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Perspectives of experimental and theoretical studies of self-organized dust structures in complex plasmas under microgravity conditions

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Abstract. **We review research aimed at understanding the phenomena occurring in a complex plasma under microgravity conditions. Some aspects of the work already performed are considered that have not previously been given sufficient attention but which are potentially crucial for future work. These aspects, in particular, include the observation of compact dust structures that are estimated to be capable of confining all components of a dust plasma in a bounded spatial volume; experimental evidence of the nonlinear screening of dust particles; and experimental evidence of the excitation of collective electric fields. In theoretical terms, novel collective attraction processes between likely charged dust particles are discussed and all schemes of the shadowy attraction between dust particles used earlier, including in attempts to interpret observations, are reviewed and evaluated. Dust structures are considered from the standpoint of the current self-organization theory. It is emphasized that phase transitions between states of self-organized systems differ significantly from those in homogeneous states and that the phase diagrams should be constructed in terms of the parameters of a self-organized structure and cannot be constructed in terms of the temperature and density or similar parameters of homogeneous structures. Using the existing theoretical approaches to modeling self-organized structures in dust plasmas, the parameter distribution of a structure is recalculated for a simpler model that includes the quasineutrality condition and neglects diffusion. These calculations indicate that under microgravity conditions, any self-organized structure can contain a limited number of dust particles and is finite in size. The maximum possible number of particles in a structure determines the characteristic inter-grain distance in dust crystals that can be created under microgravity conditions. Crystallization criteria for the structures are examined and the quasispherical chambers proposed for future experiments are discussed.**

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1. Introduction

Dust (complex) plasma is the subject of numerous recent studies (see reviews [1–4]). Although problems of dust plasma or simply dust in plasma were posed back in the mid-20th century in the physics of the interstellar medium [5, 6], star formation [7], planetary rings [8, 9], and other astrophysical applications, a boom in deeper investigations in this field (an increase in the number of publications by more than an order of magnitude) appeared in the early 1990s in connection with technological applications for manufacturing computer circuits [1, 10] and fundamental discoveries of the possibility of crystallization of the dust component [11–14] (1994, 1996).[1]

We remind the readers far from this research field that dust particles in plasma are by definition any solid particles (of any configuration, including fractal particles) with a size much smaller than the screening length of their electrostatic field. Such a definition assumes that fairly large formations (small stones in planetary rings and even artificial satellites [24] in the near-Earth plasma) can also be treated as dust particles. Some theoretical results [24] are quite often used in modern concepts of complex plasmas.

Dust plasmas encountered in experiments and nature are rather diverse in their parameters, but most often it is a low-temperature plasma with a low concentration of agents that would destroy dust particles. The size of dust particles ranges from 0.003 to 0.5 μm in space plasma, and from 10 to 100 μm in laboratory plasma. As regards temperature limitations, the myth that dust particles always quite rapidly evaporate in interactions with plasma electrons and ions was dispelled from the very beginning of studies in the physics of dust particles in plasmas. It was found that at temperatures below critical (T_{cr}), dust particles not only do not evaporate but can also slowly increase in size, accumulating electrons and ions recombining on them and even accumulating smaller dust particles and neutral atoms. Their attachment coefficients for dust particles are quite high.

In rather popular experiments on prolonged plasma etching in gas discharges, dust particles sometimes grow up to a few millimeters in size and can be visible to the naked eye. We briefly explain how such particles can be confined in a discharge and consider the mechanism of their growth. This is related to the fact that a solid particle entering a plasma quite rapidly acquires a floating potential and a fairly large charge. Dust particles in plasma can usually be negatively charged up to charges exceeding the electron charge by 3–6 orders of magnitude (the dust particle charge is $Q_{\mathrm{d}} = -Z_{\mathrm{d}} e$; $Z_{\mathrm{d}} \approx 10^3 - 10^6$, e is the electron charge). Thus, in plasma with an electron temperature of 3 eV and an ion temperature two orders of magnitude lower (typical of most high-frequency discharges), a dust particle 10 μm in size acquires the charge $Z_{\mathrm{d}} \approx (2.5-5) \times 10^4$. In this case, the charge is proportional to the dust particle size and is comparatively small (a few elementary charges) only for atomic sizes, whereas it is already $Z_{\mathrm{d}} \approx 10^6$ for sizes ≈ 200 μm.

The large charges of dust particles lead to many important effects, in particular, to a strong interaction of dust particles and their good confinement in a discharge. Even at low concentrations of dust particles, their interaction (which, neglecting the screening, is $\propto Z_{\mathrm{d}}^2$) can become strong and determine the dynamics of not only the dust component but also all other components of dust plasmas. Dust plasma with strongly interacting dust particles is often called a *complex plasma*, because strongly interacting dust particles can transfer to a liquid or crystalline state, whereas electrons and ions remain in the gaseous state. But even in the absence of such transitions, the large charges of dust particles can result in their good confinement by the walls of a gas-discharge plasma.

Usually, a potential difference of the order of the electron temperature T_{e} exists between the plasma and the chamber walls. It represents a large barrier for dust particles, which exceeds T_{e} by a factor of $Z_{\mathrm{d}} \approx 10^3 - 10^6$. An example is etching processes in a high-frequency discharge proceeding sometimes for a few days, when some dust particles grow to sizes visible to the naked eye. It is for this time (a few days) that these dust particles are confined in the discharge [10]. Most often, $T_{\mathrm{cr}} > T_{\mathrm{e}}$ in gas discharges (depending on the dust material, the value of T_{cr} changes within a few tens of electronvolts, while T_{e} lies within a few electronvolts.) According to current concepts, almost all gas discharges contacting the walls are discharges in a dust plasma (chamber walls 'raise' dust because plasma electrons and ions irregularly heat the walls of the discharge chamber and their erosion produces dust particles).

2. Setting up the problems of the existence and stability of self-organized dust structures and dust plasma crystals

The first proposals for setting up experiments in complex plasmas, in particular, on the formation of new types of crystals, where crystal structures appear only in the dust component, were made in 1986 [25] and 1992 [26] and were first realized under terrestrial conditions in 1994 [11–13] and 1996 [14].[2] We note that important estimates made before the first experiments [26] showed that Earth's gravity field should destroy crystal dust structures in terrestrial experiments. Therefore, it was commonly assumed that experiments should be performed under microgravity (zero gravity) conditions. Such experiments were performed on board the International Space Station (ISS) in the framework of the Russia–Germany Agreement. However, test experiments under terrestrial conditions conducted before space experiments showed unexpectedly that the injection of dust particles into the simplest gas discharges resulted for the first time in the formation of dust crystals on Earth. The simplicity of

[1] The author became interested in this topic even before 1990, when only the first hints at the advent of new physics appeared and its weakly pronounced features were slowly transpiring in investigations. However, after more than 20 years of active studies, it became clear that they can be transformed into an elegant scheme, which is important for future studies in and of itself. In this paper, the author attempts to show that if this had been done in time, the choice of correct steps in investigations would have been considerably simplified. The obtained indirect demonstrations of the role of such processes, which are consistent with general self-organization schemes, are objectively and critically analyzed and presented in the simplest form (by a 'rule of thumb', with a minimum of theoretical and numerical analysis), which is, however, sufficient for determining the so-called 'dry residue' and promising avenues of future studies, taking new physical effects already found into account. Some reviews and papers on complex plasma and the physics of interaction of dust particles in plasmas are presented in [15–23].

[2] The authors who discovered crystalline dust structures in plasmas called them *plasma crystals*. We use the terms *dusty crystals* or *dust plasma crystals*, emphasizing that regular crystal structures are formed only by dust particles.

observing dust crystals in the very first experiments under terrestrial conditions [11] was quite surprising. In the experiments in [11], dust particles of a certain size (~ 10 μm) were injected into a gas discharge, but crystals were also formed by injecting dye particles from a standard printer [27] with a large scatter of sizes.

What were the errors (if there were any) of the first estimates of the role of gravity? We recall that the estimates of the possible role of gravity concerned ideal conditions, where, apart from the external gravity, only the interaction of dust particles multiply increased due to their large charge was taken into account. The role of other external forces was neglected in these estimates. Could the external sources compensate for gravity in the first experiments [11]?

We have mentioned plasma sheaths and the appearance of a potential difference near the walls, which contain dust particles inside the discharge. Indeed, under the specific experimental conditions in [11], crystals were observed in the near-wall region of the discharge when the electric fields of the near-wall region could compensate for gravitational forces.

Dust crystals could be formed due to such a compensation. This interpretation for terrestrial conditions proved to be correct as a whole, if only because the formation of crystals far from the walls was hampered. However, such a treatment may be only preliminary.[3] Future experiments under zero-gravity (or microgravity) conditions or other experiments should help to understand the role of near-wall fields under terrestrial conditions. We note that the actual role of near-wall fields is not simply reduced to the levitation of dust particles in a near-wall sheath, and dust particles can and must change its structure noticeably. If experiments are performed under microgravity conditions, gravitational forces are absent, and it would be natural to perform experiments far from the walls to avoid complications related to near-wall fields.

In this case, near-wall fields (which usually have a rather complex structure) do not shadow experiments concerning the apparently new physical effect of forming crystals by particles with rather large charges. Only in the absence of such shadowing could a transparent and deeper understanding of new physical phenomena typical of dust particles be expected. Further observations under microgravity conditions aboard the ISS [28, 29] did not propose using such experimental conditions (far from other external force sources, including experiments away from near-wall sheaths). This is natural because it is common practice that the equipment tested under terrestrial conditions is used in complex space experiments. Therefore, it seems natural that space experiments involved certain difficulties in attempts to observe dust plasma crystals.

A summary of these studies is as follows. If we neglect episodic observations of very small ordered spatial distributions of dust particles, we can expect that dust crystals do not appear under zero-gravity conditions in near-wall regions of gas discharges. However, dust voids (regions where dust particles are completely absent in certain parts of the discharge) with distinct spatial boundaries were discovered. This can be expected if one of the two forces compensating each other under terrestrial conditions is absent. Recently, it was decided to extend studies and produce so-called 'pure' conditions far from near-wall sheaths. The equipment used in the first ISS experiments [28] was similar to that in which dust crystals were obtained under terrestrial conditions. In such experiments, the role of plasma sheaths is rather important.

