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PLASMA, GASES

Cooperative Formation of Dust Structures in Plasma

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Abstract—The formation and destruction of ordered dust structures in glow discharges are investigated experimentally. The initial construction phase of an ordered structure is related to the construction of its cooperative field and is determined by the number of particles and by the existence of crystallization centers. After the structure has been constructed, it influences the local plasma properties and the discharge current–voltage characteristics. The recovery of the structure after weak exposure takes place at local equilibrium, while, after intense exposure to high-voltage nanosecond pulses, it is determined by the fluctuation level and the degree of chaotization in the system. *© 2002 MAIK “Nauka/Interperiodica”.*

Plasma with charged dust particles is an object with a strong Coulomb coupling that yields record high parameters of nonideality,

$$\gamma = Z^2e^2n^{1/3}/kT \sim 10^5,$$

through a significant macroparticle charge Z. The formation of structures from micron-sized dust particles was experimentally observed in a low-pressure nonequilibrium plasma in high-frequency and glow discharges [1], as well as under intense ultraviolet and radioactive radiation [2]. The particles acquire a large negative charge (10^5–10^6 electron charges) that corresponds to the floating plasma potential, and the dissipative dust structures can form a Coulomb crystal [1]. The external conditions and the ambient-plasma properties under which ordered plasma–dust structures can be produced have currently been studied. It is not yet known how the ordering of dust particles with a strong Coulomb coupling and plasma condensation proceed; the transition from chaos to order in such systems is not understood and has been investigated neither experimentally nor theoretically. The appearing stable structure must, in turn, change the local properties of the ambient plasma, the distribution of parameters in it, the electric fields, and the charged particle fluxes. Previously, most authors have assumed the background-plasma properties to be virtually constant. Here, our goal is to experimentally investigate the formation and destruction of charged macroparticle structures, the action of force on these structures, and the changes in plasma properties.

We investigated the structures composed of Al_2O_3 particles (3–5 μm in size), polydisperse MgO particles (5–20 μm in size), and hollow glass spheres (20–60 μm in size) in glow discharges in helium, argon, nitrogen, air, and their mixtures. The experiments were carried out in cylindrical discharge tubes of 1 and 2 cm in diameter, as well as in a conical 50-cm-long discharge tube with a variable diameter from 1.5 to 4 cm [3]. Since the similarity rule, according to which the reduced electric-field strength E/P is determined by the product Pd (where d is the discharge tube diameter and P is the gas pressure), holds for a positive gas discharge column, the longitudinal electric field in the conical tube changes along its length: it is at a maximum in its lower narrow part and decreases as one rises in height. Therefore, particles with different masses can find a suitable field, causing the localization of different particles in different cross sections of the discharge tube and the particle separation in size, charge, and mass along the tube. When using the cylindrical tube of 2 cm in diameter, we pasted two metal rings of the same diameter spaced 5 cm apart in its walls. We used these rings to measure the average field in the discharge and applied high-voltage nanosecond pulses to them to act on the dust structures. The particle structures were examined with a videocamera through their illumination by two perpendicular laser “knifes” with a 0.63-μm wavelength and a 150-μm caustic. The particles were imaged along and across the tube. The structures were also examined with an optical microscope. We measured the average field along the discharge column with probes, the voltage between the metal rings, the current and voltage on the discharge tube, and the geometric parameters of the dust structure as a function of the discharge current and gas pressure.

A distinct three-dimensional dust structure is formed in strata at $Pd < 1$ torr cm. The number of particles in the structure depends on conditions and can vary from several tens to several thousand. The characteristic distances between the strata are 150–250 μm. The horizontal distances between the particles in the stratum are typically a factor of 1.5 or 2 larger and increase with particle size, tube diameter, and passing current. In air,

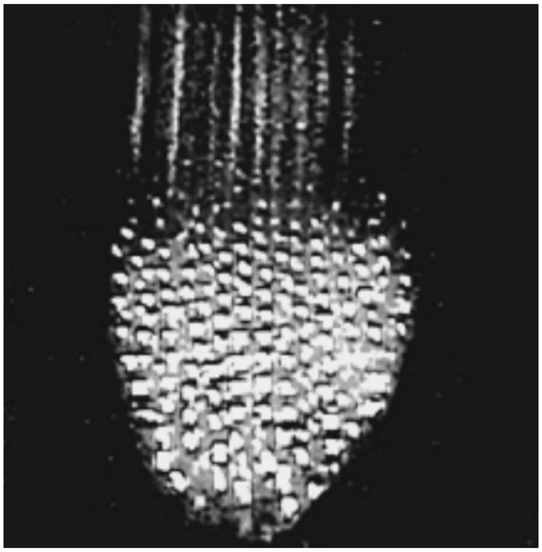

Fig. 1. Luminous jets above an ordered dust structure. The cross section is longitudinal, the glow discharge is in air, and the current is 0.5 mA.

