Transport of Microparticles in Weakly Ionized Gas-Discharge Plasmas under Microgravity Conditions

V. E. Fortov, O. S. Vaulina, O. F. Petrov, V. I. Molotkov, A. M. Lipaev, and V. M. Torchinsky
Institute for High Energy Densities, RAS, Izhorskaya 13/19, 125412 Moscow, Russia

H. M. Thomas, G. E. Morfill, and S. A. Khrapak*
Centre for Interdisciplinary Plasma Science, Max-Planck-Institut für Extraterrestrische Physik, Postfach 1312, D-85741 Garching, Germany

Yu. P. Semenov, A. I. Ivanov, S. K. Krikalev, and A. Yu. Kalery
Rocket Space Corporation "Energia," 141070 Korolev, Russia

S. V. Zaletin and Yu. P. Gidzenko
Yu. Gagarin Cosmonaut Training Center, 141160 Star City, Moscow Region, Russia
(Received 18 February 2003; published 19 June 2003)

Measurements of effective structural (pair correlation function) and transport (diffusion constant) characteristics of the system of microparticles in dc and rf gas-discharge plasmas under microgravity conditions are reported. The comparison between these measurements and numerical simulations is used for complex plasma diagnostics.

DOI: 10.1103/PhysRevLett.90.245005 PACS numbers: 52.27.Lw, 52.25.Fi

Complex (dusty) plasmas consist of neutral gas, ions, electrons, and charged micron-sized (dust) particles. The combined effect of interaction between the particles and the ambient plasma as well as between the particles themselves leads to the formation of various complex plasma states ranging from "gaseous" and "liquid" plasma to "plasma crystals" [1–6]. The level of ordering in the particle system distinguishes these states.

Gravity severely restricts laboratory investigations of complex plasmas. To support particles against gravity strong electric fields are required leading to a high degree of plasma anisotropy and suprathermal ion flows. The plasma conditions yield forces on the particles, which are comparable to the interparticle forces. Hence most complex plasmas investigated on Earth so far have been strongly compressed, inhomogeneous (in the vertical direction), and anisotropic—all due to the action of gravity.

Under microgravity conditions the particles move into the bulk of the plasma and can form large three-dimensional (3D) weakly compressed quasi-isotropic complex plasmas. In this situation earlier numerical results on 3D Yukawa systems (YS) can be applicable (see [7–10] and reference therein). This allows us to check the predictions of these models and to use them for complex plasma diagnostics. Here we report on the measurements of structural and dynamical characteristics of particles in the "liquid plasma" state in two types of gas-discharge plasmas under microgravity. Comparison with numerical simulations is used to estimate the particle charge and the plasma screening length.

Numerical simulations of particle motion in weakly ionized plasmas require the use of a Brownian dynamics method which takes into account random forces produced by the medium (e.g., plasma electric field and/or particle charge fluctuations, impact of gas molecules, etc.), as well as regular forces acting on particles and the interaction between them [7–9]. The random forces are often modeled as Gaussian white noise. Then the particle system obeys the Maxwellian velocity distribution with the kinetic temperature T_p determined by the balance between the stochastic energy supply (amplitude of random forces) and frictional dissipation [7]. If the particles are in equilibrium with neutral gas, then $T_p = T_n$. The typical assumptions in simulations are (i) the interaction between grains is described by the repulsive Yukawa (Debye-Huckel) potential $U(r) = (U_0/r)e^{-r/\lambda_D}$, where λ_D is the screening length and $U_0 = Q^2e^2$ (Q is the particle charge number); (ii) isotropic plasma conditions; (iii) the interparticle interaction dominates over external forces and/or boundary effects. The assumptions (ii) and (iii) allow one to perform 3D simulations under periodic boundary conditions. This model is not always applicable, especially when gravity or confinement is dominant (since the interaction is repulsive some confinement is necessary), as discussed in [11]. However, it should be suitable for a bulk of large "liquid" complex plasmas if the confining forces are of "surface" character (weak inside the particle cloud, but increase sharply towards its boundaries).

The behavior of YS is fully determined by three dimensionless parameters [7,8]: the *coupling parameter*, $\Gamma = U_0/\Delta T_p$—the ratio of the potential energy of unscreened interaction between particles to their kinetic temperature ($\Delta = n_p^{-1/3}$ is the interparticle distance in terms of the particle number density n_p); the *lattice parameter*, $\kappa = \Delta/\lambda_D$—the ratio of the interparticle distance to the screening length; the *dissipation parameter* $\theta = \eta/\omega_d$—the ratio of the damping rate η (frictional frequency of neutral gas in weakly ionized plasmas) to a characteristic frequency ω_d, characterizing the particle component.