We note the great success of space experiments in the observation of quite different dust structures, dust voids [29], which, as dust crystals, can be assigned to a class of *new self-organized structures in open physical systems*. This term is used below in the general description of properties typical of plasma as a state of matter. Another term, *dusty structures with a free boundary*, is also used in what follows. This term first appeared in interpreting the results of numerical calculations [30] revealing a spontaneous formation of crystals in a dust plasma, with the Coulomb screening of repulsion and specific shadowy attraction of dust particles taken into account. However, in [30], only the simplest model of Debye screening applied to small dust particles was used. Later, a numerical description was developed for general structures with a free boundary (see details in Section 9).

This paper is devoted to an analysis of the state of the art and an outlook for studying crystallization in dust plasmas and the formation of structures in the absence of gravitational and other external forces from the standpoint of self-organization processes. The problem of crystallization is regarded as a particular one within the more general problem of the formation of self-organized structures with free boundaries, and crystallization is treated as a transition from one such structure to others.

3. Wall plasma sheaths

It is necessary to explain why experiments near wall plasma sheaths cannot answer questions about the formation of self-organized dust crystals and cannot be used for studying more complex problems, including the interaction of self-consistent structures with each other in general; wall plasma sheaths also belong by their nature to the class of self-organized structures.

Wall plasma sheaths are rather complex structures. The physics of plasma sheaths has been studied for almost a century. Studies were initiated in 1922 by Langmuir [31], one the first researchers in plasma physics (see the state of the art in [32–34]).

Wall plasma sheaths have many technological applications in plasma etching mentioned above, in plasma chemistry, and in gas discharge physics. Therefore, the physics of plasma sheaths has been the subject of many fundamental and applied studies demonstrating the complexity of such structures and the important role of surface effects, electron and ion fluxes on the walls, and the complex nonlinearity of field distributions inside wall sheaths having specific inner singularities [33]. Presently, wall plasma sheaths are often treated as independent self-organized plasma structures described by their own nonlinear models. They are considered in terms of the newest self-organization theory as, for example, striations in gas discharges.

Plasma crystals are also one of the possible types of self-organized structures in a dust plasma both far from its boundaries and in wall sheaths. It would be improper to begin studies of dust crystals inside other structures or under the strong action of other structures such as wall sheaths. Of

[3] The electric field in near-wall sheaths is strongly nonuniform, and therefore different parts of a crystal are located in fields of different strengths, and it is necessary to explain why the observed distances between crystal planes located in fields differing in strength by an order of magnitude are approximately the same.

course, dust crystals were first discovered inside wall sheaths. Each of the structures, either a wall sheath or a dust crystal, self-organizes nonlinearly and, obviously, they cannot simply overlap each other or other structures. Therefore, an object such as a dust crystal inside a wall sheath is a separate self-consistent structure, which, typically, was not mentioned in most experiments.

The strategy of experiments with plasma crystals and other structures under microgravity conditions should involve first the study of structures not subjected to the action of other structures and only then the study of the interaction between structures, the physics of hybrid structures, and dust crystallization inside plasma sheaths. Wall dust structures affect not only dust crystallization processes but also the distribution of parameters inside wall sheaths.

The study of new self-organization and crystallization physics in dust plasmas appears more natural for structures considered separately. To understand the new physics in studying compact self-organized structures, it is necessary to discuss new phenomena encountered in experiments. The features of such new physics were already observed in the first space experiments. They revealed the formation of new self-organized compact dust structures *with the properties of self-confinement of all components — dust, electrons, and ions — in a bounded spatial region, which was an unexpected and new phenomenon*, and also the formation of compact structures in a bounded spatial region — the *dust voids* containing no dust.

In addition, the appearance of new structures — dust vortices — was observed, in which dust particles were mainly involved in vortex movements. We attempt to explain these observations in terms of elementary physics and consider them as a *manifestation of new properties of these systems*. The effects of dust self-confinement in a bounded spatial region outside wall sheaths, dust self-cleaning in a bounded spatial region in voids, and the generation of dust vortices are of special interest due to their novelty. They indirectly indicate the appearance of new forces between dust particles, which, however, have not been properly discussed in connection with the observation of the nonlinear screening of dust particles and excitation of collective electric fields in structures. We see below that these effects were observed in experiments only indirectly.

4. Formulation of some new problems in the physics of dust structures

In considering all the concepts described above, we can formulate a number of new problems for theoretical and experimental studies.

(1) Taking possible forces and collective fields into account, is it possible that *equilibrium configurations of dust structures localized in a bounded spatial region exist* without additional external forces and sources of plasma flows?

(2) Is it possible that *stable isolated structures* exist, which should be rather inhomogeneous because they are bounded in space?

(3) Is it possible to study and classify equilibrium self-consistent structures and find global parameters controlling these structures?

(4) Is it possible that structures with a complex configuration exist, in particular, when crystallization appears only in a part of the structures or can self-organized structures crystallize only as a whole?

(5) Is it possible that crystalline shell structures with inner voids exist?

(6) Is it possible that phase transitions in inhomogeneous structures (i.e., transitions from one inhomogeneous self-consistent gas or liquid state to another inhomogeneous crystalline state) qualitatively differ from transitions that have been considered so far in the physics studying transitions from one spatially homogeneous state to another (more exactly, when surface and volume effects are clearly separated)? Here, we are also dealing with transitions from one noncrystalline inhomogeneous self-consistent structure to another crystalline inhomogeneous self-consistent structure. We note that the inhomogeneity is inherently related to the possibility of the existence of individual isolated structures.

(7) What are formation processes and the dynamics of such structures?

(8) Does a dust plasma always decompose into structures? What are the structuring criteria for dust plasmas and *is structuring in the absence of gravity and wall sheaths universal*?

(9) Does an analogy exist with the well-studied gravitational structuring of matter? This analogy could exist if interactions between likely charged dust particles become attractive beginning from certain distances.

Thus, we are dealing with new physical problems related to the properties of isolated self-organized structures, including new spatially inhomogeneous and self-organized dust crystals and self-organized gaseous and liquid dust structures. In addition, we also discuss new phase transitions between inhomogeneous self-organized structures. To study such transitions in experiments, it is necessary to first investigate structures with free boundaries far from wall sheaths by separating them from more complex structures and ensuring that strong interactions with other structures are absent. This is the outlook for studies under zero-gravity conditions. We note that there is no answer to the old question about phase transitions between homogeneous dust states or to the question of whether such states can be realized experimentally under microgravity conditions.

We discuss proposals of new experiments below. It is necessary first to describe equilibrium structures theoretically and then to study their stability. We note that the prolonged observation of structures under appropriate external conditions already confirms their stability. However, the theoretical program should include not only a search for new self-organized equilibrium states of structures with free boundaries but also the study of their stability. We also discuss how universal the structuring effects in dust plasmas are and in which (exceptional) conditions almost homogeneous dust states can be observed.

The aim of the remarks concerning previous experiments was to define an outlook for future experiments with self-organized structures. The importance of the discovery of dust crystals near wall plasma sheaths under laboratory conditions and voids under space conditions is obvious. The results of the first observations of dust plasma crystals under terrestrial conditions and dust voids under zero-gravity conditions are presented in Fig. 1. We note that it is only in a rough approximation that dust crystals were not observed under zero-gravity conditions and dust voids were not observed under terrestrial conditions. In reality, voids were very rarely observed under terrestrial conditions (for very small dust particles) and crystals were observed under microgravity conditions (in very small regions), and their observation

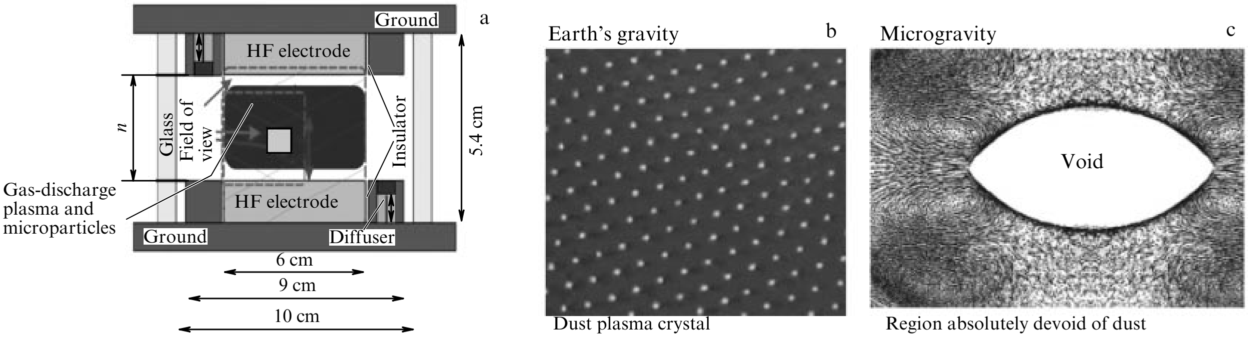

Figure 1. (a) Experimental setup in which (b) plasma crystals and (c) voids were first observed.

requires a careful search, whereas the formation of voids can easily be reproduced in observations.

This review presents the state of the art in studies of self-confined, self-organized dust structures with different configurations (including dust crystals) and evaluates the prospects for the development of these studies.

5. Experimental possibilities of observing isolated self-organized dust structures

The difficulties related to wall sheaths are due to electrostatic fields and ion flows with rather complex distributions created in the sheaths, which cannot be eliminated by applying external fields. One of the ways to eliminate wall sheaths is trivial: according to the Gauss theorem, a closed charged surface (for example, a sphere in the simplest case) does not generate electrostatic fields inside. Wall sheaths appear due to the same processes as the charging of dust particles: electrons, being more mobile, rapidly reach the surface, producing ion flows to the surface and charge separation, resulting in the formation of wall fields in which the electric field of the layer generates ion flows on the walls of a discharge chamber.

If the electric field is not produced despite the charge of the chamber surface, the electrostatic force — the second component in the equilibrium of dust particles in the wall layer under gravity conditions — also disappears. After the first experiments under microgravity conditions, spherical [35, 36] and nearly spherical [37] chambers were proposed (Fig. 2), allowing the elimination of wall sheaths, and the general results of numerical calculations were published [38] that demonstrated the advantages of experiments in spherical

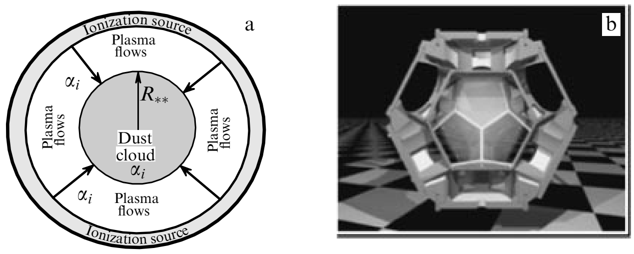

Figure 2. (a) Spherical chambers proposed by Sato [35, 36], in which a discharge in the spherical wall layer is used to produce a plasma flow converging to the chamber center, penetrating through the wall discharge net; (b) quasi-spherical Konopka chamber [37] with the surface consisting of pentagonal sectors to which microwave fields of opposite polarities can be applied from opposite sides.

chambers. In view of the more general problems of equilibrium, stability, and phase transitions in self-organized structures that we consider, we here estimate the positive and possible negative factors of the future use of such chambers [35–37].

