури. Квазістаціонарні структури можуть досліджуватися чисельно, причому обмежені області варіацій контролюючих параметрів дозволяють одержати і просканувати розподіли плазмових і пилових характеристик усередині цих структур.