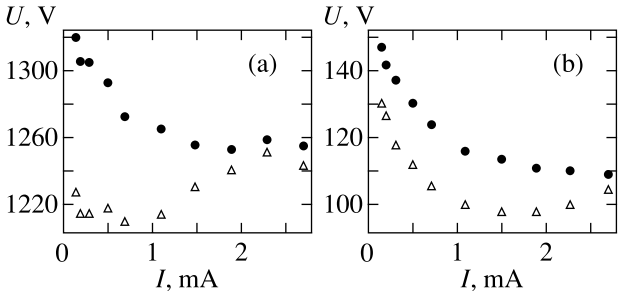

Fig. 2. The current–voltage characteristics of (a) a glow discharge and (b) a stratified discharge column between the rings with (dots) and without (triangles) glass microspheres. The air pressure is 0.2 Torr.

the conditions for the formation of an ordered crystal are fairly stringent; the range of discharge currents at a pressure of 0.2 torr is 0.3–1 mA, while, in air–argon mixtures at pressures of 0.1–0.5 Torr, it is 0.3–3 mA. As the current rises further to several milliamperes, the crystal is disordered and resembles a liquid. In this case, the particles retreat to the walls of the discharge tube and ring-shaped structures suspended in strata are observed [3, 4].

In general, a distinct spatial structure is formed when several particles are initially aligned in the stratum and then the remaining particles sequentially line up with them. The initial particles act as the crystallization centers. These are localized in the undisturbed field of the stratum and are aligned in its potential pit [4]. As the number of dust particles gradually increases, they sequentially fill the entire stratum volume to produce a spatially ordered structure. The collective field of this structure is a superposition of the stratum electric field and the spatial fields of individual dust particles. Adding several particles distorts this collective field only slightly, and these line up with the structure. The spatial order of the particle arrangement in the formed plasma–dust structure is determined by Coulomb forces, although the Debye screening length calculated from the background plasma parameters is severalfold smaller than the interparticle separation. The cooperative field of the dust structure is comparable in strength to the stratum field. Therefore, if many randomly moving dust particles whose average field greatly fluctuates and distorts the local stratum field are simultaneously injected into the stratum, then no stable ordered structures are formed. In this case, although the particles are confined to the stratum, they randomly move through its entire volume.

The cooperative behavior that facilitates the formation of a plasma–dust structure is consistent with the standard principles of nonequilibrium thermodynamics when the formation and self-organization of dissipative structures have a threshold character [5]. In a thermodynamic equilibrium, the probability that a macrosopic number of particles are spontaneously organized into a regular stream or a phased collective is negligible. A system can form ordered structures only because the external restrictions (temperature gradient, electric field, and radiation field) maintain the system in a nonequilibrium state. The new structure results from the growth of instability and arises from fluctuations [5].

The collective action of the dust grain field on the processes in the stratum can be significant, because the grain charge per unit volume is comparable to the electron number density in the stratum itself (10^8–10^9 cm^{-3}). An ordered crystal changes not only the electric fields in the stratum itself but also the properties of the adjacent plasma at distances comparable to the crystal size. When a current passes through a macrocrystal, the formation of luminous plasma jets above the crystal from the anode is observed (Fig. 1). When moving along the channels formed by neighboring parallel chains of charged macroparticles, the electrons apparently undergo grazing collisions and mirror reflections and are confined to these channels. The channeled electrons are accelerated when passing through the crystal, much as they are in a solid [6], and produce an additional plasma disturbance in the form of luminous fibers above the crystal.

The formed dust structures also affect other discharge properties, in particular, the current–voltage characteristics. We measured the current–voltage characteristics of a positive column with stationary strata at an air pressure of 0.2–0.5 Torr with structures with and without glass microspheres between the metal rings in the discharge tube of 2 cm in diameter. At all pressures, the voltage between the rings in the presence of macroparticles is higher than that in the discharge without particles (Figs. 2a and 2b). The difference between the two current–voltage characteristics at a fixed current for a small number of particles in the structure is 5–10 V. For a large number of particles in the structure, it increases to 20–30 V, which is apparently attributable to the additional electron death on particles. The electron death on macroparticles at small currents can cause the discharge to be quenched. At the minimum possible discharge current, we detected a relaxation discharge glow when the discharge periodically went out and ignited with a period of about one second. The oscillation period decreases with increasing discharge current. These oscillations can be explained as follows: an additional channel of the electron death on particles appears when the particles enter into the discharge, a voltage higher than the available one is required to maintain the discharge, and the discharge goes out. The dust particles fall and retreat to the walls. The discharge ignites again. In the discharge, the particles are charged, the dust structure is recovered, and the process is repeated.

When the dust structure is destroyed, its recovery depends on the type of exposure. For slow weak exposure, for example, a thermal [4] or electric [7] one, the structure shifts in space; part of it can be deformed or destroyed. After the exposure, the destroyed part of the structure gradually lines up with its preserved part. If the disturbing processes are less intense than the processes that produce an equilibrium of the dust structure, then a local equilibrium is maintained in the system with a certain accuracy. Otherwise, for intense exposure, the structure is completely destroyed and chaotized. The recovery of the structure from chaos is no longer determined by the local equilibrium alone. If there is no initial seed with which the structure lines up, then the formation of an ordered structure will depend on the fluctuation level. One or more sufficiently intense macrosopic fluctuations are needed for a new ordered structure to emerge in the wake of instability.