It was shown recently that an effective coupling parameter Γ^* can be introduced (instead of Γ and κ) which alone describes the structural properties of YS [7–10]. We use the following definition: $\Gamma^* = [U''(\Delta)\Delta^2/2T_p]$, where $U''(\Delta)$ is the second derivative of the pair interaction potential, evaluated at $r = \Delta$. In a similar way [using $U''(\Delta)$] we define the characteristic frequency of the particle component as $\omega_d = \sqrt{2\pi U''(\Delta)/M_p}$, where M_p is the particle mass. For a bare Coulomb interaction potential these definitions lead to $\Gamma^* = \Gamma$ and $\omega_d = \omega_{pd} \equiv \sqrt{4\pi U_0 n_p/M_p}$—the plasma-dust frequency. For the Yukawa potential we have $\Gamma^* = \Gamma f(\kappa)$ and $\omega_d = \omega_{pd}\sqrt{f(\kappa)}$, where $f(\kappa) = (1 + \kappa + \kappa^2/2)\exp(-\kappa)$. The latter definitions of Γ^* and ω_d for the Yukawa systems were already introduced earlier in Refs. [7,8].

Some properties of YS found from numerical simulations are illustrated in Figs. 1 and 2. Figure 1 shows the pair correlation function corresponding to equal values of Γ^* but different values of Γ and κ. The similarity between the corresponding curves strongly supports the choice of Γ^* as the universal coupling parameter governing the static structural properties of YS. In Fig. 2 the ratio of the particle diffusion constant D_L to the bare Brownian diffusion value (no interaction), $D_0 = T_d/M_p\eta$, is plotted as a function of Γ^* for several values of θ. The analytical approximation

$$D_L/D_0 \approx \frac{\theta\Gamma^* \exp(-3\Gamma^*/\Gamma^*_M)}{6(1 + 2\pi\theta)} \quad (1)$$

proposed in Ref. [9] for strongly correlated YS is also shown. According to Ref. [9] the error of this approximation is $\sim$30% at $\Gamma^* \sim 30$ and considerably smaller at $\Gamma^* > 50$. The constant $\Gamma^*_M \approx 105$ corresponds to the boundary between "liquid" and "solid" states (melting point). In general D_L/D_0 depends on both parameters Γ^* and θ. However, in the limit of "high" dissipation ($\theta \gg 1/2\pi \sim 0.2$) Γ^* is the unique parameter which determines the value D_L/D_0 (see [7,8]). In the opposite limit $\theta \to 0$ the diffusion constant also demonstrates universal scaling as discussed in [8].

In experiments the particle kinetic temperature, number density (mean separation), and the diffusion constant D_L can be measured simultaneously without any external perturbation of the system (by analyzing video records of particle motions). Then the comparison with numerical results can be used for complex plasma diagnostics. Here we determine the modified coupling parameter Γ^* by fitting the particle diffusion constant measurements with Eq. (1). Note that the dissipation parameter is directly related to Γ^*, $\theta = (4\pi\Gamma^*)^{-1/2}\eta\Delta/v_{Td}$ (η can be calculated, Δ and $v_{Td} = \sqrt{T_p/M_p}$ are measured).

We analyzed the motion of the particles located far from the complex plasma boundaries to minimize the effect of confinement. In the analysis up to $N \sim 150$ trajectories typically were followed for a time of $\sim$0.5–2 s (particles that leave the measurement volume

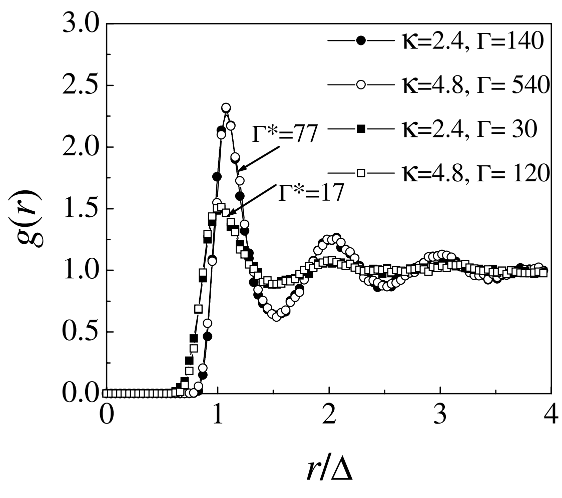

FIG. 1. Pair correlation function $g(r)$ vs the normalized distance r/Δ (Δ denotes mean interparticle separation) for Yukawa systems. The circles (squares) mark the system with $\Gamma^* = 77$ ($\Gamma^* = 17$). Open (closed) symbols correspond to $\kappa \approx 4.8$ ($\kappa \approx 2.4$).

