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Crystalline structures of strongly coupled dusty plasmas in dc glow discharge strata

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Abstract

Strongly coupled dusty plasmas are formed by suspending micron-sized dust particles in strata of a dc glow neon discharge. We have observed for the first time an ordered structure of the negatively charged particles trapped in the strata region. Image analysis reveals the crystalline structure, which is consistent with a large value of the Coulomb coupling parameter. © 1997 Elsevier Science B.V.

Keywords: Strongly coupled dusty plasma; dc glow discharge; Ordered structure

1. Introduction

A dusty plasma is a low-temperature plasma, consisting of neutral gas, micron-sized particles of solid matter (dust particles), ions and electrons. The dust particles are charged by collecting ions and electrons, or by photoemission, thermal and secondary electron emission. In the absence of emission, the particles can be negatively charged due to the higher mobility of electrons than ions in the plasma.

The thermodynamical properties of dusty plasma are determined by the Coulomb coupling parameter, $\gamma_p = Z_p^2 e^2/\bar{r}kT_p$, which is provided by the ratio between the potential Coulomb energy and the thermal energy of the particles. Here Z_p is the particle charge in electron charges, $\bar{r} = (4\pi n_p/3)^{-1/3}$ is the mean interparticle distance, n_p is the particle density, and T_p is the particle temperature. A plasma with coupling constant γ_p greater than unity may be called a strongly coupled plasma [1]. The strongly coupled dusty plasma exhibits fascinating phenomena such as the formation of an ordered (liquid or solid) structure [2-6].

For theoretical description of the strongly coupled plasma a one-component plasma (OCP) model and the Debye model are usually used. The classical one-component plasma is an idealized system of ions immersed in a uniform background of neutralizing charges such that the whole system is electrically neutral. The charged particles interact via the Coulomb potential $Z_p e/\bar{r}$ [1,2]. The three-dimen-

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sional system is found to form crystalline structures for values of γ_p greater than critical parameter $\gamma_c \approx 170$. For the two-dimensional system $\gamma_c \approx 130$ [1]. In the Debye model the shielding effects by the background charge are taken into account which changes the interaction potential to the Debye–Hückel type: $Z_p e \exp(-\bar{r}/r_D)/\bar{r}$ [4,5], where r_D is the Debye shielding length. Numerical calculations for a screened potential show that the critical parameter γ_c depends on $\bar{r}/r_D$. For example, numerical simulations suggest that crystallization requires $\gamma_p \approx 99$ when $\kappa = 0.7$, $160 < \gamma_p < 850$ when $1 < \kappa < 5$, and $\gamma_p = 4.8 \times 10^4$ when $\kappa = 10$ [5].

It was observed in laboratory rf plasmas that negatively charged particles tend to self-organize in ordered structures. In a typical experiment, the dust particles (their charge is $\sim 10^3$–$10^5 e$) are embedded in the sheath region where the balance between the gravitational and electrostatic forces is established [7–10]. Recently, an ordered structure of macroscopic particles was experimentally observed in a classical neutral thermal plasma under atmospheric pressure and temperature of about 1700 K [11,12].

In the present experiment we investigate for the first time the ordered structure of a cloud of charged particles levitated under conditions of a weakly ionized plasma in strata of a dc glow neon discharge.

2. Experimental setup and procedure

The discharge was formed in a cylindrical glass tube with cold electrodes (see Fig. 1). The 3 cm inner diameter and 60 cm long glass tube was positioned vertically. The electrode separation was 40 cm. The discharge current was varied from 0.4 up to 2.5 mA, the pressure of neon was changed between 0.2 and 1 Torr. Under these conditions, the natural standing strata were produced. The strata are characterized by periodic changes of electron density, electrical field and potential along an axis of the discharge tube [13]. It should be remarked that we observed slight oscillations of the strata under certain conditions.

A few grams of micron-sized particles are placed in a dust dropper in the upper side of the glass tube. The falling particles are trapped and suspended in the strata. Two types of dust grains used in our experiments are (1) borosilicate glass microballoons ($\rho = 2.3$ g/cm^3), and (2) alumina particles ($\rho = 4.0$ g/cm^3). The glass microballoons were hollow thin-walled spheres of 50–63 μm diameter. The wall thickness of spheres was no more than 5 μm. The selected sizes of alumina particles were in the range of 3–5 μm.

