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Formation of Liquidlike and Crystalline Structures in Dusty Plasmas

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Under certain conditions in a dusty plasma, which is a low-temperature plasma with dust grains, the strong interaction between grains can give rise to gas–liquid–solid-state phase transitions. A study is made of ordered (liquidlike and crystalline) grain structures in various kinds of dusty plasmas: a thermal plasma at atmospheric pressure, a plasma of a dc glow discharge, and a UV radiation–driven plasma. The results of experimental observations of ordered dust structures are reported, and the characteristic features of the dust structures and the conditions for their appearance are discussed. © *2000 MAIK “Nauka/Interperiodica”.*

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1. INTRODUCTION

The grains in a dusty plasma can be intrinsically charged either by electron and ion fluxes or as a result of photoemission, thermal emission, and secondary emission of electrons from the grain surface [1, 2]. The grains that emit electrons acquire a positive electric charge, in which case the electron density in a dusty plasma increases. In contrast, the grains that collect electrons acquire a negative charge, so that the electron density decreases.

Since the sizes of dust grains are relatively large (from a few hundredths of a micron to several tens of microns), the grains may acquire a very large charge Z_d (about ~10^2–10^5 elementary charges). As a result, the mean energy of the Coulomb interaction between grains, which is proportional to Z_d^2, can be much higher than the grain thermal energy; this circumstance reflects the highly nonideal nature of a dusty plasma, in which the charged grains play the role of multiply charged heavy ions [3]. Theoretical calculations of the equilibrium properties of such a plasma show that, under certain conditions, the strong electrostatic interaction between grains and the low energy of the grain thermal motion give rise to both gas–liquid–solid-state phase transitions and the formation of ordered spatial structures analogous to those in liquids or solids. In these processes, the electron and ion components behave as ideal gases, as in a Debye plasma. In contrast to conventional solids and atomic liquids, individual dust grains are large enough to efficiently scatter light and to be recorded by a video camera or even to be observed visually. Crystalline structures formed by charged grains in dusty plasmas are called Coulomb or plasma crystals [4].

The interaction between dust grains is traditionally described by the one-component plasma (OCP) model or by the model with a screened (Debye) potential [3, 4], which is also known as the Yukawa model. These models, which assume a classical quasineutral unbounded plasma, make it possible to describe phase transitions by numerically calculating the critical values of the Coulomb coupling parameter $\Gamma = (Z_d e)^2/\bar{r}kT_g$, where T_g is the plasma temperature, $\bar{r} = (4\pi n_d/3)^{-1/3}$ is the mean distance between the grains, and n_d is the grain number density.

In the OCP model, the dusty plasma is treated as an idealized system of ions against the uniform background of neutralizing dust grains, so that, on the whole, the plasma is electrically neutral. The interaction between grains is described by the Coulomb potential $U(r)$, and three-dimensional regular crystalline structures form when the parameter Γ is above the critical value $\Gamma_c = 171$. For small Γ values ($\Gamma < 4$), the plasma is in a “gaseous” state [2–4]. In the Yukawa model, the grain charge is assumed to be screened by plasma electrons and ions, in which case the interaction between grains is described by the Debye–Hückel potential. Taking into account the screening effect, which is described by the ratio $\kappa = \bar{r}/r_D$ (where r_D is the Debye radius), makes it possible to introduce the parameter $\Gamma_s = (Z_d e)^2\exp(-\bar{r}/r_D)/\bar{r}kT_g = \Gamma\exp(-\bar{r}/r_D)$. As a result, in the Yukawa model, the plasma thermodynamics and, accordingly, the conditions for phase transitions, are described by the two parameters: Γ and κ. In the limit $\bar{r}/r_D \longrightarrow 0$, the Yukawa model passes over to the OCP model; and, in the limit $\bar{r}/r_D \longrightarrow \infty$, it passes over to the solid-sphere model.

In early experiments, crystalline structures were observed in plasmas with iron and aluminum micron-sized charged grains confined by alternating and static electric fields. More recently (see, e.g., [5, 6]), results have been reported on the Coulomb crystallization of dust grains in a weakly ionized plasma of low-pressure RF discharges. In such plasmas, the electron energy is about several electron volts and the ion energy is close to the thermal energy of atoms (about 0.03 eV) [7].

In the absence of emission processes, the grains acquire a negative charge. This effect is attributed to the fluxes of background electron and ions onto the grain surface. It is generally assumed that the electron flux onto the grain surface is absorbed by the grain, while the incident ions knock the electrons out of the grain surface and recombine. Since the electrons are much more mobile than the ions, the electron fluxes are far more intense than the ion fluxes, so that the grains begin to be charged negatively, thereby repulsing the electrons and attracting the ions more and more efficiently. The grains continue to acquire a negative charge until the electron and ion fluxes onto the grain surface become equal to one another.

In experiments on RF discharges, the dust grains acquire a fairly large negative charge (about 10^4–10^5 electron charges), in which case a cloud of dust grains forms near the solid (electrode) surface with a negative potential, in the region where the gravitational and electrostatic forces are in equilibrium. A cloud several centimeters in diameter may contain several tens of horizontal layers of dust grains, the distance between the grains in the layers being several hundred microns.

