Analysis of spatial correlation of macroparticles in dusty plasma

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Abstract. Results of experimental study of particle correlation are presented for liquid dust structures in rf- discharge plasma. The triplet correlation functions for experimental and numerical data are analyzed and compared with the superposition approach.

The dusty plasma is an ionised gas containing micron-size charged dust grains (macroparticles). Micron-sized dust particles in a gas-discharge plasma assume a significant negative charge ($eZ \sim 10^3e$-10^5e) and may form dust structures similar to a liquid or a solid.

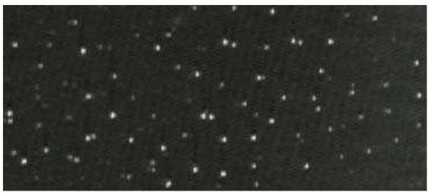
The equilibrium properties of a liquid are fully described by a set of probability density functions $g_s(\mathbf{r}_1,..,\mathbf{r}_s)$ of location of particles at points $\mathbf{r}_1, .., \mathbf{r}_s$. In the case of isotropic pair interaction, the physical properties of a liquid (pressure, energy density etc.) are defined by the binary correlation function $g(r) = g_2(|\mathbf{r}_1-\mathbf{r}_2|)$ [1]. However, even in the approximation of pair interaction, higher-order correlation functions are of interest. Information on the triplet correlation function $g_3(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3)$ is of importance in calculating the characteristics of the medium (entropy, thermal expansion coefficients etc.) that depend on the derivatives of $g(r)$ with respect to temperature T or density n. The superposition approach is most frequently employed to approximate the triplet correlation function

$$g_3(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) \approx g_3^{sp}(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = g(\mathbf{r}_1-\mathbf{r}_2)\, g(\mathbf{r}_2-\mathbf{r}_3)\, g(\mathbf{r}_3-\mathbf{r}_1). \quad (1)$$

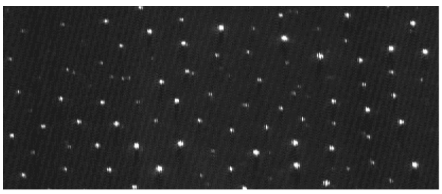
The experimental verification of this approach for real liquids is made difficult by the fact that, unlike the binary correlation function whose determination may be based on the inversion of the structure factor measured by spectroscopic methods, no direct determination of $g_3(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3)$ is possible without information on the particle's coordinates [1, 2].

In contrast to real liquids, the laboratory dusty plasma is a good experimental model for studying the properties of non-ideal systems, because, owing to their size, dust particles may be videofilmed, which significantly simplifies the use of direct diagnostics. The best-known model for interaction of dust particles in plasma is based on the screened potential: $U = (eZ)^2 \exp(-r/\lambda)/r$, where r is the distance, λ is the screening length. The numerical simulation of particles interacting with this potential demonstrate that the effective coupling parameter, $\Gamma^{*}= (eZ)^{2} (1+\kappa+\kappa^{2}/2) \exp(-\kappa)/(T r_{p})$, fully defines the form of the binary function $g(r)$ for systems with $\kappa < 6$ (here $r_{p} = n^{-1/3}$ is the mean interparticle spacing, $\kappa = r_{p}/\lambda$) [3, 4].