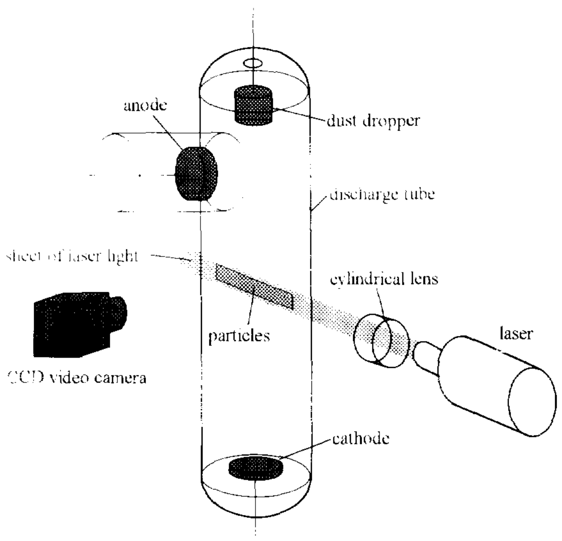

Fig. 1. Schematic of apparatus.

When standing or slightly oscillating strata were formed in the positive column of the glow discharge, the dust particles were seen as a cloud levitated in the center of the luminous parts of the strata. Usually we observed a few clouds of particles in adjacent strata. Typical distances between the particle cloud and the electrodes were 15–20 cm. Observations were made by illuminating a horizontal or vertical plane with a sheet of Ar laser light, with a thickness of 150 μm and a breadth of 4 cm. It is adjustable to various heights. Scattered light was viewed at 60° to the horizontal plane through a transparent wall of the glass tube. To observe particles in the vertical plane, receiving optics was positioned at an angle of 90° to the vertical. Individual particles were easily seen with the unaided eye and with a CCD video camera fitted with a macro objective. A 58-mm macro objective with extension tubes provided magnification from ×2 to 30 for the data shown below.

3. Results and discussion

The cloud diameter was 5–10 mm for large glass particles and was increased up to 20 mm for small alumina ones. Figs. 2 and 3 show typical images of the particle cloud in a single plane (horizontal and vertical) in these two cases. By properly adjusting the plasma parameters, the shape of the particle cloud in the vertical plane is changed from an ellipsoidal to cylindrical one (see Fig. 4a and 4d). Note the organized structure and quasi uniform particle spacing. A typical image area is 12×17 mm^2 and contains from 90 to 280 particles. In the vertical plane the structural ordering appeared as a formation of particle chains.

In the ellipsoidal case particles were organized in 10–20 (for glass particles) and more (for alumina particles) planar layers. In the cylindrical case the longitudinal size of the crystalline structure was increased up to 60 mm. Distances between layers were in the range of 250–400 μm. Interparticle distances in the horizontal plane were 350–600 μm. This corresponds to $n_p \sim 10^3$–10^4 cm^{-3}. It is obvious that the observed particle structure is more crystalline than gaslike. The video showed the particle clouds oscillating in accordance with the strata oscillations.

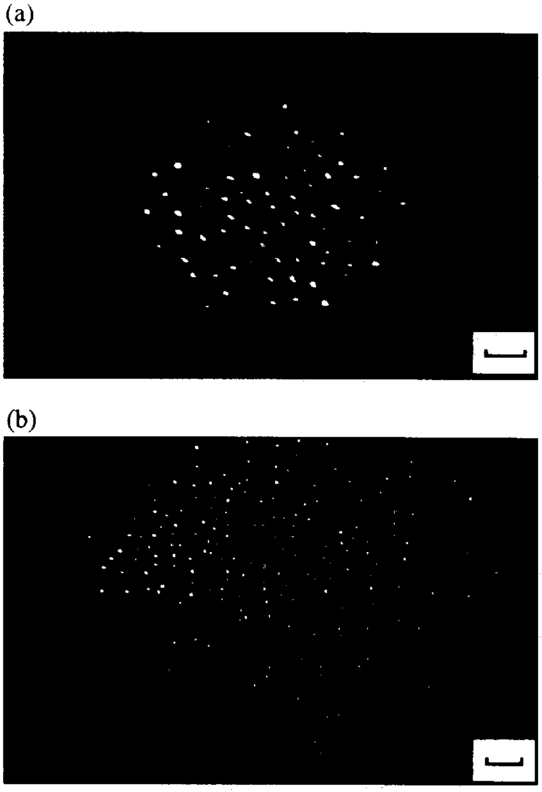

Fig. 2. Video images of the glass particle cloud in horizontal (a) and vertical (b) planes at 1.2 mA and 0.2 Torr. The bars correspond to 1 mm.