In more recent experiments, attempts have been made to produce three-dimensional extended ordered structures in the bulk of a quasineutral dusty plasma (rather than in region near the electrode). The grains that formed these structures were charged via various mechanisms, in particular, photoemission and thermal emission. Thus, liquidlike ordered structures were observed to appear in a quasineutral thermal plasma with a temperature of about 1700 K at atmospheric pressure, and three-dimensional crystalline structures were produced in the positive column of a dc glow discharge. The formation of ordered structures in a plasma consisting of dust grains charged by UV radiation was also studied in microgravity experiments carried out aboard the Mir space station.

2. ORDERED DUST STRUCTURES IN A THERMAL PLASMA

Our experiments were carried out with low-temperature thermal atmospheric-pressure plasma flows in which the temperatures of the electrons, ions, and neutral particles were equal to each other and which contained suspended cerium dioxide (CeO_2) grains. The plasma temperature was varied in the range 1700–2200 K (atmospheric pressure) [8, 9]. The distinguishing feature of cerium dioxide is that its work function for emission of thermal electrons is low (~2.75 eV). As a result, the dust grains were charged not only by background electron and ion fluxes, but also via thermionic emission, which may give rise to a positive grain charge. In the course of experiments, the electron density varied from 10^9 to 10^{11} cm^{-3}.

Our measurements provided information about such plasma parameters as the densities of the electrons and positive ions, the plasma temperature, the dust density, and the mean diameter of the grains. The spatial dust structures were analyzed using the pair correlation function $g(r)$, which is defined as the probability for a grain to occur at a distance r from the test grain and, accordingly, characterizes the relative spatial positions of the grains, i.e., shows whether the grains form stochastic (liquidlike) or regular (crystalline) ordered structures. The correlation function in the plasma flow was measured with a time-of-flight laser counter based on the phenomenon of the scattering of a focused laser beam by individual dust grains moving through the measurement region. The radiation scattered by individual grains as they traversed the laser beam was collected by an objective and fed to a photodetector. The received pulsed signals were then processed in order to calculate the pair correlation function.

The results of measuring spatial dust structures were compared with the experimental data obtained for an air jet with CeO_2 grains at room temperature. Such a flow models a “gaseous” plasma, i.e., a plasma with a random (stochastic) spatial distribution of the dust grains.

Figure 1 shows representative pair correlation functions $g(r)$ for CeO_2 grains in an air jet at room temperature and in a thermal plasma. It is seen that the correlation functions for dust grains with the density $n_d = 2.0 \times 10^6$ cm^{-3} in an air jet (Fig. 1a) and in a thermal plasma with the temperature $T_g = 2170$ K (Fig. 1b) are essentially the same. Thus, we can conclude that, in this case, the interaction between grains in a thermal plasma is weak and ordered dust structures cannot form.

According to Fig. 1c, in a thermal plasma with a lower temperature ($T_g = 1700$ K) and higher grain density ($n_d = 5.0 \times 10^7$ cm^{-3}), the correlation function has the form characteristic of a liquidlike structure. In such a plasma, the ion density ($n_i \sim 10^9$ cm^{-3}) is about one order of magnitude lower than the electron density ($n_e \sim 5 \times 10^{10}$ cm^{-3}). The grain charge evaluated from the quasineutrality condition is positive and equals $10^3 e$. The experimentally obtained parameter values $\Gamma > 120$ and $\kappa = 1.6$ indicate a strong interaction between grains, thereby evidencing the appearance of liquidlike dust structures. That the experimentally observed structures were relatively slightly ordered (see Fig. 1c) is attributed to the finite plasma lifetime (about 7 ms), which is too short for the ordered structure to form completely.

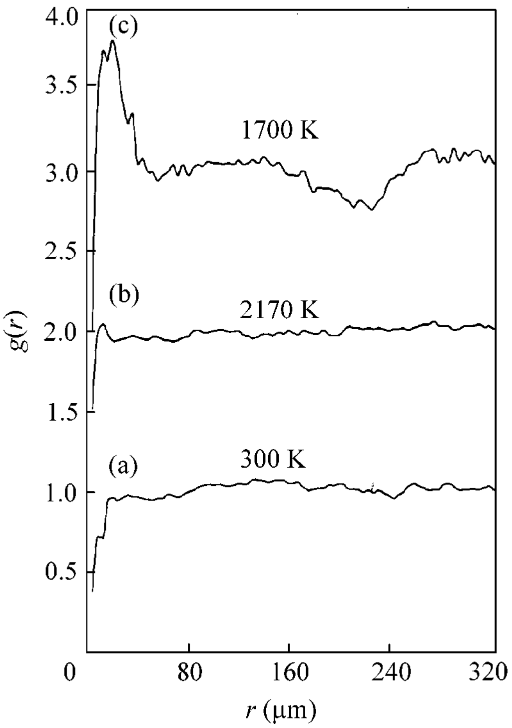

Fig. 1. Pair correlation function $g(r)$ for CeO_2 grains with the charge $Z_d = 500$ in an air jet at room temperature ($T_g \approx 300$ K) and in plasmas with the temperatures $T_g = 2170$ and 1700 K.