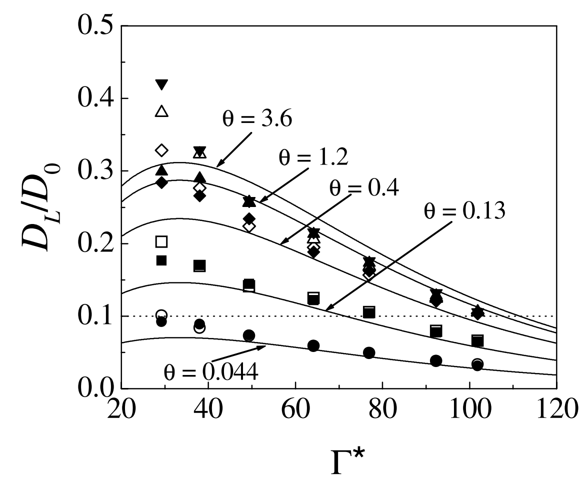

FIG. 2. The ratio D_L/D_0 for strongly interacting Yukawa systems as a function of the effective coupling parameter Γ^* for different values of the dissipation parameter θ (for definition see text). Solid symbols correspond to $\kappa \approx 2.4$; open symbols correspond to $\kappa \approx 4.8$. The values of θ are 0.044 (circles), 0.13 (squares), 0.4 (diamonds), 1.2 (triangles), 3.6 (inverted triangles) [only for $\kappa = 2.42$]. The solid lines represent the analytical approximation of Ref. [9] for different values of θ [Eq. (1)].

faster were ignored). The particle kinetic temperature was determined by approximating the experimental spectrum of "instantaneous" velocities with a Maxwellian distribution function. The diffusion constant was obtained by the appropriate time and ensemble averaging of particle trajectories.

The first measurements were performed in a dc discharge under microgravity conditions on board the "Mir" space station. The sketch of the experimental apparatus is shown in Fig. 3(a) and described in detail in Ref. [12]. The major difference from ground-based experiments (e.g., [3]) was the existence of two grids placed in the discharge tube. The electric field of the grids provided axial confinement of the particle cloud, while the radial confinement was due to the radial electric field increasing sharply towards the tube walls. The basic plasma parameters were the following: Ne gas at pressure $p \approx 130$ Pa, the electron temperature $T_e \approx 3$–7 eV, and the plasma number density $n_e \approx n_i \approx 2 \times 10^9$ cm^{-3}. Bronze particles ($\rho = 8.2$ g/cm^3) of mean radius $a = 65$ μm were used. The discharge current varied in the range $I = 0.1$–1 mA. With increasing discharge current from 0.1 to 0.8 mA, the interparticle separation increased from $\Delta \approx 700$ μm to $\Delta \approx 1000$ μm, while the measured particle temperature was practically constant, $T_p \approx 10^5$ eV. The dependence of Γ^* found from particle diffusion measurements on the discharge current is shown in Fig. 4. The pair correlation function measured for the highest value of $\Gamma^* \sim 80$ is plotted in Fig. 5. It is in reasonable agreement with the pair correlation function found from numerical simulation for a similar value of Γ^*. The estimated dissipation parameter increases monotonically with increasing discharge current (mainly due to the increase in Δ) from $\sim$0.03 to $\sim$0.05. This indicates that the investigated system is "weakly dissipative."

The second measurement we report was carried out in an rf gas discharge in microgravity within the international scientific program Plasma Kristall Experiment-3 [13]. A sketch of the experimental setup is shown in Fig. 3(b). The plasma parameters were Ar gas at $p =$ 36–98 Pa, discharge power $W = 0.14$–1 W, $T_e \approx$ 1–3 eV, and $n_e \approx n_i \approx 10^9$ cm^{-3}. Particles with radius $a = 1.7$ μm were used. In rf discharge microgravity experiments the particles formed a cloud between the electrodes with an ellipsoidal void (region free of particles) in the center. The void is caused by the ion drag force, which is pointed outwards and exceeds the electrostatic force in the center. The outer confinement is provided by strong electric fields near the walls and electrodes of the discharge (sheaths). Measurements of particle diffusion were performed below the void, where a vortex-free "liquid" complex plasma was formed. The dependence of the particle temperature on neutral pressure was nonmonotonous, but all measured values were in the range $T_p \approx 0.4 \pm 0.1$ eV. The interparticle separation was practically insensitive to the pressure, $\Delta \approx 200$ μm. The dependence of the estimated effective coupling parameter on the neutral pressure is shown in Fig. 4 for $W =$ 0.49 W. Note that the dependence of Γ^* on p turns out to be highly nonmonotonic. The comparison of the pair correlation function (measured in the experiment for