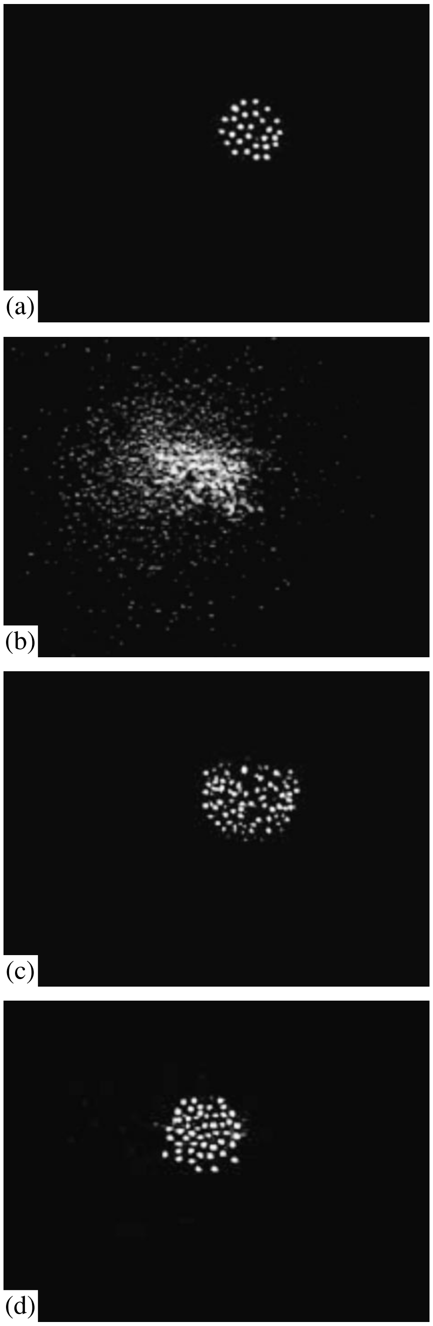

Fig. 3. Exposure of a dust crystal in a glow discharge in air (cross section) to nanosecond pulses: (a) before the exposure, (b) during the exposure with a pulse repetition frequency of 40 Hz, (c) recovery of the structure after the exposure, and (d) an ordered structure after the exposure.

The ordered dust structure was intensely exposed to nanosecond high-voltage pulses. Since the pulse duration is very short, the particle displacement in the structure in the exposure time of the pulsed electric field is negligible. The dust structure was produced in the stratum between the two metal rings in the cylindrical discharge tube (Fig. 3a). High-voltage pulses of negative polarity, 40 ns in duration and 10 kV in amplitude, with a repetition frequency of 1–100 Hz were applied to the rings through blocking capacitors. After exposure to a single pulse, the particles slightly oscillated about their stable state. After pulse-periodic exposure with a frequency of about 10 Hz, the order in the structure broke down, while, at a higher frequency, the particles scattered over the entire volume and began to randomly move with large velocities (Fig. 3b). After the nanosecond voltage was removed, the particles gathered in the stratum in several seconds. The number of particles in the new structure always exceeded their initial number, which stems from the fact that a larger number of particles were drawn into the construction process. The number of returning particles increases with exposure intensity. When the number of particles after the exposure to nanosecond pulses ended was smaller than some critical number, the particles gradually formed an ordered structure in several seconds (Figs. 3c and 3d). If their number was too large, then the particles were confined to the structure but they were not aligned into an ordered structure; the dust structure resembled in form a boiling liquid with randomly moving particles. Such a chaotic state could be stable for a long period.

The destruction of the structure and the scatter of particles under nanosecond exposure primarily result from an increase in their charge. High-voltage nanosecond pulses produce many high-energy electrons (with energies of several hundred eV [8]) in plasma that rapidly increase the dust-particle charge, which is proportional to the electron energy. The surplus negative charge is neutralized much more slowly, because this neutralization is determined by the ion flux. The action of this surplus charge results in their Coulomb repulsion. Chaotization proceeds gradually from pulse to pulse. If the system of dust particles does not completely return to its initial ordered state in the time between pulses and if this time depends on the extent of the structure destruction and is several seconds for complete chaotization, then the structure falls apart, which is observed in the experiment.

Thus, the initial construction phase of an ordered structure is related to the construction of its cooperative field. It is determined by the initial electric-field distribution in plasma, the number of particles, the degree of their chaotization, and the existence of crystallization centers. After the structure has been constructed, it influences the local plasma and discharge properties. After weak exposure, the structure is recovered at local equilibrium, while after intense exposure, it is determined by the fluctuation level and the degree of chaotization in the system.

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