3. MODELING OF THE DYNAMICS OF THE FORMATION OF ORDERED DUST STRUCTURES IN A THERMAL PLASMA

In order to interpret the experimental results, we numerically simulated the dynamics of the formation of ordered dust structures in a thermal plasma. We begin by analyzing the main physical processes that govern the formation of such structures. In our experiments, when stochastically distributed neutral dust particles enter the plasma, they are heated to the temperature of the surrounding gas, acquire an electric charge, and start to interact with each other. The simplest estimate for the thermalization time is

$$\tau_{th} = \left[\pi a^2 n_n \sqrt{\frac{8kT}{\pi m_n}} \frac{2m_n}{m_d}\right]^{-1}, \qquad (1)$$

where m_n and n_n are the mass and density of the gas molecules and a and m_d are the radius and mass of a dust grain.

Under our experimental conditions (see table), the thermalization time $\tau_{th} \approx 5 \times 10^{-6}$ s is far shorter than the plasma lifetime $t_{ft} \sim 7$ ms; consequently, we can assume that the dust grains are heated practically instantaneously. This assumption is also justified by the results of investigating the grain dynamics by the correlation spectroscopy technique. Spectroscopy measurements indicate that the dust plasma component is in equilibrium with the surrounding gas (in which case we can also neglect anomalous heating of grains in a gas-discharge plasma).

The formation of ordered dust structures in a thermal plasma was modeled using the methods of molecular dynamics. For each dust grain, we solved the two-dimensional equation of motion

$$m_d \frac{d^2\mathbf{r}_k}{dt^2} = \sum_{j \neq k} \mathbf{\Phi}(r)\Big|_{r = |\mathbf{r}_k - \mathbf{r}_j|} \frac{\mathbf{r}_k - \mathbf{r}_j}{|\mathbf{r}_k - \mathbf{r}_j|} - m_d \nu_{dn} \frac{d\mathbf{r}_k}{dt} + \mathbf{F}_{br}. \qquad (2)$$

into which we incorporated the interaction between grains; the friction force of the grain on the neutral gas particles; and the random (Brownian) force $\mathbf{F}_{br}$, which results from the impacts of the molecules of the surrounding gas. Under the assumption that the interaction between grains is described by the Debye potential, the force $\mathbf{\Phi}(r)$ can be written as

$$\mathbf{\Phi}(r) = -Z_d e \frac{\partial \varphi_D}{\partial r^2} = \frac{Z_d^2 e^2}{r^2}\left[1 + \frac{r}{\lambda_D}\right]\exp\left(-\frac{r}{\lambda_D}\right). \qquad (3)$$

Parameter values used to simulate the formation of ordered dust structures in a thermal plasma

Parameter	Value	Parameter	Value
Plasma temperature	$T = 1700$ K	Grain charge	$Z_d = 500$
Neutral gas pressure	$P_n = 1$ atm	Mean intergrain distance	$l = 17$ μm
Electron plasma density	$n_e = 7 \times 10^{10}$ cm^{-3}	Screening length	$\lambda_D = 11$ μm
Ion plasma density	$n_i = 4 \times 10^{10}$ cm^{-3}	Dust–neutral-gas friction rate	$\nu_{dn} = 9.6 \times 10^4$ s^{-1}
Dust density	$n_d = 5 \times 10^7$ cm^{-3}	Coupling parameter	$\Gamma = 90$
Grain radius	$a = 0.4$ μm	Parameter κ	$\kappa = 2.5$
Grain mass	$m_d = 1.6 \times 10^{-12}$ g	Coupling parameter with allowance for screening	$\Gamma_s = 8$

The table lists the model parameters, which are close to those of our experiments. Now, we turn to the main simulation results. We found that, by the end of the relaxation process, the system evolves into a well-ordered state, which can be formally referred to as a liquidlike state. Figure 2 illustrates the evolution of the pair correlation function $g(r)$ calculated from the instantaneous positions of the grains. The profiles in Fig. 2e were evaluated by averaging the function $g(r)$ over time; the averaging procedure is justified, because, during the time interval $40 < t < 70$ ms, the system evolves into a steady state and the pair correlation function remains essentially unchanged. For comparison, Fig. 2 shows the correlation function that was obtained directly from experiments and corresponds to Fig. 1c.

Analyzing Fig. 2, we can qualitatively describe how the ordered dust structures form. First, the grains that occur at short distances from each other start to fly apart; as a result, a region arises in which the pair correlation function vanishes (Figs. 2a, 2b). This process is very fast, because the repulsive forces between the grains increase sharply as the distance between them decreases. Then, a pronounced first peak appears in the profile of the pair correlation function (Fig. 2c). As time elapses, the first peak becomes higher; this process is accompanied by the appearance of additional peaks (Fig. 2d). The steady-state correlation function (Fig. 2e) is characterized by several pronounced peaks. Such a function is typical of a closely ordered system. It is for this reason that the final state of the system was called a liquidlike state.

The time required for an ordered structure to form can be defined rather arbitrarily, depending on the correlation scale length in which we are interested. The larger the distance, the longer the time required for the pair correlation function at this distance to relax to the final state. Thus, in the case under analysis, the first three peaks appear in the profile of the correlation function on a time scale of about $t_f \approx 35$ ms. We can also introduce the time t_1 needed for the formation of the first peak in the pair correlation function. Physically, this is the time scale on which any short-scale correlation in the system comes into play. For the parameter values at hand, numerical calculations give $t_1 \approx 5$ ms.

