Diffusion in Microgravity of Macroparticles in a Dusty Plasma under Solar Radiation

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Diffusion of macroparticles, charged by solar radiation in microgravity, is studied by analyzing experimental data obtained on the MIR space station. Temperature, velocity distributions, friction coefficient, and diffusion constants were obtained for bronze particles. A comparison of experimental and theoretical estimates shows that the dynamic behavior of the macroparticles for short observation times can be determined by observing the ambipolar diffusion.

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Problems associated with transport processes in dissipative systems of interacting particles are under discussion in the varied fields such as plasma physics, molecular biophysics, thermodynamics, physics and chemistry of polymers, etc. [1–4]. One basic transport phenomena is diffusion. Diffusion is a nonequilibrium mass transfer process caused by thermal motion of particles, which leads to a steady state of distribution of their concentrations and is one basic source of energy loss in real physical systems. Diffusion occurs in various regimes, for example, the Brownian diffusion of macroparticles suspended in a background gas, or the self-diffusion of particles. For clouds consisting of positive ions and electrons, the joint diffusion transport of oppositely charged particles (ambipolar diffusion) may appreciably influence the dynamic properties of the system. The case of ambipolar diffusion of low-ionized plasma in the absence of a magnetic field was surveyed by Shottky in 1924. The experimental observations of ambipolar diffusion without the attendant processes such as ionization or vortex currents are missing at the present time [3,5]. It should be noted also that direct measurements of diffusion constants based on an analysis of concentrations or mean-square displacements of particles exist only for specific cases (Brownian motion, the diffusion of thermalized electrons in the absence of an electric field) [2,3].

Most of the techniques for experimental determination of diffusion constants for ions, or electrons, are based on indirect measurements of a mobility of particles in the external electrical fields [3]. These techniques are unsuitable for diagnostics in plasma samples, as they contribute the significant perturbations in the studied systems. For diffusion measurements of weakly interacting macroparticles (molecules, colloidal solutions, viruses), photon correlation methods are widely used [2]. Application of these methods is restricted by the short-range order of the interparticle interaction, as the usual hydrodynamic and thermodynamic descriptions give a successful explanation for a diffusion of particles only in this case. When the forces of interaction are not so small, as in gases, the construction of correct kinetic equations fails. Thus, the basic problem is determining values of the interparticle interaction for which these approaches are valid.

A good experimental model for a study of transport phenomena in the systems of interacting macroparticles is a dusty plasma. A dusty plasma consists of neutral gas, ions, electrons, and micron-size particles (dust). Owing to their size, the dust particles can be recorded by a videocamera, which considerably simplifies application of direct methods for their diagnostics. A low-ionized dusty plasma can be considered as a dissipative system of particles interacting with a model Debye-Huckel potential [6–8]. The phase state of these systems is closely related to the dust diffusion [4,8] and may be qualified by the ratio of the energy of electrical interaction to a kinetic temperature T_p of the particles through the Coulomb Γ, or modified Γ^*, coupling parameters. The results of numerical studies have shown that the macroparticles have a gaslike structure when $\Gamma = (eZ)^2/l_pT_p < 1$ and can form a solid for $\Gamma^* = \Gamma(1 + \kappa + \kappa^2/2)\exp(-\kappa) > 106$ [6–8]. Here, Z is the dust charge in elementary charges e, $l_p = (n_p)^{-1/3}$ is the mean interparticle distance, n_p is the dust concentration, $\kappa = l_p/\lambda$, and λ is the screening length.

In this Letter, results of an experimental study of diffusion of dust particles, charged by photoemission under microgravity conditions, are presented. The data were obtained during complex investigations of dusty plasma induced by solar radiation on the MIR space station, and this has shown that under the action of intensive solar radiation the micron-size particles can acquire considerable positive electric charges [9]. The experimental study of dust diffusion was performed for bronze particles with the mean radii $a \cong 37.5$ μm in background gas (neon) at the pressure $P \cong 40$ Torr. The particles were contained in a cylindrical glass tube, the bottom of which was the uviol window intended for the solar irradiation of the dust cloud. Extra irradiation of particles by a laser beam was used for improved diagnostics. The image was registered by a videocamera with the field of view $\sim 8 \times 9$ mm; the definition in depth was about 9 mm (see Fig. 1). Subsequently, videorecords were handled by a special program for the identification of the displacement of separate particles. Under solar radiation, the number of recorded particles was determined by the definition in depth of the videosystem, which allowed tracing positions of particles during times sufficient for the analysis of dust dynamics. The number of identified