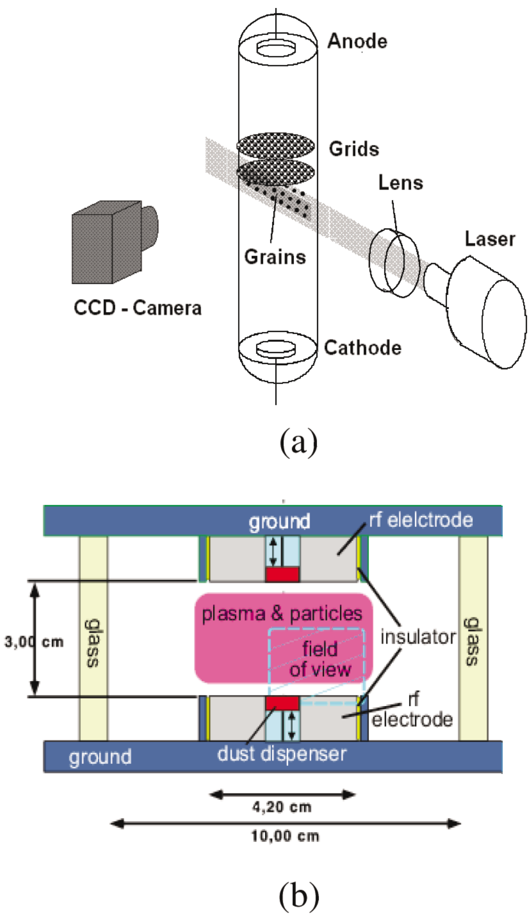

FIG. 3 (color online). Sketch of the experimental setup for the dc (a) and rf (b) discharge experiment under microgravity conditions.

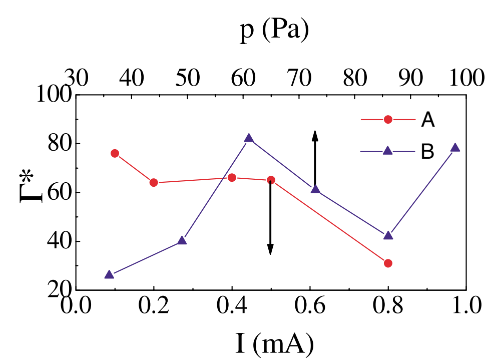

FIG. 4 (color online). The dependence of the effective coupling parameter Γ^* estimated from dust diffusion measurements on the discharge current in the dc discharge [curve (*A*)]; on neutral gas pressure in the rf discharge [curve (*B*)].

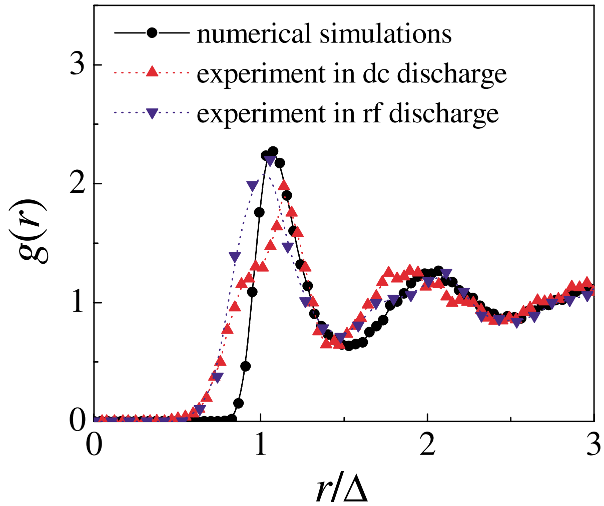

FIG. 5 (color online). The measured pair correlation function $g(r)$ vs the normalized distance r/Δ for the retrieved effective coupling parameter $\Gamma^* \sim 80$ for experiments in dc (▲) and rf (▼) discharges. Symbols (●) represent the numerical result for Yukawa systems at $\Gamma^* = 77$.

$\Gamma^* \sim 80$) with the results of numerical simulations is shown in Fig. 5. The estimated dissipation parameter increases with neutral gas pressure (mainly due to an increase in friction) from ~0.8 to ~1.3. The system is "highly dissipative."