A distinctive feature of our experiments is the finite plasma lifetime $t_{fl} \approx 7$ ms. According to our simulation results, this indicates that the formation of ordered dust structures revealed in the experiments was in progress; consequently, we experimentally determined unsteady pair correlation functions. Nevertheless, the plasma lifetime was long enough for short-scale correlations to come into play.

Figure 2 enables us to compare the pair correlation function obtained experimentally with the functions calculated numerically. We point out the following two circumstances. First, the experimental correlation function was found to have only one peak, which agrees well with the simulation results. In fact, Fig. 2d indicates that, at $t = 7$ ms, the first peak in the experimental function is already close to its final shape, while the higher order peaks are only beginning to form. The presence of only one peak provides conclusive evidence that the plasma lifetime is insufficiently long for an ordered structure to form completely. Second, the first peak in the experimental correlation function is far wider (by a factor of approximately five) than that in the function calculated numerically. This discrepancy may in principle be attributed to the specific features of the measurement technique using a time-of-flight laser counter [8, 9].

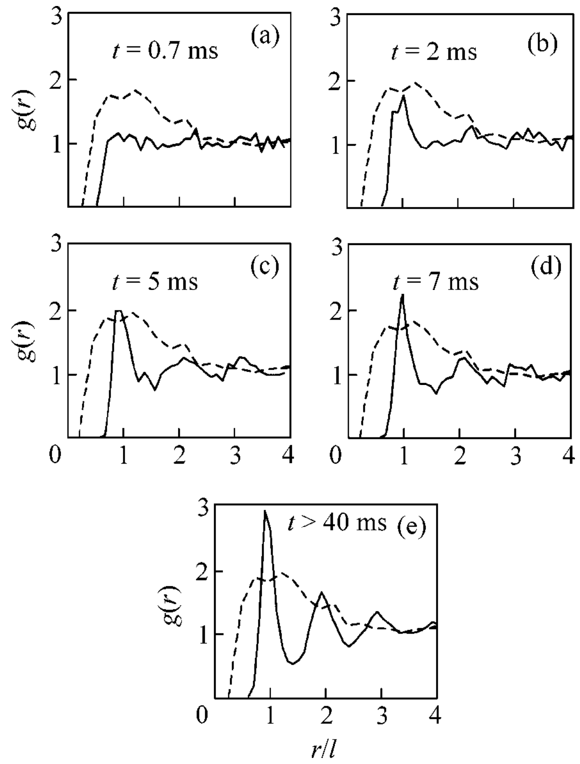

Fig. 2. Evolution of the pair correlation function. The solid curves plot the profiles calculated numerically at the times t = (a) 0.7, (b) 2, (c) 5, (d) 7, and (e) 40 ms. The dashed curves are for the experimentally obtained profile.

4. THREE-DIMENSIONAL CRYSTALLINE DUST STRUCTURES IN A DC GLOW DISCHARGE

In contrast to the thermal plasma, the plasma of a low-pressure glow discharge in a gas at room temperature is nonisothermal. We carried out a series of experiments with dc glow discharges in neon over the pressure range from fractions of a torr to several torr and for discharge currents from fractions of a milliampere to several milliamperes.

We observed ordered dust structures in the positive column of a glow discharge with standing strata—immobile dark regions alternating with bright zones with nonuniform luminosity, the characteristic spatial

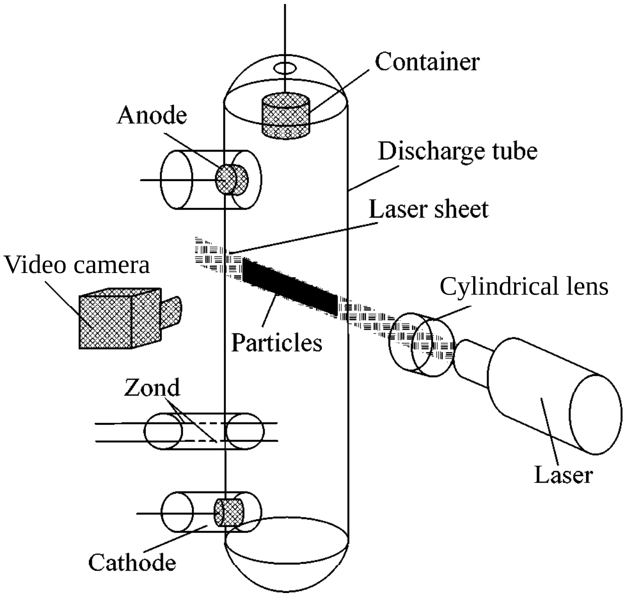

Fig. 3. Layout of the experimental device for studying ordered dust structures in a gas-discharge plasma.

scale of the strata being about several centimeters [10]. The electric field is relatively strong in the head of a stratum (i.e., in its bright part) and is weak outside the head. The floating potential of the discharge-tube wall is high. As a result, the head of each stratum acts as an electrostatic well capable of trapping highly dispersed grains in the positive column of a glow discharge in a vertically oriented tube, in which case the strong radial electric field does not allow the grains to escape from the well and reach the tube wall.