During a discharge in any chamber, a balance between the generation and absorption of plasma components is usually established. Electrons and ions are produced in ionization and their recombination in the plasma volume is usually weak and occurs in the absence of dust on chamber walls. When the dust component appears, additional recombination from the dust occurs, but conditions are also possible when recombination on dust is the main mechanism in the balance of electron–ion creation in ionization. Sato assumes that the ionization mechanism is an additional discharge near the spherical chamber surface (Fig. 2a). The electron and ion flows from this discharge are directed to the chamber center through the inner grid of a gas-discharge layer. These flows should be absorbed by dust particles inside the chamber. But the absorption intensity depends on the total number of dust particles, i.e., constraints on the injection of the particles should be consistent with the flow or the flow should be consistent with the number of particles. The possibility of achieving such a consistency should be additionally provided. The additional homogeneous ionization, as usual, could be produced by microwave fields with the wavelength greatly exceeding the chamber size.

Ionization in a Konopka chamber (Fig. 2b) can be produced by microwave fields applied to opposite segments, with a phase shift between different segments. If ionization with a maximum at the chamber periphery can be produced in this case, flows to the chamber center should also appear, to be absorbed by dust particles. In both cases, dust particles should play a considerable role in the global balance of the discharge, making it qualitatively different from other discharges. In the absence of dust, the wall is the only sink for particles, but in the absence of fields and flows on the wall produced by them, the absorption by the walls is determined by slow diffusion to the walls, and therefore the discharge balance and ignition strongly depend on the neutral gas pressure. Due to the presence of dust in spherical chambers, absorption and the discharge itself can be determined by the dust component.

6. Studies of a new class of forces in a dust plasma determined by plasma flows

As already mentioned, the assumed universality of structuring processes in dust plasmas most likely can be related to a new type of interaction between dust particles. As is now becoming clear, the interactions typical of dust particles are related to the electron and ion flows generated by the structure itself. As early as 1990–1992, before the discovery of dust crystals, the agglomeration of small dust particles attracted special attention. Attempts were made to explain it by assuming the presence of attraction forces between likely charged particles caused by a change in plasma flows to dust particles and a change in the charge of interacting dust particles when they approach each other. The possible role of such effects was first mentioned in [39]. We recall that dust particles are charged by electron and ion flows, and in the absence of electrons and ions in the plasma, the charge of dust particles disappears. Even in the absence of directed flow velocities, the charging processes proceed quite efficiently, because thermal flows exist (while in nonequilibrium plasmas, fluctuation flows exist).

The charging processes for an individual dust particle can be most simply described by such electron and ion flows, but describing the charging process in the most interesting case of a compact cluster of dust particles is not so simple. If the surface of a dust particle is spherically symmetric, thermal flows on the surface are also spherically symmetric. But it is difficult to assume that the flows preserve such a symmetry for a cluster of dust particles. The flows can be spherically symmetric only far from the cluster of dust particles. Already for two particles, in the case first considered in [39], a change in the flow during the approach of the particles changes their charges. In principle, qualitatively different consequences of this effect are possible. First, near one of the particles, another particle can be injected, with the flow determined by the first of them, and the formation of the charge of the injected particle and the change in the charge of the previously existing particle occurring for times much shorter than the time of the change in the existing flow. Then the plasma flow is determined by the first of the previously existing particles and should be redistributed between two particles. As a result, the charges of both particles are smaller than the charge of the previously existing particle and the self-energy of the particles decreases, as a rule, stronger than the interaction energy increases in repulsion [39]. This suggests that the approaching of particles is energetically advantageous and particles can agglomerate.

Another case corresponds to approaching particles with the already formed flows on each of their surfaces. Then the asymmetry of the flows is manifested first and foremost, which can be called the shadow effect, and the effect of momentum transfer from the flow to particles can be called the shadow attraction. Unlike electrostatic repulsion, this attraction is not screened, as is clear from simple considerations, and there always exist distances between dust particles at which the attraction force, decreasing as $1/r^2$ (the solid angle of the shadow) dominates over screened repulsion. The estimate of characteristic distances at which this occurs depends on the shadow model. If it corresponds to a geometric shadow, first considered in [41], the attraction turns out to be rather weak. In reality, however, ions are rather strongly attracted by negative dust particles and the trajectories of their motion toward dust particles are not straight lines. The collision cross section for ions scattered on a dust particle can greatly exceed the geometrical cross section of the particle, which is the case in most experiments: the shadow is not geometrical. The cross section is then T_e/T_i (usually, 10^2) times greater, and the real shadow attraction that appears should be much greater than that produced by the geometrical shadow. This was first mentioned in [40]. The shadow attraction also increases when the charge of dust particles exceeds a critical charge such that the scattering cross section for ions by dust particles is mainly determined by large-angle scattering. The ions scattered by the first particle cannot reach the second particle, the size of the screening region also increases [2, 42–44], and screening becomes nonlinear.

Attraction can be even more efficient if the collective effect [43–46] is taken into account by considering the attraction of an individual particle to an agglomerate of many dust particles and finding attraction per any pair of particles (an individual particle and one of the agglomerate). This characterizes the effective pair attraction in a collective and can be compared with the attraction of an isolated pair. Unlike gravity, collective attraction is not additive and cannot be expressed as a sum of shadow attraction forces for individual agglomerate particles, because the perturbed flows intersect with each other.

This effect was first mentioned in [43] and described in detail in [2, 44–46]. In the analysis of such processes, of interest are distances greatly exceeding the mean distance between dust particles, such that only the directional component of the ion distribution is important. If we observe a dust particle at a distance from the center of a cluster of particles (agglomerate), it is located in a flow that is directed as whole to the cluster center, and therefore the particle is located in a directionally asymmetric distribution of ions having the mean directional velocity near this particle. We recall that symmetric flows absorbed by a dust particle do not impart the momentum to it and do not produce additional forces. The momentum transferred by the flow with the mean directional velocity should be imparted to particles absorbing the flow. Ions in this flow, having a mass greater than the electron mass, interact with the charge of a dust particle and impart their momentum to this particle. This force is the *drag force acting on dust particles from the flow*. It can lead to the collective attraction and affect the equilibrium in any cluster of dust particles [45–47] (see details in Sections 6 and 7).

As shown in [43, 44] with the example of linear screening, the drag force, with the change in the ion flow due to its absorption during momentum transfer to dust particles taken into account, completely determines the collective shadow attraction force. The size of the inhomogeneity of such a force is of the order of the cluster size, i.e., greatly exceeds the mean distance between dust particles, which in the first approximation allows averaging the drag force over the velocity distribution of ions and using the averaged hydrodynamic description. The drag force depends on the cross section of the interaction of ions with a dust particle and, of course, on the type of screening of the field of particles: linear Debye screening [45, 46] or nonlinear screening [24, 47]. In the latter case, as shown in [47], the drag force and collective attraction increase with increasing the screening nonlinearity.

The theoretical description of collective attraction in the point-particle approximation has some uncertainty because the expression for the interaction contains the permittivity in the denominator, which should change sign (i.e., pass through zero) depending on the value of wave numbers (reciprocal distances). This occurs because the permittivity characterizes repulsion at small distances, and attraction at large distances.

This problem was solved in [2, 45, 46] by considering finite-size particles and proving that for particles of a finite, although small, size, the Landau prescription for bypassing the pole can be used in the point-particle limit. At present, the theoretical description of processes increasing the shadow attraction is quite comprehensive for making predictions that can be verified experimentally.

The drag force is also related to the *appearance of large-scale self-consistent electric fields in structures*. We explain this effect by analogy with the electric field excited by a current proportional to the electron drift velocity. For dust structures, in the simplest case where the locally directed ion velocity is much smaller than the thermal velocity of ions, the drag force is proportional to the directional ion velocity. Of course, for large velocities, the dependence of the drag force on the drift velocity is more complex, but the proportionality is preserved.

The limit case of a small drift velocity is convenient for drawing an analogy with Ohm's law, where the current is also proportional to the drift velocity, although of electrons rather than ions, and the presence of the current produces the so-called step voltage, i.e., the corresponding electric field. Therefore, the presence of drag forces in a dust plasma should be accompanied by the appearance of a collective electric field with a scale much larger than the mean distance between dust particles. This was first demonstrated by numerical calculations of the equilibrium of compact structures under the assumption of local quasi-neutrality [48] and with drag forces taken into account, and by the first theoretical descriptions of voids [49, 50] in which the equilibrium of the collective field and virtual drag forces is used to find void boundaries.

Incidentally, we note that many calculations of the equilibrium of structures interacting via the screened Yukawa potential (so-called Yukawa balls or Coulomb balls [51]) neglect collective fields and the drag force, because electron and ion flows and their absorption by a screened particle are not taken into account (Yukawa screening turns out to be for many other reasons inapplicable to processes in dust plasmas; see Section 9). Studies of this type rather concern some imaginary problem, but not a dust plasma, where dust particles acquire their charge by absorbing electron and ion flows.

Ions in a flow in a dust plasma lose their energy and momentum due to the drag by dust, resulting in the appearance of an additional friction force proportional in the first approximation to the drift velocity, which, as in Ohm's law, cannot but excite collective electric fields, with the characteristic size greatly exceeding the mean distances between dust particles. Collective fields cannot be neglected in the balance of forces in a dust cluster or in collective shadow attraction. Neglecting them is illegal in calculations of so-called Yukawa clusters, but this approximation is used in all of the subsequent analysis. These effects were confirmed experimentally; they belong to a new class of phenomena in a dust plasma.

A few words about averaged large-scale and 'fluctuation' fields are in order. Microscopic fields determine the size of screening and 'fluctuation' shadow forces with a characteristic size small compared to collective inhomogeneities of a size greatly exceeding the distances between particles and the screening of the field of dust particles.