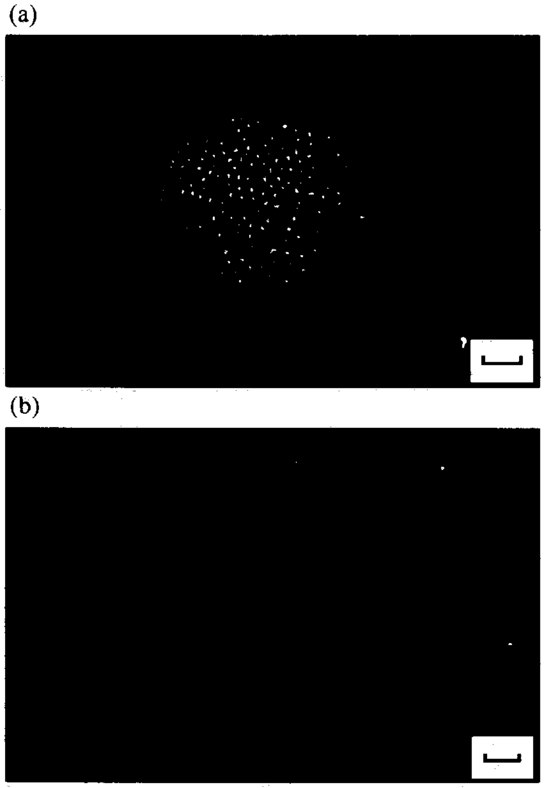

Fig. 3. Video images of the alumina particle cloud in horizontal (a) and vertical (b) planes at 1.15 mA and 0.5 Torr. The bars correspond to 1 mm.

A numerical analysis of Figs. 2, 3 verifies it as crystalline structure. Directly measuring the distance between particles, we obtained pair correlation functions [1]. The two-dimensional functions $g(r)$ in the horizontal plane of the particle structures are presented by curves in Fig. 5a and 5b for glass microballoons and alumina particles, respectively. The sharp first peak and the following peaks with slowly descending heights manifest the crystalline structure of particles. The correlation length is at least four nearest neighbour distances. The nearest neighbour distances are 400 and 500 μm for alumina and glass particles, respectively. For alumina particles in the vertical plane $g(r)$ displays decaying oscillations characteristic of a fluid (see Fig. 5c).

Recently, strata in the neon dc glow discharge have been studied extensively in Refs. [14–16]. The experimental data show that the strata are characterized by periodically alternating regions of strong and weak electric fields along the axis of the discharge tube. The strong electric field ($E_s \sim 10$ V/cm) at the head of strata is extended for a small part of the strata. In some region of strata the balance of electric field and gravity produces an electrostatic potential well. Due to the high floating potential of the tube wall (~ 30 V), a potential well is also formed in the radial direction. Based on these data, we can conclude that particles are suspended by the strong electric field and are confined by the trap.

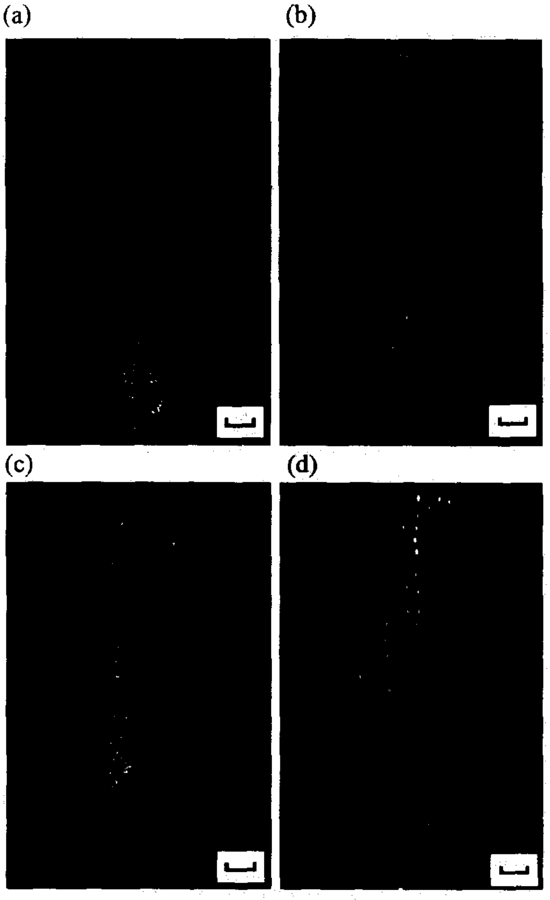

Fig. 4. Video images of the glass particle cloud in the vertical plane at different current and pressure: (a) 0.5 mA and 0.47 Torr; (b) 0.5 mA and 0.44 Torr; (c) 0.4 mA and 0.37 Torr; (d) the magnified fragment of the cylindrical structure in (c). The bars in (a), (b), (c) correspond to 3 mm, in (d) to 1 mm.