A schematic of the experimental device is shown in Fig. 3. The grains irradiated by a vertical or horizontal laser beam were recorded by a video camera (some of the grains were even observed visually). The formation of ordered structures can be described as follows. Micron-sized grains falling from the container into a glass tube enter the discharge plasma from above and acquire an electric charge when moving through the plasma. After the charged grains have fallen below their equilibrium positions, they stop falling down and move upward for several seconds; then, they form an ordered structure, which remains unchanged for an arbitrarily long time (as long as the discharge parameters remain unchanged) [11]. Experiments on the formation of ordered dust structures in the positive column of a glow discharge were carried out with several kinds of grains: grains in the form of hollow borosilicate glass microspheres 50–60 μm in diameter, polydisperse Al_2O_3 grains 3–5 μm in size, and monodisperse melamine-formaldehyde grains 1.87 μm in diameter.

The grains were seen to form a cloud at the center of a stratum. As a rule, we observed several clouds simultaneously in the neighboring strata. Glass microspheres formed clouds 5–10 mm in diameter, and the diameter of the clouds of Al_2O_3 grains amounted to 20 mm. A cloud of glass microspheres consisted of 10–20 plane horizontal layers; the number of layers in a cloud of Al_2O_3 grains was even larger. In the vertical direction, the grains in a cloud built chains. The distance between the vertical chains was 250–400 μm; and the distance between the grains in the horizontal direction was 350–600 μm, so that the grain density was about $n_d \sim 10^3$–10^4 cm^{-3} [12].

Figure 4a displays a portion of the horizontal cross section of a dust crystal formed by 1.87-μm-diameter monodisperse melamine-formaldehyde grains in a discharge plasma in a neon–hydrogen mixture at a pressure of 0.8 torr, the discharge current being 1.1 mA. The shape of the pair correlation function $g(r)$ for this ordered structure (see Fig. 4b) provides evidence for long-scale correlations between the grains, thereby indicating the crystalline nature of the structure.

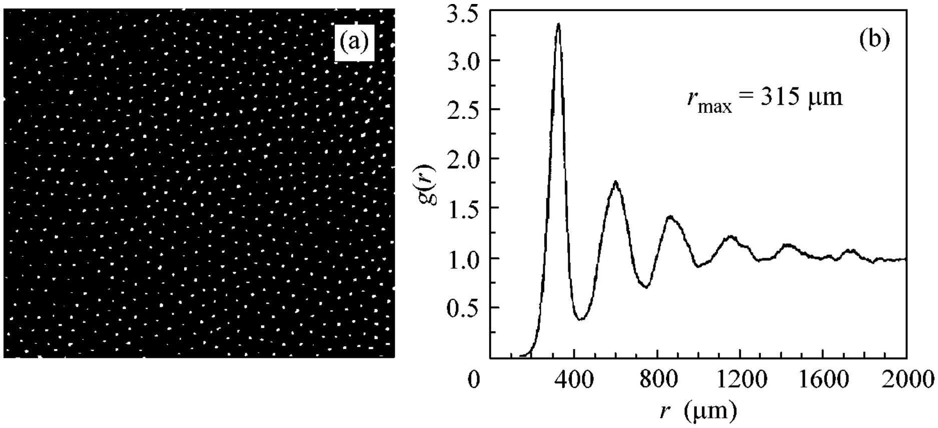

Fig. 4. (a) Image of a horizontal cross section of an ordered dust structure in a stratum of the positive column of a glow discharge and (b) pair correlation function for this structure.

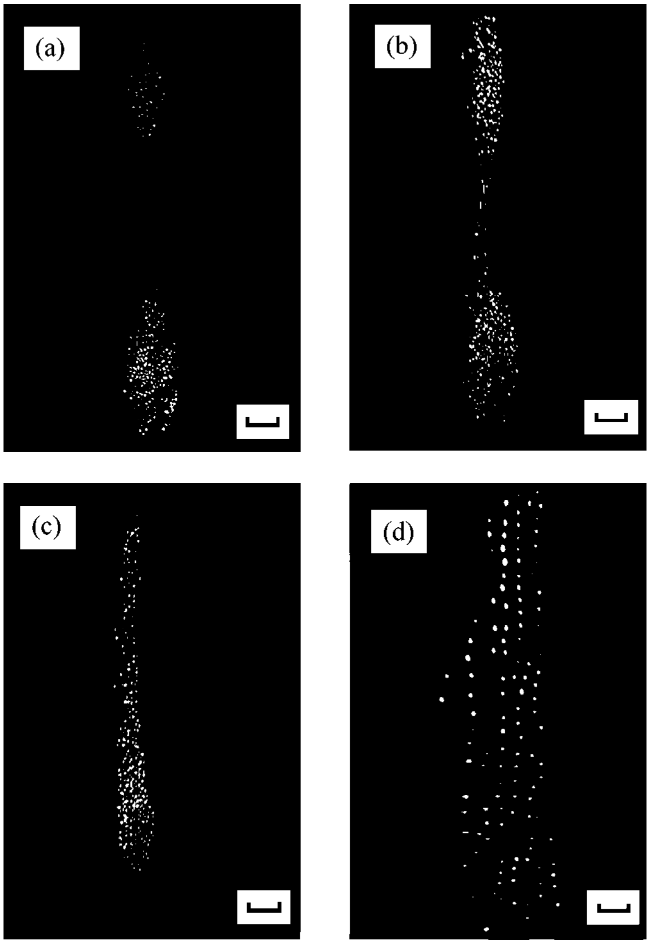

Fig. 5. Images of glass microspheres in a vertical cross section at different discharge currents and plasma pressures: (a) 0.5 mA and 0.47 torr, (b) 0.5 mA and 0.44 torr, and (c) 0.4 mA and 0.37 torr. Figure 5d is a magnified image of a part of the cylindrical structure shown in Fig. 5c. The scale in images (a)–(c) is 3 mm, and the scale in the magnified image (d) is 1 mm.