We note that the measured particle kinetic temperatures were quite different in dc ($T_p \sim 10^5$ eV) and rf ($T_p \sim 0.4$ eV) discharges. While a difference is expected to be due to the large difference in particle masses (more than 5 orders of magnitude), the source of the kinetic energy supply (the energy is effectively dissipated through friction with neutrals) is not yet identified. This difference in temperatures is also the reason why the values of Γ^* for different experiments were in a similar range: It compensated large difference (~ 2 orders of magnitude) in particle charges, which was mainly due to the difference in particle sizes and electron temperatures.

Finally, we apply our complex plasma "diagnostics" to estimate particle charge Q and lattice parameter κ (plasma screening length). As the combination of these two parameters enters into the determination Γ^* they cannot be determined individually. We need to make a reasonable assumption about one of them to estimate the other. In the first (dc) case, the particle size is comparable with the ion Debye length and the ion mean free path ($l_i \sim \lambda_{Di} \sim 30$ μm). For this reason the orbit motion limited (OML) approach cannot be used to calculate particle charge (it requires the condition $l_i \gg \lambda_D \gg a$ to be satisfied, [14]). However, estimations of Ref. [12] suggest that in this case $\kappa \leq 1$. This is also in reasonable agreement with numerical investigation of a sheath structure around the particle [15], which shows that when the particle becomes large compared to λ_{Di}, the characteristic size of the sheath ("effective" screening length) can grow from λ_{Di} to several electron Debye lengths. Therefore, $\Gamma^* \approx \Gamma$, and the particle charge can be deduced from measurements. This gives $Q \sim 1.9 \times 10^6$ for all currents except for the highest one (0.8 mA), where $Q \sim 1.6 \times 10^6$. These estimates correlate well with the charge determined from an analysis of directed particle motion to the grids [12]. The dimensionless charge $z \equiv Qe^2/aT_e \sim 6$ is larger than OML predicts ($z_{\rm OML} \approx 2$).

In the rf discharge experiment much smaller particles were used, $l_i > \lambda_{Di} \gg a$. Then the OML theory can be applied as a first approximation yielding $Q \sim 5 \times 10^3$. The parameter κ (which varies nonmonotonically with pressure) is estimated to be $\kappa \approx 5 \pm 1$. This corresponds to $n_i \approx (1 \pm 0.4) \times 10^9$ cm^{-3} assuming room temperature for ions. Theses values of κ and n_i are in reasonable agreement with other experiments performed in similar devices as well as with plasma numerical simulations.

In conclusion, static and dynamical properties of microparticle systems in the liquid complex plasmas have been studied in experiments under microgravity conditions. Comparison with the results of numerical simulations of Yukawa systems was used to estimate the effective coupling parameter, which governs particles structural and dynamical properties. This diagnostic tool allowed us to estimate particle charge and plasma screening length, which are very important characteristics of complex plasmas.

This work was supported by RFBR Grants No. 01-02-16658 and No. 00-02-32281, by CRDF Grant No. RP2-2250, by INTAS Grants No. 2000-0522 and No. 2001-0391, and by DLR/BMBF Grant No. 50WM9852. The authors wish to acknowledge the excellent support from the PKE team (see Ref. [13]).

*Email address: skhrapak@mpe.mpg.de

[1] J. H. Chu and Lin I, Phys. Rev. Lett. **72**, 4009 (1994).
[2] H. Thomas *et al.*, Phys. Rev. Lett. **73**, 652 (1994).
[3] A. M. Lipaev *et al.*, JETP **85**, 1110 (1997).
[4] Y. Hayashi, Phys. Rev. Lett. **83**, 4764 (1999).
[5] G. E. Morfill *et al.*, Phys. Rev. Lett. **83**, 1598 (1999).
[6] M. Zuzic *et al.*, Phys. Rev. Lett. **85**, 4064 (2000).
[7] O. S. Vaulina and S. Khrapak, JETP **92**, 228 (2001).
[8] O. Vaulina, S. Khrapak, and G. Morfill, Phys. Rev. E **66**, 016404 (2002).
[9] O. S. Vaulina and S. V. Vladimirov, Phys. Plasmas **9**, 835 (2002).
[10] O. S. Vaulina and S. A. Khrapak, JETP **90**, 287 (2000).
[11] H. Totsuji *et al.*, Phys. Scr. **T89**, 117 (2001).
[12] A. P. Nefedov *et al.*, JETP **95**, 673 (2002).
[13] A. P. Nefedov *et al.*, New J. Phys. **5**, 33 (2003).
[14] J. Goree, Plasma Sources Sci. Technol. **3**, 400 (1994).
[15] J. E. Daugherty *et al.*, J. Appl. Phys. **72**, 3934 (1992).