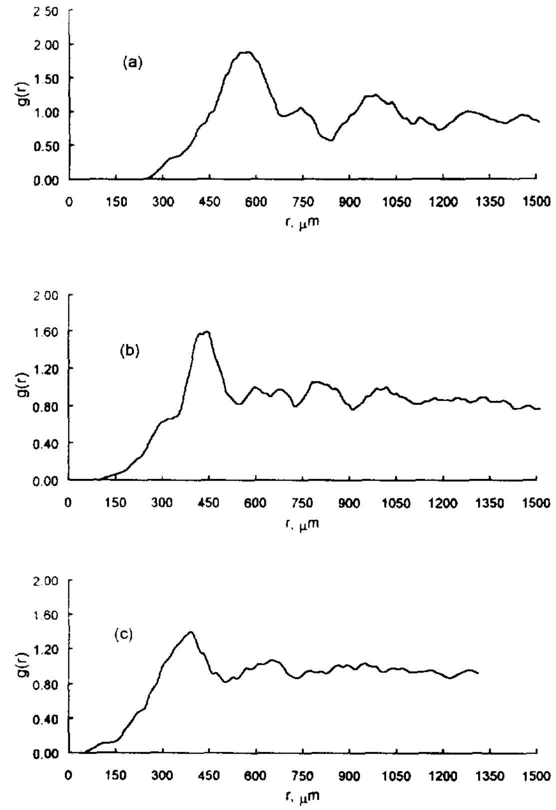

Fig. 5. The pair correlation function of the ordered structure: (a) in the horizontal plane for glass microballoons at 1.2 mA and 0.2 Torr; (b) in the horizontal plane for alumina particles at 1.15 mA and 0.5 Torr; (c) in the vertical plane for alumina particles at 1.15 mA and 0.5 Torr. Curves a, b and c correspond to the states in Figs. 2a, 3b, and 3c, respectively.

Our conclusions are verified by experiments with micron-sized (3–5 μm) alumina particles. Due to large values of Z_p/M_p the particles tend to organize along equipotential surfaces of the electric field. As seen from the location of particles in the vertical plane the distinctive pattern of the well and its changes varying discharge parameters are revealed (see Fig. 6). Fig. 6a shows the near ellipsoidal cloud of particles at 1.15 mA discharge current and 0.3 Torr neon pressure. Increasing current causes the strata oscillations. It leads to the transformation of the electric field that confines the particle cloud.

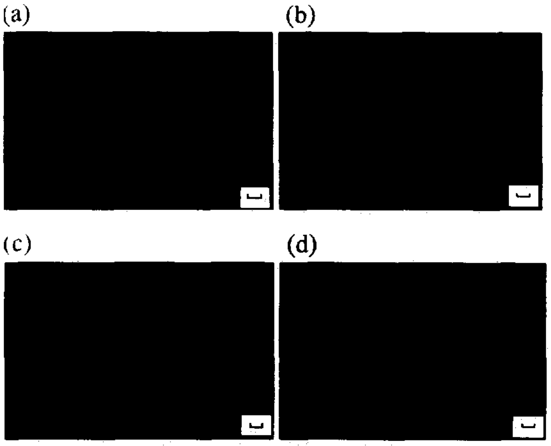

Fig. 6. Video images of the alumina particle cloud in the vertical plane at different current and pressure: (a) 1.15 mA and 0.3 Torr; (b) 2.2 mA and 0.3 Torr; (c) 2.2 mA and 0.3 Torr; (d) 2.85 mA and 0.8 Torr. The bars correspond to 1 mm.

Figs. 6b and 6c show the well pattern for limiting upper and lower positions of oscillating strata. Increasing neon pressure to about 0.8 Torr changes the well shape as shown in Fig. 6d.