Varying the parameters of the discharge plasma (the plasma pressure and discharge current) made it possible to change the shape of a dust cloud. Thus, from Figs. 5a–5c, we can see that, as the discharge current and plasma pressure decrease, two neighboring elliptically shaped clouds merge into a cylindrical ordered dust structure, which extends to several tens of centimeters in the vertical direction. Figure 5d presents a magnified image of a part of the cylindrical structure.

On increasing the discharge current, we observed the evolution of crystalline structures, first, into liquidlike structures and, then, into gaseous structures. In a sense, we may speak of the "melting" of dust crystals. Thus, for Al_2O_3 grains at a plasma pressure of 0.3 torr and a discharge current of 0.4 mA (Fig. 6a), the correlation function has four pronounced peaks (Fig. 7a), thereby providing evidence for long-scale correlations between the grains and, accordingly, for the crystalline nature of the ordered structure. When the discharge current is increased by almost one order of magnitude (to 3.9 mA, see Fig. 6b), the shape of the correlation function implies the existence of only short-scale correlations between the grains; this indicates that the dust crystal "melts" and "evolves" into a liquidlike structure (Fig. 7b). We emphasize that, during this "phase transition," the distance between the grains (250 μm) remains almost unchanged [13].

Under certain conditions, we observed the effect of anomalous heating of the dust component in dc glow discharges, in which case the grains acquired very high energies (up to 50 eV). This effect can be explained as being due to the melting of dust crystals, which was observed when the plasma parameters changed. Under certain discharge conditions, increasing the number of small-sized grains gives rise to composite dust structures: in some regions, the grains are highly ordered (plasma crystals), and, in other regions, they experience convective and oscillatory motions (dust–plasma liquid) [14]. Most of the central region of the composite

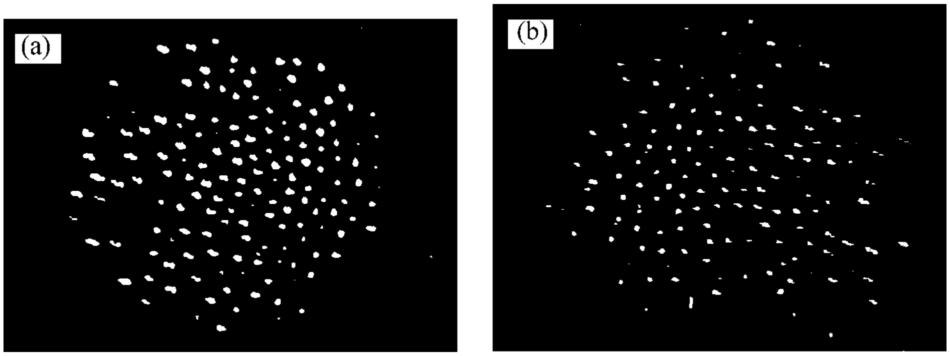

Fig. 6. Images of Al_2O_3 grains in a vertical cross section for a plasma pressure of 0.3 torr at different discharge currents: (a) 0.4 and (b) 3.85 mA. The scale is 1 mm.

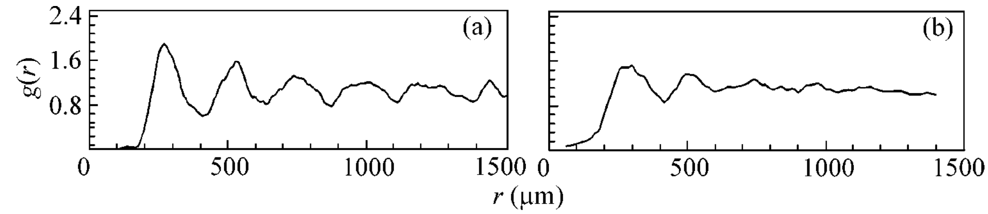

Fig. 7. Pair correlation function for Al_2O_3 grains in a vertical cross section at a neon pressure of 0.3 torr and discharge currents of (a) 0.4 and (b) 3.85 mA.

structure is occupied by a highly ordered dust–plasma crystal with a pronounced chainlike configuration of the grains. In the upper region of the structure, the grains experience convective motion, whose intensity decreases toward the center of the structure. In the lower region, the grains are observed to oscillate in the vertical direction (grain density waves) at a frequency of about 10 Hz and a wavelength of about 1 mm, the mean intergrain distance being 200 μm (Fig. 8). Such self-excited oscillations can be driven by the instability of dust acoustic waves; the nature of this instability requires a separate study [15].