Both large-scale drag forces and large-scale electrostatic fields appear in the background of small-scale flows and fields that are locally directed to the surface of each of the dust particles and therefore rather strongly vary in space. Only averaging these flows gives the picture of drag forces and electrostatic large-scale fields slowly changing toward the center of the dust particle cluster. Relations between large-scale and small-scale processes in a dust plasma can be studied not only theoretically but also experimentally, because we can observe, if not small-scale fields, at least the dynamics of each of the dust particles. All standard theories in usual (not dusty) plasmas deal with fluctuations and fluctuation-averaged quantities. But the dynamics of individual particles cannot be observed, and the analysis of observations often requires the use of theoretical approaches for averaging over fluctuations, in particular, by introducing concepts of the decoupling of correlation functions. The advantage of investigations in dust plasmas is the possibility of observing the dynamics of individual dust particles and directly verifying hypotheses of the decoupling of fluctuations. But if such investigations are performed, it is unlikely that their results can be applied to a plasma without dust because of the specific interaction of dust particles.

Both local [40, 41] and macroscopic [42, 43] attraction forces are similar to the Lesage shadow attraction model for gravity interactions related to the screening of flows of a nonexistent 'ether' toward one of the interacting particles by another, neighboring particle. Unlike the Lesage model, forgotten after the creation of the theory of relativity, which has no place for ether, flows in a dust plasma are absolutely real (electron and ion flows) and their efficiency strongly depends on the characteristic size and the efficiency of the interaction of flows with particles.

Shadow forces in a dust plasma are similar in a certain approximation to gravitational forces and can be characterized by the effective gravitational constant G_{eff} [47, 52] depending, unlike the gravitational constant G, on the dust density and other parameters. Therefore, such interactions are collective. The collective attraction caused by drag forces and the collective field play an important role in the interpretation of voids and observations of the injection of test dust particles into the void center [50], allowing one to see how injected particles are 'swept out' from the void to its periphery. The drag forces acting on dust particles are caused by plasma flows dragging dust particles. For voids, such flows should be stationary, produced at the center of the void, and directed from the center to the periphery, while for compact structures, the flows should 'squeeze' the structure outside and confine dust particles in a bounded spatial region, producing collective attraction. Only the electron and ion flows that are naturally formed by the dust plasma itself rather than by additional external sources are important.

We note that the appearance of flows on the surface of particles is a natural process of maintaining the floating potential. When dust particles are introduced into plasma, these flows can often be thermal: electrons, being more mobile, reach the surface before the ions do and are adsorbed on the dust surface, which becomes negatively charged, and its charge grows until most of the slow electrons of the thermal distribution are reflected from the dust particle, and only electrons from the tail of the thermal distribution reach the dust particles. Although ions are attracted to the negative charge of the dust particle, they can diminish the charge increase only when their flow becomes equal to the reduced electron flow. To provide the equilibrium of the dust charge, the electron and ion flows should be equal, and to maintain this charge, *neither the electron nor the ion flow should vanish*. The plasma flow on the dust surface is not zero after reaching the equilibrium charge; the dust serves as the plasma sink, and to provide a balance, the plasma recombining on the dust should be restored by an ionization source.

In this sense, a dust plasma is an open system. Only ions in the flow play a role in the momentum transfer and creation of drag forces. The fields of the drag forces, determined by the local parameters of the concentration distribution and the ion drift, are virtual in the absence of dust particles and act on dust particles only when dust particles appear at the corresponding place in the system. Thus, the drag field inside a void acts on a dust particle only after its injection into a certain place inside the void. The concept of virtual drag fields clearly explains the mechanism of the appearance of voids. Plasma flows also appear in any other spatial structures of dust particles.

As mentioned, the first experiments with dust plasma crystals under laboratory terrestrial conditions were performed in wall sheaths when the electric fields of the plasma sheath produced an external plasma flows in addition to the thermal flows discussed in Section 2 and related to the charging of dust particles. Apart from drag forces, plasma flows contribute to variations of the charge of dust particles. This effect also involves the appearance of vortex forces acting on dust particles in a purely potential electrostatic field and giving rise to vortex dust structures. Vortices can also be formed as perturbations of equilibrium self-organized structures. Their excitation can be described using the theory of stability of self-organized structures. At present, a number of experiments [53, 54] confirm the shadow attraction effects, and these experimental results are explained by the shadow attraction model with the nonlinear screening of dust particles.

7. Qualitative description of the self-confinement of dust, ions, and electrons in a dust spherical self-organized structure

We assume that the self-confinement of dust particles in sufficiently large structures is determined only by large-scale flows and describes qualitatively how equilibrium can be established in such structures in the absence of wall sheaths and gravitation. For simplicity, we also assume that the structure has a limited size and is spherical (this assumption does not simplify the qualitative picture but allows us to performing numerical calculations; see Sections 11 and 12). We also suppose that the flow outside the structure is spherically symmetric and is directed to the structure center.

We assume that the structure contains dust particles with a large charge $Z_d \gg 1$. As follows from estimates, the drag forces are at least proportional to Z_d, and therefore should be first of all taken into account in the equilibrium conditions. They are directed to the interior of the structure. The forces of the collective electric field are also proportional to Z_d. But due to the negative charge of dust particles, these forces are directed outside from the structure center. The balance of these two forces can locally determine the equilibrium of dust particles for $Z_d \gg 1$. Under the assumption that $Z_d \gg 1$, equilibrium can be established using a relatively weak electric field (to confine dust particles in the wall layer, a relatively weak electric field is also sufficient).

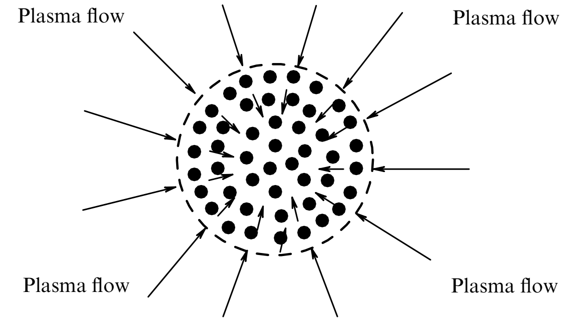

Figure 3. Diagram of a self-organized free-boundary structure.

The electric field force acting on ions is directed to the interior of the structure and confines ions in the structure. Electrons, being the lighter particles, are distributed adiabatically (their distribution being locally Maxwellian), with the local electron density determined by the balance of the electric field and electron pressure. Thus, all plasma particles can be in equilibrium in a nonuniformly distributed structure. Typically, such a structure should have a finite size R_{str}. The values of the external flow and R_{str} are determined by the number of confined dust particles capable of charging at the structure center, where the flow absorbed by dust particles should arrive.

Such concepts are valid for dust structures with a free boundary, which will possibly be produced in chambers (see Fig. 2). The basic equations for such structures, which can be used in numerical calculations, are discussed in Sections 11 and 12, and a qualitative drawing is presented in Fig. 3. These calculations allow finding conditions under which the sharp boundary of the structure shown in Fig. 3 is realized. We mentioned above that flows for spherical chambers can be formed only by diffusion. We can assume that the boundary sharpness for structures with free boundaries is determined by the approximation neglecting diffusion. This is confirmed by numerical calculations performed for the model of self-consistent spherical structures, in which collisions of plasma ions with dust particles dominate in diffusion processes.

We note that the effect of sharp dust boundaries is quite often observed in dust plasmas, as can be seen, in particular, from the dust distribution on the void boundary in Fig. 1c. The question of possible future experimental studies of the boundaries of dust structures and the role of diffusion in the structure of boundaries is discussed in Sections 16 and 17.

Figure 3 shows that dust particles inside the structure have a certain interparticle distance, which defines a certain density of dust in the structure. In fact, the question of how many dust particles can be confined by an individual structure and therefore what the dust density is in the equilibrium structure is quite important. A number of important observations in this respect already exist, but they do not concern self-organized structures with free boundaries. In particular, when dust was injected into gas discharges with striations [11], it was found that the produced structures could contain only a certain number of dust particles, the excess particles dropping out to the chamber bottom. In Section 13, we discuss how this effect of a finite number of particles in the structure and restrictions on the dust density in the structure can be illustrated by numerical models and what future experiments with self-organized structures can confirm.

8. Compact structures found in dust plasmas under microgravity conditions

Compact dust structures similar to those that we considered in the model discussed above were first observed accidentally in experiments under microgravity conditions, when dust particles of a smaller size were injected into a void that had been produced by dust particles of a larger size. Such compact structures formed spontaneously before the smaller particles reached the region of particles forming the void [55–57] (Fig. 4) and then, as observations show, larger particles were ejected from the central axial region. Larger dust particles cannot stop the formation of the compact structure of smaller particles up to the void region.

The balance of forces transverse to the direction of motion of dust particles is determined by the equality of the force from the produced collective electric field and the drag force across the injection direction, which depend differently on the dust particle size. If the field decreases in the direction from the system axis, a smaller drag force is sufficient to achieve balance at large distances from the axis. Therefore, if the ratio of the drag force to the electric field force decreases with increasing the dust particle size, the ejection of dust particles from the center should be observed. In this case, particles of different sizes cannot be in equilibrium at a given point in the discharge because of the different dependences of the drag force and the electric field force on the particle size.

The ejection of larger particles from the region of smaller particles found recently has its prehistory related to the very first experiments in a complex plasma in which equilibrium distributions were studied in discharges with particles of different sizes. It was shown in some of the first experiments that particles of different sizes in equilibrium configurations are separated in space[4] and, as in recent experiments, smaller particles experience relatively larger drag forces (Fig. 5). This had a profound meaning, which was not explained at that time. The simplest estimate of drag forces, taking linear screening into account, gives the opposite result. We discuss the correct interpretation in Section 12.

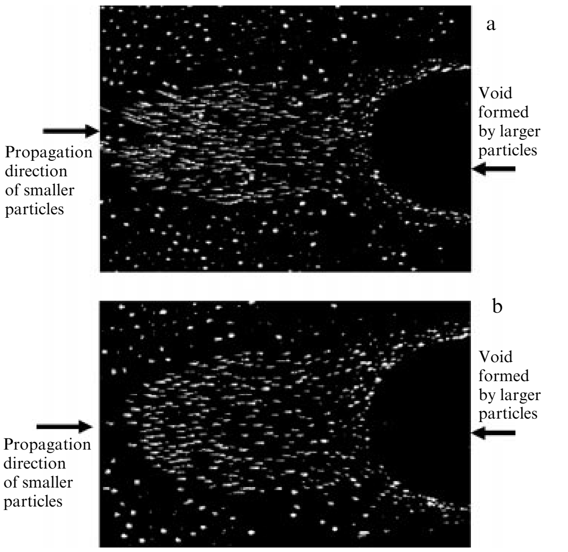

Figure 4. Observation of compact dust structures during the injection of smaller particles into a region close to a dust void of larger particles; Fig. 4b corresponds to a later instant of time than Fig. 4a.