This paper contains the results of an experimental investigation of triplet correlation for liquid dust structures formed in the electrode layer of a radio-frequency (rf) capacitive discharge. Schematic of the experimental facility is detailed in [5]. The experiments were performed in argon at pressure P of 2 to 10 Pa with the latex particles of radius $a_{p} \approx 1.7$ μm and density $\rho_{p} \approx 1.5$ g cm^{-3}. The macroparticles formed four to eight dust layers with the mean spacing r_{p} varied from 260 to 350 μm. The diagnostics involved the illumination of the single layer of dust cloud by a laser sheet, after which this layer was videofilmed. Fragments of videoimage are shown in Fig. 1. The pair correlation functions $g(r)$ (see Fig. 2) and triplet correlation functions $g_{3}(\mathbf{r}_{1},\mathbf{r}_{2},\mathbf{r}_{3})$ averaged over a period ~ 2.5 s under constant experimental conditions were obtained. The cross sections of $g_{3}(r_{12},r_{23},r_{31})$ ($r_{ij} = |\mathbf{r}_{i}-\mathbf{r}_{j}|$) for a fixed value of r_{12} equal to the most probable interparticle spacing r_{p}^{max} ($r_{12} = r_{p}^{max}$) determined by the position of $g(r)$ maximum are given in Fig. 3 together with the results of calculation of $g_{3}^{sp}(r_{12},r_{23},r_{31})$ within the approach (1). In order to represent these functions in a "two-dimensional" form convenient for comparison, they were normalized to the maximum of $g_{3}(r_{12},r_{23},r_{31})$: black color corresponds to unity, and white color corresponds to $g_{3} = g_{3}^{sp}=0$.



(a)



(b)

Fig. 1. Videoimage of dust cloud particles for different experiments: (a) $P = 5$ Pa; (b) $P = 7$ Pa.

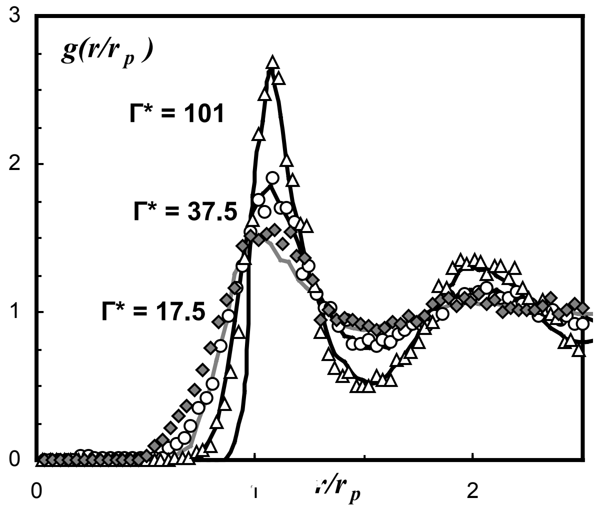


Fig. 2. Functions $g(r/r_{p})$ measured in the experiments: (♦) $P = 5$ Pa; (o) $P = 3$ Pa; (Δ) $P = 7$ Pa; and those obtained by numerical simulation for different Γ^{*} (solid lines) indicated in the figure.

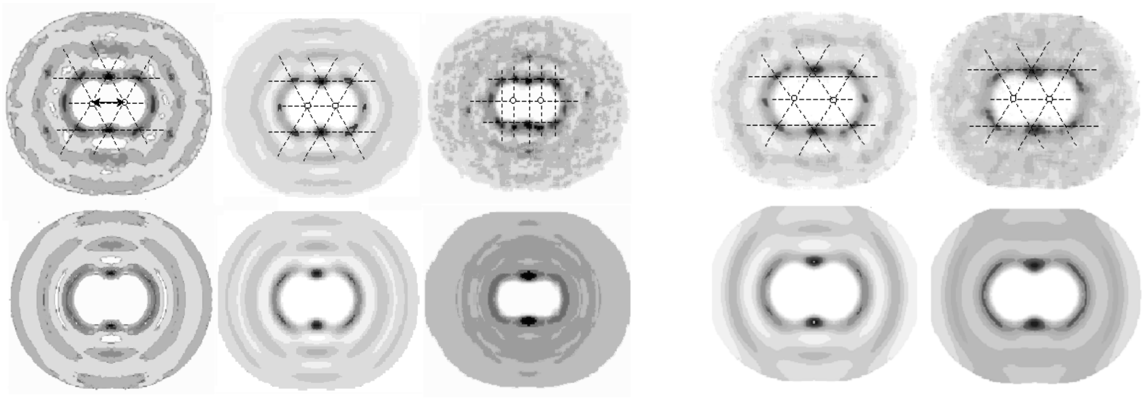


Fig. 3. The functions g_3 (top row) and the approximation g_3^{sp} (bottom row) measured for different experiments: (**a**) $P = 7$ Pa, $\delta = 0.61$; (**b**) $P = 3$ Pa, $\delta = 0.28$; (**c**) $P = 5$ Pa, $\delta = 0.3$; and those obtained by numerical simulation for different Γ^*: (d) $\Gamma^* = 37.5$, $\delta = 0.62$; (e) $\Gamma^* = 17.5$, $\delta = 0.61$.