Let us estimate the grain parameters under conditions typical of glow discharges: the electron thermal energy is $kT_e \sim 3$ eV, the ion thermal energy is 0.03 eV, and the electron density is approximately 10^9 cm^{-3}. In a glow discharge in neon, the floating potential of the grains amounts to $V_d \sim (kT_e/e) \sim 3$ V. The grain charge can be found from the relationship $Z_d = aV_d$. Consequently, the charge of glass microspheres 50–60 μm in size is estimated to be $\sim 10^5$ e.

The grain charge can also be deduced from the balance between the gravitational and electrostatic forces in a stratum, $Z_d = m_d g/eE_s$. At $E_s \sim 10$ V/cm, the charge of glass microspheres with the mass $m_d \sim 10^{-8}$ g is estimated to be $Z_d \sim 10^6$ e. This estimate is about one order of magnitude larger than what we have just obtained for typical discharge parameters. This discrepancy can be explained by noting that, in the region occupied by the stratum, there is a second peak (at 15 eV) in the profile of the electron energy distribution function, so that, inside the stratum, the grains acquire a negative charge until the grain floating potential becomes as high as $V_d \sim (kT_e/e) \sim 15$–30 V, which corresponds to the floating potential of the discharge-tube wall. As a result, the

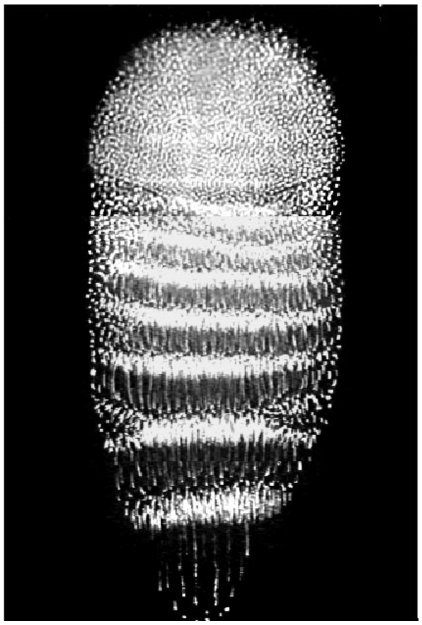

Fig. 8. Image of an ordered dust structure of monodisperse grains 1.87 μm in diameter at a discharge current of 5 mA and a plasma pressure of 0.3 torr. The vertical dimension of the frame is 10.6 mm.

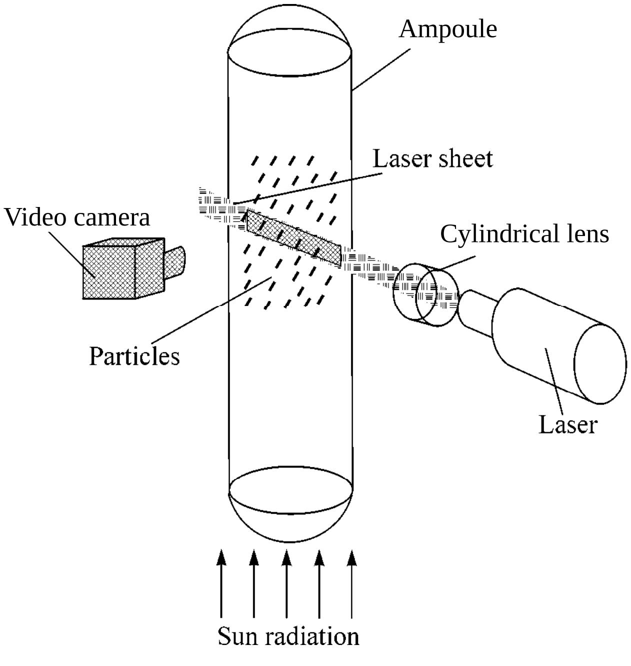

Fig. 9. Layout of the experimental device in space experiments.

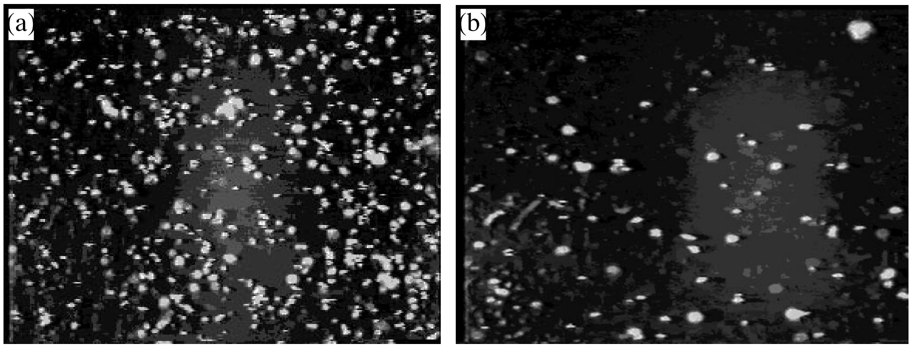

Fig. 10. Sequence of states of an ensemble of bronze grains in an ampoule at a pressure of 40 torr (a) 20 and (b) 110 s after shaking the ampoule.

charges of glass microspheres and Al_2O_3 grains are approximately equal to ~10^6 and 10^5 *e*, respectively.