Varying the discharge parameters (pressure and current), we change the dimensions of the electrostatic well and thus the shape of the particle cloud. As can be seen from Figs. 4a, 4b and 4c the decreasing of discharge current and pressure leads to successive modification of two nearest ellipsoidal clouds into the cylindrical ordered structure. Fig. 4d shows the magnified fragment of the cylindrical structure in Fig. 4c.

The analysis of the obtained images of a cloud of particles and appropriate correlation functions show that the investigated system of particles is close to the liquid–solid transition. Numerical simulations for the Debye system, which well describes phase transitions in plasma with shielding effects, suggest that crystallization requires $\gamma_p \sim 10^3$ when $\bar{r}/r_D \approx 4$–6 [6].

In order to estimate the coupling parameter γ_p we need to know the particles' kinetic energy (or temperature) and charge. We estimate the plasma parameters and the grain charge in the following way. We assume parameters that are typical of a small current dc glow discharges: $kT_e \approx 3$ eV, and mean plasma density $n_e \sim 10^9$ cm^{-3}. The particles charge up negatively to a floating potential $V_p \sim kT_e/e \sim 3$ V in a Ne discharge plasma. The charge on the particles is determined by $Z_p = CV_p$, where C is the capacitance of the particle. For an isolated sphere of radius R_p, $C = R_p$ and for hollow glass microspheres with size in the range 50–63 μm the charge is about 10^5.

The particle charge Z_p can be estimated from the balance of the gravity and electric field E_s in strata: $Z_p = M_p g/eE_s$. For glass spheres we have $Z_p \sim 10^6$ when $M_p \sim 10^{-8}$ g and $E_s \sim 10$ V/cm. This value is approximately 10 times larger than the particle charge calculated for the discharge parameters above. To explain this fact we take into account that the electron energy distribution in the region of the strong electric field is bimodal with the second peak of about 15 eV. The increasing of the electron energy leads to the growth of the particle charge up to a value that is restricted by the secondary electron emission (for glass the electron energy is no more than 40 eV [16]). The particles charge up negatively to a potential $V_p \sim kT_e/e \sim 15$–30 V in the strata region. This is in general agreement with the value of the float potential of the discharge tube wall measured in Ref. [15]. As a result the charge Z_p is of the order of 10^6 and 10^5 for glass and alumina particles, respectively.

Under glow discharge conditions the kinetic temperature of particles is generally taken to be equal to $T_p \approx 300$ K, which is close to room temperature. The shielding effects (ion Debye length) are estimated from the balance of electrostatic forces in the radial direction: $(Z_p e)^2 \exp(-\bar{r}/r_D)/\bar{r}^2 \approx (Z_p e)E_r$, where E_r is the radial electric field in discharge. For typical values of the electric field $E_r \sim 1$ V/cm and interparticle distance $\bar{r} \approx 300$–600 μm we have $r_D \approx 80$–100 μm and $\bar{r}/r_D \approx 4$–5. The Coulomb coupling parameter γ_p is then estimated to be $\sim 10^6$ and 10^8 for alumina and glass grains, respectively. These γ_p values are 3 or 5 orders of magnitude larger than considered above in the Debye model. However, at low pressures the observed particle mean kinetic energy can be increased up to ≈ 50 eV [17]. As a result the corresponding values of coupling parameter γ_p are decreased. We are able to estimate the kinetic energy of small alumina particles at the liquid–solid transition. As can been deduced from the video recording, the particle displacement from the equilibrium position in the crystalline structure was of the order of the particle diameter D_p.

From this it follows that $kT_\mathrm{p} \sim (Z_\mathrm{p}e)E_\mathrm{r}D_\mathrm{p}$. Under plasma parameters $Z_\mathrm{p} \sim 10^5$, $D_\mathrm{p} \sim 5$ μm and $E_\mathrm{r} \sim 1$ V/cm, the coupling parameter γ_p is estimated to be $\sim 10^3$ ($kT_\mathrm{p} \sim 50$ eV).

4. Conclusion

In conclusion, we have demonstrated an ordered structure of the charged particles levitated under conditions of a weakly ionized plasma in strata of dc glow neon discharge. Image analysis reveals the crystalline structure, which is consistent with a large value of the Coulomb coupling parameter for the Debye system. The particles form crystalline structures in horizontal planes, whereas they are found to be aligned in the vertical direction. Varying the discharge parameters, we change the dimensions of the electrostatic well and thus the shape of the particle cloud. In particular, the shape of the particle cloud in the vertical plane is modified from an ellipsoidal to a cylindrical one.

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