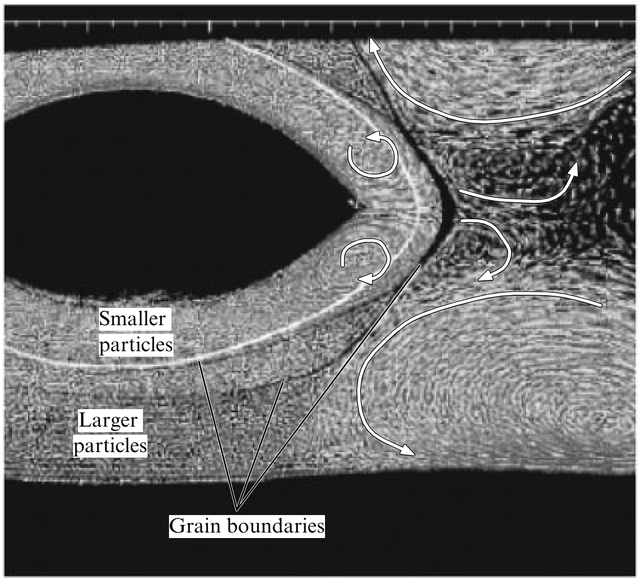

Figure 5. Observation of a void first surrounded by smaller particles and then by larger particles [28]. New dust structures — dusty vortices — were also observed around the void.

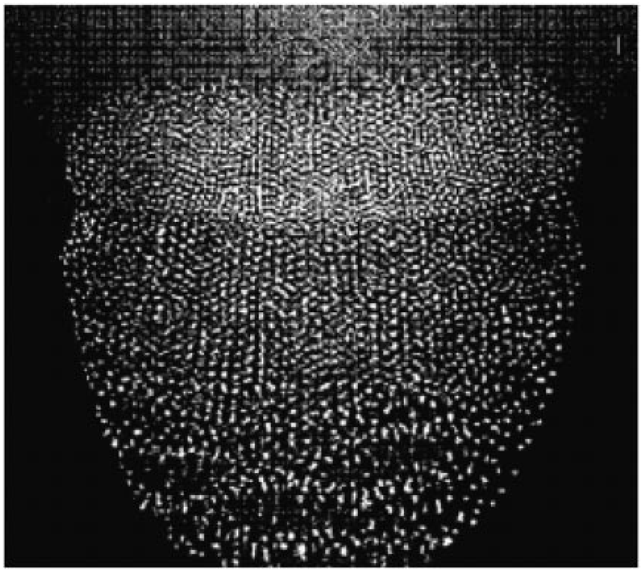

Figure 6. Compact structures found in discharges with striations containing crystalline, liquid, and gas phases. The observation shows how crystalline, liquid, and gas states can simultaneously be present in the structure.

The observation of compact dust structures in some laboratory experiments, where the role of boundaries and the field structure was not determined, was also quite accidental [14] (Fig. 6).

Compact structures were later observed in several special experiments. However, they typically contained a small number of dust particles, which did not allow verifying the fundamental properties of self-organized structures, and experiments were performed not in spherical chambers

[4] This was pointed out in [11] and clearly shown in the first ISS experiments in 2003 [28] (see Fig. 5).

where the action of plasma sheaths can be avoided, albeit far from the chamber walls. We return to the discussion of these experiments after the description of qualitatively new properties of dust structures with free boundaries.

9. Nonlinearity of the dust particle screening

The dependence of the drag force on the particle size described in Section 6 was explained in [55, 56] by the screening nonlinearity. This question, related to the role of the nonlinearity of the polarization charge in screening a sufficiently large charge, was considered more than half a century ago as the problem of screening artificial Earth satellites [24], which, just as dust particles, have a much smaller size than the linear Debye screening radius. The linear screening model can be almost completely carried over to the screening of dust particles. Screening is usually performed by plasma electrons and ions, which can have the Boltzmann distribution

$$n_{\mathrm{e,i}} \propto \exp\left(-\frac{e_{\mathrm{e,i}}\phi_{\mathrm{d}}}{T_{\mathrm{e,i}}}\right)$$

near a dust particle, where $n_{\mathrm{e,i}}$ are the electron and ion concentrations, $T_{\mathrm{e,i}}$ are the electron and ion temperatures, and ϕ_{d} is the potential of the dust particle. Linear or Debye screening is the screening under conditions that the electron and ion distributions are weakly perturbed and only the linear term in the expansion with respect to the dust particle potential can be retained in the exponential:

$$\exp\left(-\frac{e_{\mathrm{e,i}}\phi_{\mathrm{d}}}{T_{\mathrm{e,i}}}\right) \approx 1 - \frac{e_{\mathrm{e,i}}\phi_{\mathrm{d}}}{T_{\mathrm{e,i}}}\,.$$

The Poisson equation in this case leads to the exponential screening,

$$\phi_{\mathrm{d}} = -\frac{Z_{\mathrm{d}}e^2}{r}\exp\left(-\frac{r}{\lambda_{\mathrm{D}}}\right), \qquad \frac{1}{\lambda_{\mathrm{D}}^2} = \frac{1}{\lambda_{\mathrm{D,i}}^2} + \frac{1}{\lambda_{\mathrm{D,e}}^2}\,.$$

We note that $\tau \equiv T_{\mathrm{i}}/T_{\mathrm{e}} \lesssim 0.01$ in most experiments, and screening is mainly determined by ions. As the charge of dust particles increases, first of all for ions, it becomes impossible to expand the screening charge in the potential of dust particles. Then the criterion for screening linearity becomes $\beta \equiv Z_{\mathrm{d}}e^2/T_{\mathrm{i}}\lambda_{\mathrm{D,i}} \ll 1$.

Because $Z_{\mathrm{d}} \propto a$, where a is the dust particle size, the criterion for the screening nonlinearity is rapidly violated. For example, estimates for existing experiments show that the linearity is realized only for $a < 0.1-0.03$ μm. At the same time, to study the interaction of dust particles, it is desirable to increase their charge under the standard experimental conditions, to $a > 10-15$ μm. In this case, the linear screening approximation is invalid. The simplest linear screening model [24] assumes that the expression for the perturbed charge of ions includes only those ions of the distribution that, starting from distances where the potential of the particle field is negligibly small, can reach a specified distance near a dust particle: $\epsilon(r) > -e\phi_{\mathrm{d}}(r)$, where $\epsilon(r)$ is the energy of the screening ion at a specified distance r. The screening factor ψ for nonlinear screening differs from the exponential one:

$$\phi_{\mathrm{d}} = -\frac{Z_{\mathrm{d}}e^2}{r}\,\psi(\beta, r)\,.$$

Because of the restriction on the energy of particles responsible for screening, the polarization charge density for nonlinear screening is smaller than that for linear screening, and therefore the characteristic size of the nonlinear screening region is larger than that for linear screening. Calculations predict an increase in the screening region to approximately $(7-8)\lambda_{\mathrm{Di}}$, which often remarkably coincides with observations. In the literature, this has often been attributed to the ion drift decreasing the linear polarization of ions to the value at which the linear polarization of electrons is manifested, with the screening nonlinearity neglected. However, in reality, polarization is nonlinear, and correct estimates in this case show that the drift is much weaker, and electrons cannot provide the observed screening.[5]

Knowing the nonlinearly screened potential, for example, by using the model in [24], we can calculate the scattering of the ion flow by dust and the drag force by standard formulas [2, 47] and also calculate the dependence of the drag force on the particle size. It is convenient to compare the ratio η of the drag force F_{dr} and the electric force F_{E}. For linear screening, $\eta \propto a$, while for nonlinear screening [47], $\eta \propto 1/a^{0.35}$, which completely explains why, during the formation of a compact structure by smaller particles, the larger particles are pushed out by smaller ones. Thus, it is clear that nonlinear screening should be involved in explaining the observations. The nonlinear screening model used in [24] is necessary, but is not the only one [58]. Some models assume that captured ions can play a noticeable role in screening [58]. However, the authors of some papers believe that this is unlikely because of the instability of distributions with captured ions.

10. Observed manifestations of collective electric fields

Such manifestations include the observed ejection of large particles from a forming compact structure of smaller particles (see Fig. 4). The drag force for smaller particles for nonlinear screening is greater, and if these particles begin to control the collective electric field, then this field is too strong to compensate the smaller drag force acting on larger particles, and it is the collective field that ejects them from the structure, which is easy to observe in experiments. Thus, the ejection of large particles from the axial region of the forming structure controlled by smaller particles clearly demonstrates the formation of a collective field.

The spatial separation of small and large particles around a void arises somewhat differently, but such a separation is also impossible without a collective electric field. The collective field inside the void is directed from the center and increases with the distance from the void center. For negatively charged dust particles, the electric field force is directed to the center, while the drag force is directed from the center. The surface on which these forces become comparable corresponds to the void surface. The drag force inside it is greater and outside it is smaller than the electric field force. The surface is stable when particles outside the void approach

[5] To 'maintain the importance' of studies with exponential screening, it was proposed in some studies to treat exponential linear screening as a phenomenological or even fitting parameter with an efficient screening length and the effective particle charge. The nonlinear screening can be fitted to this so-called Yukawa potential only at limited distances with an accuracy of 200–300%.

its surface under the action of the drag force. At a certain distance outside the void surface, the collective field begins to decrease and larger particles are ejected to distances exceeding the equilibrium distance for small particles.

The dust concentration (and the Havnes parameter $P = Z_d n_d / n_i$) on the surface should experience a jump, being zero inside the void; the jump has a certain magnitude proportional to the Havnes parameter and the electric field force. Almost all observations of voids reveal this sharp jump and the complete absence of dust particles inside the void. The ejection of larger particles is natural because the equilibrium at a specified distance holds for smaller particles. According to the result of the experiment shown in Fig. 5, larger particles acquire equilibrium at longer distances from the void center, which means that the collective field strength decreases as the distance from the void center increases. This is expected and confirmed by numerical calculations, because dust particles at a certain distance outside the void should reduce the field strength by their charge.