5. PLASMA DRIVEN BY UV RADIATION UNDER MICROGRAVITY CONDITIONS

A dusty plasma with positively charged grains can also be produced by irradiating the neutral grains in a buffer gas by a flux of photons with energy above the work function for photoelectronic emission from the grain surface. The conditions in such a plasma may be favorable for the appearance of ordered crystalline structures. Since, for most substances, the characteristic work function for photoelectronic emission is lower than 6 eV, the fluxes of photons with energies lower than, or on the order of, 12 eV can be used to charge the grains positively without ionizing the buffer gas (such as helium and argon).

Ordered structures of the grains charged by solar radiation have been studied in microgravity experiments aboard the Mir space station [16]. Investigation of the formation of ordered dust structures in such experiments provided fundamentally new information that cannot be obtained under terrestrial conditions. Note also that intense fluxes of UV radiation in space can charge dust grains via photoemission, in which case, grains several microns in size acquire a positive charge of about ~10^2–10^4 *e*.

Space experiments were performed with glass ampoules filled with neon at different pressures (0.01 and 40 torr) and containing spherical bronze grains coated with cesium (Fig. 9). Before the experiment, the ampoule was placed in front of the window of the Mir station. The grains were irradiated by a planar laser beam (“laser sheet”) with a width less than 200 μm and were recorded by a video camera.

Since the grains were deposited on the ampoule wall, the experiments were carried out as follows: first, the ampoule underwent an external dynamic action (it was shaken up); then, the grains relaxed to the initial state (they were again deposited on the wall). Figure 10 illustrates the evolution of an ensemble of grains in an ampoule at a pressure of 40 torr under the action of solar radiation. Experimental observations revealed that, initially, the grains moved in a random fashion. Then, the grain motion usually became ordered; at a high pressure, the grain motion along certain trajectories in an ampoule was found to be more intense. In some experiments, the grains were observed to experience not only translational, but also oscillatory motion. When processing the measured data on grain trajectories, the grain velocity was found to vary periodically in all the experiments. Such velocity variations may be attributed either to the fluctuations of the grain charge or to the dynamic action of microaccelerations aboard the Mir space station.

Experiments on the Mir station revealed another interesting effect—the formation of agglomerates in which the number of grains varied from three or four to several hundred and which could be detached from the ampoule wall by slightly shaking up the ampoule. The agglomerates primarily appeared several seconds after the ampoule was shaken up, and thereafter they decayed under the action of solar radiation. Presumably, the agglomeration of grains in the ampoule is explained by the fact that, in the initial stage of irradiation, some of the grains were charged positively (via photoelectronic emission) and others were charged negatively (by the fluxes of the emitted electrons).

According to the estimates obtained when analyzing the grain dynamics, the grains may acquire a charge as large as several units of 10^4 elementary charges, the coupling parameter being $\Gamma \sim 10^4$. Although the grain charge and coupling parameter were both large, no strong correlations among the grains were observed: the grains formed only liquidlike structures.

6. CONCLUSION

Our experimental study of strongly interacting dust grains in a thermal plasma at atmospheric pressure and in the positive column of a dc glow discharge demonstrates the possibility of the formation of ordered dust structures (including crystalline structures) in dusty plasmas with specific parameters (e.g., in a thermal plasma, which characteristically occupies a fairly large region and in which the dust structures are essentially three-dimensional). The ordered dust structures appear in a quasineutral plasma region rather than in an electrode sheath. That the experimental pair correlation function has only one maximum is explained by the finite lifetime of the thermal plasma: the correlation function was measured over the time interval during which the formation of an ordered structure was still in progress.

In a stratum of a dc glow discharge, we observed various kinds of ordered structures of micron-sized grains: from liquidlike structures with short-scale correlations, to crystalline structures (dust–plasma crystals) with long-scale correlations. The ordered structures differ in shape; in the inner region of the structure, the grains can experience convective motion.

A comparative analysis of the results from experimental and theoretical studies of an ensemble of dust grains charged by solar radiation via photoemission under microgravity conditions confirm the conclusion that the grains may form extended liquidlike ordered structures even in a plasma in which the agglomeration processes are very intense.

The results of our investigations may have some important applications. Ordered structures in dusty plasmas can be successfully used to solve both theoretical and practical problems. One of the most important theoretical problems in plasma physics is that of studying strongly nonideal multicomponent plasmas. The results of experiments with crystalline dust structures can be conveniently used to develop and validate analytic models of such plasmas. It is also important to investigate the lattice dislocations in crystals, the thermodynamics of crystal lattices having dislocations and dislocation-free lattices, the interaction of laser light with crystals, oscillations and waves in ordered structures, and related resonance phenomena. In solid state physics, the results of these investigations can be used to model atomic and molecular crystals. In the physics of critical phenomena, the study of phase transitions in dusty plasmas can provide new insights into the condensation processes. The possibility of creating small systems consisting of several dust grains and an analysis of their stochastic motion and their response to external fields can be very useful for investigating the dynamic processes in such systems.

Among microelectronics-related applications, we can mention the problem of removing particles in manufacturing integrated circuits and the problem of modeling small crystals (nanocrystals) in studying plasma methods for film deposition. Commercial applications of our results may include the following issues: the creation of coatings through the UV radiation–controlled deposition of grains suspended in a plasma onto a substrate for the purpose of fabricating new artificial materials with the desired properties (including porous and composite materials), the production of granules with multilayer coatings from substances with different properties, etc.

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