The deviation of the measured function $g_3(r_{12},r_{23},r_{31})$ from $g_3^{sp}(r_{12},r_{23},r_{31})$ is given in the caption of Fig. 3 and was calculated proceeding from the relative mean-square error

$$\delta = \frac{1}{N^{1/2}}\left[\sum_{i=1}^{N}\{g_3(r_{12},r_{2i},r_{i1}) - g_3{}^{sp}(r_{12},r_{2i},r_{i1})/g_3(r_{12},r_{2i},r_{i1})\}^2\right]^{1/2}, \quad (2)$$

where N is the number of elements of space d$\mathbf{r}_i$ in the vicinity of the point with coordinate $\mathbf{r}_i$.

Visual comparison of the results reveals that the recorded structures exhibit the forming of a close-range orientational order of dust particles, which is reflected in the emergence of maxima of $g_3(r_{12},r_{23},r_{31})$ in nodes of hexagonal clusters shown by dashed lines in Figs.4a, 4b. As the maximum of the pair correlation function increases, the magnitude of these maxima located at distances r close to r_p^{max} grows, and new maxima arise at distances $r \approx 2\, r_p^{max}$. This effect does not show up when the approximation $g_3^{sp}(r_{12},r_{23},r_{31})$ is analyzed. Some experimental conditions (see Fig. 3c.) were characterized by the simultaneous presence in dust systems of both hexagonal clusters and cluster structures similar to the arrangement of particles on the faces of cubic lattices of different types.

The numerical simulation were performed for a three-dimensional Yukawa system (at $\kappa < 6$) using Langevin's method of molecular dynamics with periodic boundary conditions for 512 independent macro-particles and the cut-off of pair potential equal to $7r_p$. In order to simulate the experimental observation of dust particles in the laser sheet plane, the computational cells were divided into layers of thickness ~ $r_p/2$, and the correlation of particles was investigated in each layer. Triplet correlation functions and their superposition approaches are illustrated in Figs. 3d,e for different Γ^* at $r_{12} = r_p^{max}$. The pair correlation functions are given in Fig. 2. One can readily see that the experimental results well fit systems with $\Gamma^* \sim 100$, 37.5, and 17.5. In the latter case, the differences between calculated and measured $g(r)$ are most pronounced, because the experimental curve exhibits a broader first maximum associated with the formation of dust clusters of different types.

Analysis of the calculations reveals that the pronounced maxima of $g_3(r_{12},r_{23},r_{31})$ in the simulated system arise with the emergence of such maxima for a pair correlation function at $\Gamma^* > 5$. As Γ^* increases from 5 to 22, the maxima of $g_3(r_{12},r_{23},r_{31})$ increase and, at $\Gamma^* > 25$, the emergence of regular clusters of particles is registered in the system. The shape of such clusters is close to the hexagonal shape observed in laboratory experiments. Nevertheless in some experimental situation the shape of observed clusters may be considerably different from hexagonal form (Fig. 3c). This may be associated with difference of the experimental conditions from the simulated problem, for example, with non-Yukawa type of experimental potential. In spite of this, good agreement is observed between three-particle correlation functions determined for numerical and experimental data, at least in the cases where similar agreement is observed between the shapes of their binary correlation functions.

To conclude, here we studied the triplet correlation of dust particles in plasma. Analysis of the experimental results has revealed that the difference of superposition approximation from the recorded three-particle correlation function for the analyzed cross sections ranges from 30 to 60%. Note further that experimental investigations of three-particle correlation enable one to obtain additional information about the physical properties of plasma-dust systems and may be used for structure analysis of complex plasma.

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