Another important manifestation of collective fields is dust vortices at the sides of voids related to the non-collinearity of the fields and gradients of the charge of dust particles (see Figs 1 and 5). The equations for the vortex motion of dust particles in dimensionless variables $E \to eE\lambda/T_i$, $v_d \to v_d/v_{Ti}$, $t \to tv_{Ti}/\lambda$, $m_d \to m_d/m_i$ has the form

$$m_d \frac{d(\mathrm{rot}\,\mathbf{v}_d)}{dt} = -\mathrm{rot}\, Z_d \mathbf{E} = -[\boldsymbol{\nabla} Z_d, \mathbf{E}]\,. \qquad (1)$$

In the top part of Fig. 5, the field is directed upwards and in the bottom part, downwards, while at the edges the concentration gradients are directed at an angle to these directions. The rotation of particles corresponds to the right-hand screw rule. The rotational velocity can be used for measuring the collective electric field strength.

We recall that because of the large charge of dust particles, $Z_d \gg 1$, even a relatively weak collective field E can eject particles with a strong enough force $Z_d E$ and produce dust vortices. This is also confirmed by numerical calculations presented in Sections 11 and 12.

11. General results of numerical calculations of equilibrium in self-consistent dust structures

The characteristic features of dust plasmas discussed above are sufficient for formulating the simplest problems of numerical calculations of equilibrium in self-consistent dust structures. Such problems can be formulated in the most interesting case of nonlinear screening under conditions when diffusion is suppressed by collisions of ions with nonlinearly screened dust particles [59, 60] and in the absence of quasi-neutrality. Quite extensive preliminary calculations showed that these are the most correct and simplest assumptions for most experiments performed.

Diffusion can be taken into account and the requirement of quasi-neutrality can be discarded, but, although these conditions are violated in a limited region of structures, such restrictions can be imposed to avoid a bulky analysis obscuring the general picture. However, this question was not clarified at the first stages of studying these structures. The first preliminary calculations of an equilibrium were performed under the conditions of local quasi-neutrality [55, 46], taking only the diffusion due to collisions of ions with the atoms of a neutral gas into account [61, 62]. Studies [60] showed that although the first condition is approximately satisfied, it holds with an accuracy of 25–35% in a number of calculations, while the second condition is valid only in a narrow layer near the structure boundary.

The equilibrium of forces under stationary conditions should exist for all components: the field, dust, ions, and electrons. For the equilibrium of dust particles, only electrostatic forces and drag forces were taken into account in [59] (for $Z_d \gg 1$, other forces are small). For the equilibrium of ions, friction forces related to the dust drag force and to friction with neutral gas atoms are taken into account, as are thermal pressure and dynamic pressure forces of the flow and electric field forces. For electrons, the electron pressure and electric field forces are taken into account; for the charges of dust particles, the equality of electron and ion flows to dust particles; and for the flow velocity, the continuity equation including the ionization and absorption of flows on dust. It is important that the charges of dust particles in all calculations are not assumed to be fixed and vary with distance in accordance with variations of other local parameters of structures. In this case, the values of charges vary quasi-adiabatically, in accordance with the fact that the charging of dust particles occurs quickly compared to the characteristic times of the structure dynamics (this assumption about the adiabaticity is also used in the consideration of the stability of equilibrium structures).

The equations obtained for equilibrium contain only first spatial derivatives and for spherical structures are determined by the structure parameters at its center. The number of such parameters is reduced to two, because the flow velocity and the electric field strength vanish, and this condition determines a relation between the values of other parameters at the center. As two such parameters, we can take the ion concentration and the charge density of dust particles at the center. The solution of equilibrium equations assuming weak ionization inside structures when the structures are maintained by external flows gave the following results:

(1) equilibrium solutions exist in a limited range of values of the two mentioned parameters;

(2) equilibria are possible only for certain distances from the center not exceeding R_{str}, which can be called the structure size;

(3) inside a structure, only a limited number N_d of dust particles can be confined;

(4) collective electric fields inside a structure under conditions of approximate quasi-neutrality are not zero and allow determining the total charge of the structure;

(5) collective charges of the structure can exceed the charges of individual dust particles, although the mean density of the collective charge is much smaller than the charge density of individual dust particles;

(6) compact equilibrium structures appear only when ionization inside the structure is small enough;

(7) the increase in ionization from values at which it barely affects the structure to values at which variations in the structure become noticeable does not qualitatively affect the distribution of parameters inside structures in a broad range of the ionization power, but a further small increase in the ionization power leads to a drastic change in the structure topology and the appearance of a void at the center;

(8) voids, like compact structures, have sharp boundaries;

(9) the proposed method can be used for rigorous calculations of structures when quasi-neutrality is violated;

(10) the sharpness of boundaries is preserved when quasi-neutrality is violated;

(11) the sharpness degree of the boundaries for compact structures and voids is determined by diffusion;

(12) the sharpness of the diffusion boundary increases with increasing the dust concentration in the structure, which is caused by suppression of the ion diffusion on neutral atoms in collisions of ions with dust particles, the collision frequency increasing due to nonlinear screening;

(13) the dust concentration first increases with the distance from the void surface and then decreases to values close to zero, forming a spherical dust shell around the void;

(14) blurred boundaries appear only in a structure in the form of a void surrounded by a sufficiently thin dust spherical layer;

(15) many results of calculations are, as a whole, consistent with observations; numerical calculations describe new qualitative phenomena that will be available for future experiments.

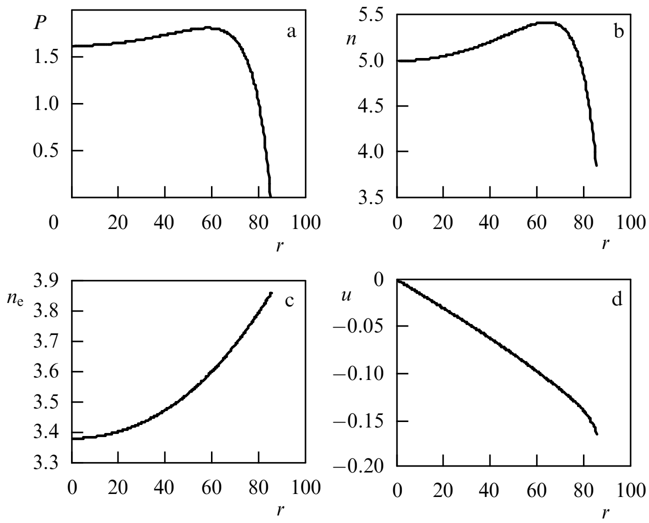

Figure 7. Distributions of (a) the dust charge density, (b) the ion concentration, (c) the electron concentration, and (d) the ion drift velocity for a structure with $n(0) = 5$. The calculation of the structure size by solving the equation $P(R_{str}) = 0$ gives a rather large value $R_{str} = 85.077$. The curves in the figures are calculated up to distances $r = R_{str}$ from the center; the distance is measured in units of the mean free path λ in collisions of ions with neutral atoms.

12. Numerical calculation of the equilibrium of a compact dust structure

We consider a numerical calculation that was performed, following the method in [59], especially for this paper as the most typical one, confirming the statements made in Section 11.

To perform numerical calculations of structures, it is necessary to choose the normalizations of densities and drift velocity convenient for the comparison with experiments, such that the normalization constants in experiments be approximately constant. For this, it is convenient to normalize the densities to $n_* \equiv T_i/4\pi e^2\lambda^2$ and the ion drift velocity to $\sqrt{2T_i/m_i}$, where λ is the ion mean free path in collisions with neural gas atoms; the charge of dust particles is normalized to aT_e/e^2 and the electric field strength is normalized to the value at which an ion acquires the thermal velocity on the mean free path: $n \to n_i/n_*$, $n_e \to n_e/n_*$, $P \to n_d Z_d/n_*$, $z \to Z_d e^2/aT_e$, $E \to eE\lambda/T_i$, $r \to r/\lambda$. We note that the Havnes parameter P_H often used in the literature is here equal to P/n. It is convenient to choose $n(0)$ and $P(0)$ as two independent parameters determining the structure. Constraints on these parameters are determined from the system of equations for equilibrium (briefly described in Section 11), which we now present for completeness (in the simplest case):

$$2u\,\frac{du}{dr} + \frac{1}{n}\,\frac{dn}{dr} + u f_{dr}(u) = E\left(1 - \frac{P}{n}\right), \qquad \frac{\tau}{n_e}\,\frac{dn_e}{dr} = -E\,,$$

$$\tau = \frac{T_i}{T_e}\,, \qquad \frac{1}{r^2}\,\frac{d}{dr}(r^2 n u) = -aPn\alpha_{ch}(u)\,, \tag{2}$$

$$E = f_{dr}(u,\beta)u\sqrt{n}\,, \qquad \beta = \frac{az\sqrt{n}}{\tau}\,,$$

where $f_{dr}(u,\beta)$ is the drag coefficient and $\alpha_{ch}(u)$ is the charging coefficient for dust particles. The first coefficient is expressed in terms of the numerically calculated transport scattering cross section for ions scattered by nonlinearly screened dust particles, while the second coefficient is expressed in terms of adhesion cross sections (absorption of ions by dust particles). The assumption about the large charge of dust particles is reflected in the last relation for the balance of forces in dust particles preserving only electric and drag forces. System of equations (2) is written in the simplest case of quasi-neutrality (first analyzed in [48]), where $P = n - n_e$. The system of equilibrium equations for a problem without the quasi-neutrality assumption is not fundamentally much more complicated, although it is more cumbersome. Its solution shows that P is expressed in terms of all the coefficients related to the drag and charging of dust particles, and the quasi-neutrality degree depends on them to some extent. However, an analysis gives a more accurate description, approximately coinciding with the simplest quasi-neutral description (but discrepancies can amount to 25–30% in a number of examples). We consider the example with $P = n - n_e$ in (2).

First of all, we find that for a large number of values of the initial parameters, system (2) does have self-consistent solutions describing compact structures of limited size. Of the maximum size are the structures that are flat at the center. For such structures, system (2) gives $n_{min} < n(0) < n_{max}$. We note that small structures appear for $n(0)$ close to $n_{min} \approx 2-3$, while $n_{max} \approx 400$, i.e., the range of parameters for which equilibria are possible is rather broad. Here, we consider the results for one structure with $n(0) = 5$ in detail (Fig. 7). We note at once that calculations can give the dust density in the structure, and this has important consequences. Although the ion density distribution is almost flat, its maximum is located at the structure periphery. At the structure boundary, $n_{str} = 3.761$. We note that the Debye screening radius λ_D in dimensionless units is $1/\sqrt{n}$ and changes with the distance from the center, being equal to $\lambda_{D,\,str} = 0.509$ at the boundary. The ratio of the Debye length to the characteristic inhomogeneity size $n(r)/|dn(r)/dr|$ in the structure is small, reaching the maximum value 0.036 on the surface, while the ratio of the nonlinear screening length to the characteristic inhomogeneity size is approximately 0.3. The distributions of the Havnes parameter $P_H = P/n$ and the dimensionless dust density $n_d \equiv P/z \to n_d 4\pi a\lambda^2/\tau$ (in units of $\tau/4\pi a\lambda^2$) are somewhat different (Fig. 8). Although the electron concentration decreases toward the center, but not strongly (see Fig. 7),

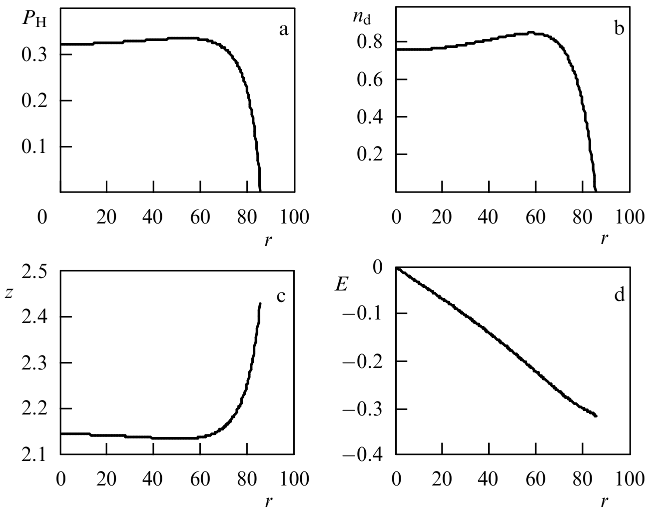

Figure 8. Distributions of (a) the Havnes parameter, (b) the dust density, (c) the dust charge, and (d) the electric field in a structure with $n(0) = 5$.

and therefore the charge z of individual dust particles also decreases toward the center (see Fig. 8), the drift velocity of ions near the structure surface $u_{str} = -0.164$ is small compared to the thermal velocity. The electric field strength on the structure surface is $E_{str} = -0.316$ and it determines the total negative collective charge of the structure, which is small. The collective charge of the structure is $Q_{str} = -Z_{str}e$, $\beta_{str} = Z_{str}e^2/R_{str}\lambda T_i = -E_{str}R_{str} = 9.006$ (the fraction of the collective charge per individual particle is very small compared to the charge of an individual particle, because the structure contains more than 10^6 particles; see Section 13). The collective electric field is screened in a rather thin layer around the structure, because the plasma flow on the structure weakly changes its screening (the relative contribution of the flow $\propto u_{str}^2 = 0.027$). The screening layer width δr_{scr} is in the range between 0.509 and 3 (because $\beta_{str} \approx 9$) and is much smaller than the structure size $R_{str} = 85.077$.

The results giving the dust distribution in the structure volume (see Fig. 8), which can be easily measured in all experiments, should be emphasized. The optimization of the structure size (in a search for structures of a larger possible size) can be achieved in experiments by varying the parameter $n(0)$ depending on the neutral gas pressure (the ion mean free path in a neutral gas) and the number of dust particles.

13. Total number of dust particles in a structure

An important conclusion is that equilibrium structures cannot contain the number of dust particles exceeding a certain maximum. The value

$$N_d \equiv \int \frac{P}{z} 4\pi r^2 \, dr = \frac{4\pi a}{\lambda\tau} N_{d,str} , \qquad (3)$$

where $N_{d,str}$ is the total number of dust particles in the structure and N_d is the number of particles in the structure calculated from the dimensional quantity n_d/n_*, introduced above and related to the dust density by expression (3), is calculated numerically directly from the data on the dust density distribution. For a structure with $n(0) = 5$, discussed in Section 12, we have

$$N_{d,str} = 1.738 \times 10^6 \, \frac{\lambda\tau}{4\pi a} , \qquad N_d = 1.738 \times 10^6 ,$$

which, although large, is not the maximum value desirable for experiments.

The question about the possibility of existing structures containing a larger number of particles is natural. Numerical calculations show that increasing $n(0)$ to 10 leads to a decrease in the structure size by approximately a half (more exactly, the size is $R_{str} = 47.66$ for $P_0 = 5.369$), but the total number of particles in the structure in this case does not change significantly: $N_d = 1.097 \times 10^6$. It is rather difficult to scan all possible equilibrium structures to find the maximum possible number of particles confined in the structure and, besides, this would not give the final answer until the question of which equilibrium structures are stable is studied (see Section 15). It is simpler to perform experiments assuming that equilibrium structures exist and can be observed.

Such structures have been observed in experiments, but far from walls, and they contained a small number of particles, no more than 10–30 [53, 54]. For self-organized structures far from the walls, the question remains open. It is also unclear why structures with a large number of particles could not be produced in the experiments performed. The analysis of a possible role of volume ionization processes shows that they do not lead to a considerable increase in the structure size.

14. Can numerical calculations of self-organized structures determine dust crystallization conditions?

It is necessary to formulate the question of how crystallization in structures differs from usual phase transitions between homogeneous (quasi-homogeneous) states of a system. Quasi-homogeneous states are usually characterized by global parameters such as density and temperature. Phase diagrams describing phase transitions in complex plasmas are still being constructed using these parameters, which should not be done, strictly speaking. The transition from one self-organized structure to another should be described using parameters that characterize structures, such as $n(0)$ and $P(0)$ and, for example, the dust temperature T_d.

The crystallization criteria taken from the theory of homogeneous systems contain the dust density and other parameters that are inhomogeneous in the structure. So far, no numerical calculations for phase transitions between structures are available that would be similar to those performed for the homogeneous state. There are two possibilities: crystallization can always appear in the entire structure or only in a part of the structure. Partial crystallization has been observed experimentally (see Fig. 6), but not for self-organized structures.

It is not yet clear whether the crystallization criteria obtained for homogeneous distributions can be applied to inhomogeneous distributions inside structures. It is necessary to develop the crystallization theory for transitions from completely gaseous self-organized structures to both completely crystalline and partially crystalline self-organized structures. In the absence of such a theory, it is still possible to obtain some new information if the crystallization criteria obtained for homogeneous states are used, with reservations, locally inside structures. One of the important features of numerical calculations being performed at present is that they give the dust distribution n_d in structures (see Fig. 8). The dust density determines distances $r_{intgr} = (3/4\pi n_d)^{1/3}$ between dust particles, which, in turn, determine the known crystallization criteria. We write them in the symbolic form

$$\Gamma_{coupl} = \frac{Z_d^2 e^2}{r_{intgr} T_d} > \Gamma_{cr} . \qquad (4)$$

This relation is written in terms of usual nonnormalized quantities. Before writing normalized quantities involved in all numerical calculations, it is necessary to make an important remark. The interaction of a pair of dust particles depends on screening, which is estimated theoretically in most cases. The screening factors can be measured only at sufficiently large distances between particles, which can and must be known in the crystallization criterion. However, the exponential screening used in most estimates is reduced not to the choice of the factor in the exponent from experiments, but in fact to its fitting to experimental data, to say nothing of the fact that this factor is not equal but much greater than the Debye radius. Therefore, it is more convenient to absorb the screening factor into Γ_{cr}. Then Γ_{cr} is in fact almost completely a theoretical quantity, while Γ_{coupl} contains only easily measurable quantities. By passing to dimensionless variables, we can introduce the relation

$$\Gamma(r) = P(r)^{1/3} z(r)^{5/3} , \qquad (5)$$

containing quantities that can be directly calculated numerically. Then relation (4) can be written in the form

$$\Gamma_{coupl} = \Gamma_0 \Gamma(r) \frac{T_i}{T_d} , \qquad \Gamma_0 = \frac{Z_d}{z} \left(\frac{a}{\lambda\sqrt{3\tau}} \right)^{2/3} . \qquad (6)$$

The quantity $\Gamma(r)$ describes the dependence of the crystallization criterion on the distance from the structure center. For a structure with $n(0) = 5$, this dependence is shown in Fig. 9, and criterion (4) corresponds to $\Gamma > \Gamma_{cr}/\Gamma_0 = \Gamma_{cr,0}$. As the dust temperature decreases, crystallization, taking place only at the structure center (see Fig. 9), passes through the melting stage at the structure periphery before complete melting. Hence, structures with a more complex sequence of crystalline and melted states are possible in principle. However, this question can be elucidated only in future studies. The usual experimental estimate gives $\Gamma_0 \approx 10^3 - 10^4$. This order of magnitude is predicted by relation (6), which follows from the large value of Z_d.

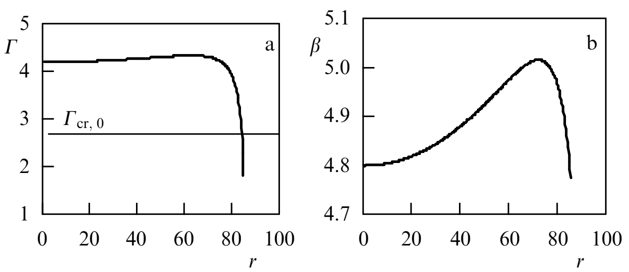

Figure 9. Dependences of (a) the critical crystallization parameter Γ and (b) the nonlinear screening parameter on the distance from the center of a structure with $n(0) = 5$.

15. Stability of self-organized equilibrium structures

Long observations of structures are possible only if they are not only equilibrium but also stable. In studying the dynamics of dust structures, of interest are low-frequency perturbations involving dust particles, while electrons and ions experience only perturbations at which they adiabatically adjust to dust perturbations. For linear perturbations of electrons and ions, small changes in the equilibrium relations initiated by dust perturbations can be taken into account, while for dust particles, additional effects related to a finite velocity of dust particles can be included (the velocity of dust particles in equilibrium is zero): these are the dust inertia and friction in neutral gas [63]. We can assume that all linear perturbations depend on time as $\exp(-i\omega t)$, where ω is the frequency of the perturbations.

The inhomogeneity of the structure requires finding the dependence of perturbations on the distance from the structure center, which can be done only numerically. We let δP, δn, δn_e, $\delta \mathbf{u}$, δz denote the perturbations of equilibrium parameters with the previous normalization and introduce new variables: the dimensionless dust velocity $\mathbf{v}_d \to \mathbf{v}_d / v_{d,eff}$, the dimensionless perturbation frequency $\omega \to \omega/\omega_{eff}$, and the dimensionless mass of dust particles $m_d \to m_d/m_{d,eff}$, where

$$v_{d,eff} = v_{Tn} \frac{3T_n}{4T_i} \frac{\sigma_{i,n}}{\pi a^2} \frac{aT_e}{e^2} ,$$

$$m_d \to m_d \frac{v_{d,eff}^2}{T_i} \frac{e^2}{aT_e} , \qquad \omega_{eff} = \frac{v_{d,eff}}{\lambda} .$$

Here, $\sigma_{i,n}$ is the cross section of ion collisions with neutral atoms. According to (2), we can then write equations for perturbations using variations δ of the corresponding quantities and additionally taking the inertia and friction into account in equations for dust:

$$\delta \mathbf{E} = \delta\left(f_{dr} \mathbf{u} \sqrt{n}\right) - \frac{\mathbf{v}_d}{z} (1 - i m_d \omega) . \qquad (7)$$

Other equations are not written because they can be simply obtained by varying Eqns (2), taking only linear perturbations into account. Perturbations depend, of course, not only on ω and the coordinate r along which equilibrium exists but also on other coordinates (in particular, on spherical angles θ and ϕ). This is important in studies of the stability of structures with respect to excitations, for example, dust vortices.

We describe the general scheme of perturbations of spherical structures, which, only thanks to *the finding in* [63], *specific for this problem*, allows obtaining a relatively simple closed system of equations for perturbations. It is naturally reasonable that perturbations for spherical structures should be expanded in spherical functions specified by integers $l = 0, 1, \ldots$ and $m = 0, 1, \ldots, \pm l$. For example,

$$\delta n = \sum_{l,m} \delta n_{l,m}(r)\, Y_{l,m}(\theta, \phi) . \qquad (8)$$

The substitution of all perturbations in form (8) in the equations for perturbations leads in general to a system of equations in the form of an infinite chain relating perturbations with different values of l and m. Such a chain is difficult to solve without a simplifying assumption about the smallness of some harmonics l and m. An important way out, the possibility of obtaining a system of dispersion equations for each value of l not containing m, was found in [63]. It was found that equations separate into equations for each l if the variables δn, δn_e, δz, δu_r, $\delta s = \mathrm{div}\,(\delta\mathbf{u})$, $v_{d,r}$ are used. For these variables, we can solve equations for their derivatives as linear functions of these variables with coefficients depending on the distance from the center of the equilibrium structure. These coefficients are determined by the dependence of the equilibrium solution on the distance from the center.

The asymptotic behavior of perturbations at the center and conditions for the conservation of the external flow and the number of dust particles in the structure give a dispersion equation that allows finding a number of solutions $\omega_i(l)$ in increasing order in the fundamental mode frequency determined by the characteristic size of the structure. Preliminary calculations show that real perturbations are stable, and instabilities can appear for $l \neq 0$ when gradients of the charge of dust particles are noncollinear to the collective electric field. Instabilities are possible only for frequencies close to the fundamental frequency $\omega \approx v_{Ti} 2\pi/R_{str}$. These results are preliminary, however; to obtain dispersion relations for particular applications, it is necessary to perform voluminous numerical calculations. It is reasonable to conduct them in the future in parallel with the experimental search for stable structures.

We also note that the instability of structures under small perturbations does not necessarily mean that they cannot exist if linear perturbations are saturated for small deviations from equilibrium. This is confirmed by the observations of structures surrounded by dust vortices, because perturbations of the ion and electron density and the parameter P for vortices already formed around cylindrical structures are small (see Figs 3 and 5).

16. Is structuring in a dust plasma universal?

If the volume ionization is taken into account, homogeneous equilibrium distributions not limited in size are possible. The stability of such states can be easily investigated. Of interest are low-frequency perturbations in which dust particles are involved, where electrons and ions have adiabatic responses (similarly to the perturbations of structures described above). The first such study [52] took only the inertia of ions and the shadow attraction of dust particles at large distances into account. The dispersion equation obtained in [52] is similar to that describing the gravitational instability,

$$\omega^2 = -G_{eff} n_d m_d \,,$$

with the effective gravitational constant G_{eff} determined by the shadow attraction effect. These results were later refined for linear screening, including the weak nonadiabaticity of perturbations of the charge of dust particles, plasma electrons, and ions (all of which change G_{eff}) and the presence of dust sound (which defines the instability threshold).

To answer the question about the universality of instability, it is necessary to consider the lowest-frequency perturbations with a frequency much lower than that of collisions with neutral atoms, taking the nonlinearity of screening of individual dust particles into account. Such calculations [47], performed only recently, showed that collisions and the screening nonlinearity can change only the instability threshold, but not its universality. The screening nonlinearity reduces the critical size of the inhomogeneity above which the instability develops (the instability always develops at sizes exceeding the critical size and with increasing nonlinearity for any values of the nonlinear parameter $\beta > 3$). The only process that could suppress the instability at low frequencies is dissipation due to collisions of ions with neutral atoms. For $\beta > 3$, this process becomes absolutely inefficient.

We can therefore assume that the structuring instability is universal at least for the most commonly encountered case of nonlinear screening. This means that attempts to find structures of increasing size with an almost uniform distribution of parameters inside the structure should meet with considerable difficulties. These theoretical assumptions require careful verification. If such restrictions do take place, this means that the maximum size exists for self-organized structures that are approximately homogeneous only in their central part.

17. Possibilities of testing kinetic concepts and diagnosing structures

There is a dubious opinion in the current literature that the study of the dynamics of dust particles allowing the experimental monitoring of each dust particle can provide verification of many hypotheses of modern kinetics concerning the use of different correlation functions and the decoupling of higher correlations. We note that all kinetic processes essentially depend on the type of the interaction between particles, and dust particles are involved in specific interactions that are not typical for other atomic particles in usual phase transitions. The specific kinetics of a dust plasma can be studied by investigating the dynamics of individual dust particles. But it is unlikely that these results can be applied to the dynamics of all phase transitions.

New possibilities exist for diagnosing self-organized structures and verifying the results of numerical calculations. First of all, this concerns predictions about correlations in the structures of distributions of various components such as dust particles and ions or dust particles and electrons. In the case of ions, the well-developed method of resonance laser fluorescence can be used. The electron distribution can be studied by the method of microwave radiation scattering from structures. Such scattering becomes coherent for wavelengths exceeding the characteristic size of structural inhomogeneities, i.e., the scattering intensity is determined by the total number of coherent electrons in the structure squared and greatly exceeds the usual Thomson scattering [65]. Coherent scattering can be calculated for each of the structures by the method of nonlinear scattering determined by the distribution of coherent electrons in the structure [66]. The boundary of the possible use of such calculations is the smallness of the field strength of the scattered wave compared to the collective-field strength of the structure that can be realized in experiments.

18. Conclusions

The state of the art in studies of coherent dust structures allows us to make the following conclusions:

(1) It is shown theoretically that equilibrium stable dust structures with free boundaries can exist, and their study is worth future experimental efforts.

(2) Spherical chambers are the most acceptable for future experimental studies under microgravity conditions.

(3) It is useful for experimental searches that self-organized dust structures, as any other self-organized structure, depend on a small number of global parameters. The small number of such parameters is demonstrated by the presented theoretical calculations. Theoretical parameters can strongly differ from experimental ones (pressure, temperature, etc.), but different parameters in self-organized structures are uniquely related.

(4) For transitions to a crystalline state, the possibility of existing structures in which phase transitions can appear inside the structure is doubtful. This problem can be solved experimentally for structures with a free boundary.

(5) Phase transitions of structures cannot be described by the parameters of homogeneous structures (temperature and density). Instead, parameters characterizing strongly inhomogeneous dust structures (the ion density and the Havnes parameter at the center of structures) should be used.

(6) For dust structures, new singularities appear, such as jumps of the density derivative at the boundary of compact structures and jumps of the Havnes parameter at the surface of voids. However, double layers with jumps of the charge density do not appear.

(7) The study of dust crystals in plasma sheaths is unsuitable because a strong interaction of singular structures can considerably distort them. Plasma sheaths are structures also having singularities at the interface with plasma pre-sheaths. The first dust crystals were produced such that the first layer of the crystal fell approximately within this singular boundary, which complicated not only the physical interpretation of the crystallization processes but also the estimates of how gravity can be compensated by the considerably weaker field of the pre-sheath (in front of the plasma sheath). This shows why one structure with a singularity (a dust crystal) is difficult to study if it interacts with another singular structure (a plasma sheath). Under microgravity conditions, it is advisable to study crystals with a free boundary.

(8) It is found for free-boundary structures that the production of fairly large crystals under microgravity conditions is problematic.

(9) Just as dust particles are the main elements of dust structures, the structures themselves can be the main elements of superstructures and supercrystals with a further hierarchy (which was first discussed in [64]).

(10) There are convincing arguments that the structuring of a dust plasma is one of its fundamental properties.

(11) It is possible that the study of self-organized dust structures allows solving some general problems of self-organization.

(12) Numerical studies of cylindrical structures are performed using the same program as for the study of spherical structures described in Section 7.

(13) At present, only vortices around cylindrical structures with approximately free cylindrical boundaries are studied experimentally and theoretically [67, 68].

(14) An important question is whether rather long self-organized cylindrical free-boundary dust structures can exist that correspond to helical structures in the limit of a small number of particles per unit length [69].

(15) Of interest is the question of whether self-organization processes in helical structures can be used for simulating some biological structures, because DNA electrostatics, which is quite popular in biology, has much in common with the electrostatics of cylindrical and helical dust structures [68, 69]. The main problems of screening a large DNA charge by ions in aqueous solutions have long been solved for helical dust structures in which the charge is screened by more mobile plasma ions, to say nothing of the fact that dust plasmas occur in nature much more often than aqueous solutions do.

(16) In particular, it is necessary to theoretically and experimentally analyze the bifurcations produced by vortices surrounding cylindrical and helical structures and to study the behavior of such bifurcations during the interaction of structures. Such a program can be fulfilled in the future.

(17) In connection with the discussion of the possibilities of inorganic living structures appearing in a dust plasma [70], it is necessary first of all to solve the problem of data transfer via bifurcations during the interaction of bifurcation cylindrical and helical structures.

(18) General conclusions about the structuring of a dust plasma also apply to astrophysical plasma [71] and are used in [71] to explain a number of astrophysical observations (accounting for the astrophysical specificity of screening linearity, the size distribution of dust particles, and the positive charge of dust particles in the presence of intense UV radiation).

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