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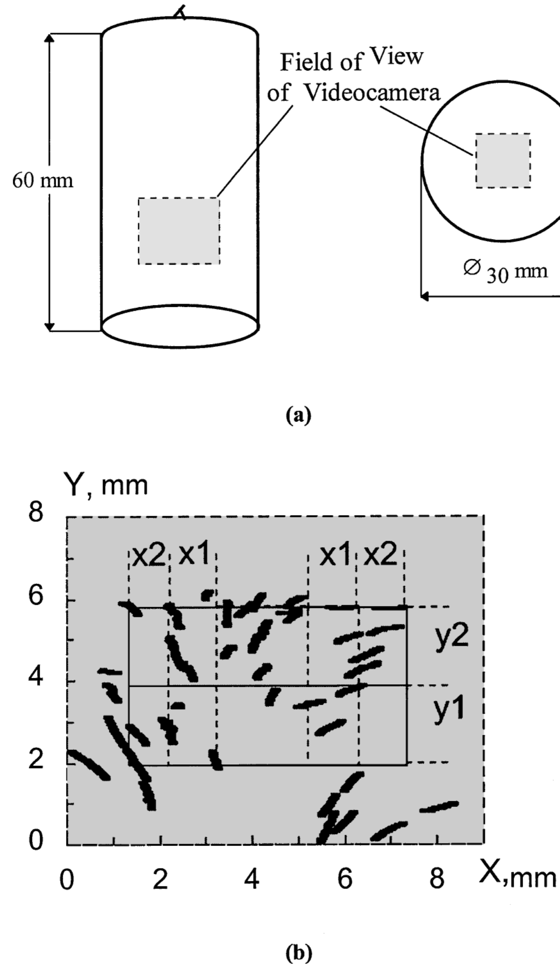

FIG. 1. The geometry of the glass tube (a) and trajectories of dust motion (b) after the action of solar radiation.

trajectories was less than 40% of the total number of particles present at the initial moment of time.

The first step of the experiments was the observation of dust particles without the action of solar radiation. During the observations (~20 min), the number of particles in the field of view of the videosystem did not vary significantly. The second step was the observation of macroparticles while irradiating the dust cloud with solar radiation. In an initial state, the bronze particles were on the walls of the tube. Therefore, the experiments were carried out under the following plan: (i) dynamic action (jolt) on the system with the closed window; (ii) exposure in darkness ~ 4 s $\gg \nu_+^{-1}$ (ν_+ is the frequency of the collision of dust with the gas molecules) to reduce initial dust velocities; (iii) irradiating the tube by solar radiation; (iv) relaxation of the particles to the initial state (leaving to the ampoule walls) for the time ~3–5 min. This interval is about 3 orders of magnitude shorter than the time for full diffusion losses of particles at room temperature for their Brownian motion.

The experiments were performed 3 times. The initial dust concentration n_o was varied from 195 to 300 cm^{-3}. The dependencies of the relative dust concentration $n_p(t)/n_o$ on the time t are shown in Fig. 2. The photo-

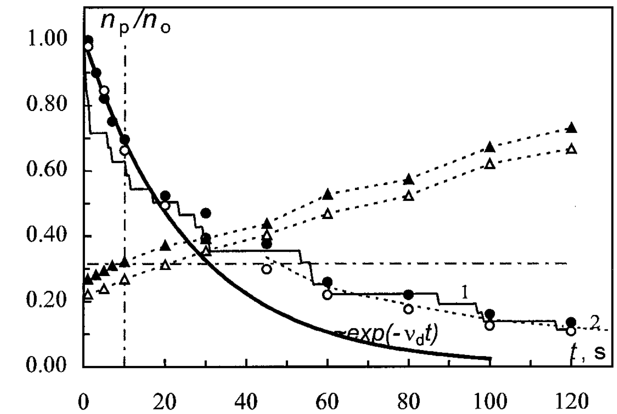

FIG. 2. Dependencies of relative concentration n_p/n_o (○; ●) and the ratio of λ/R (△; ▲) versus time t for the different initial concentration n_o: (●; ▲) 195 cm^{-3}; (○; △) 300 cm^{-3}.

emission charge of the particles was obtained from the approximations of the curves $n_p(t)/n_p(t = 40\text{ s})$ at $t > 40$ s by the method detailed in [9] and was close to $Z \approx 4 \times 10^4$ (±15%). Illustrations of the simulation of dust transport due to the mutual Coulomb repulsion of particles by the molecular Brownian dynamic method (curve 1) and its analytical approximation (curve 2), which was used for determining dust charge [9], are presented in Fig. 2 for conditions close to experimental ones. Velocities of the particles at the initial stage of irradiation were chaotic. Under solar action, the dust motion acquired a directed motion forward from the tube walls. For a time ~3 s after the beginning of solar irradiation, the dust stochastic kinetic energy is increased, and the interparticle correlation changed. The pair correlation functions of particles obtained by the exclusion of interparticle distances less than $l_p/2$ are shown in Fig. 3. These functions may not be suitable for quantitative analyses of the phase state of the dust structure, but they are reflected in the qualitative changes in the system. According to numerical calculations, the stabilization time for correlation in the dust cloud with $\omega_o/\nu_+ \ll 1$ [$\omega_o = Ze(n_o/m_+)^{1/2}$, and

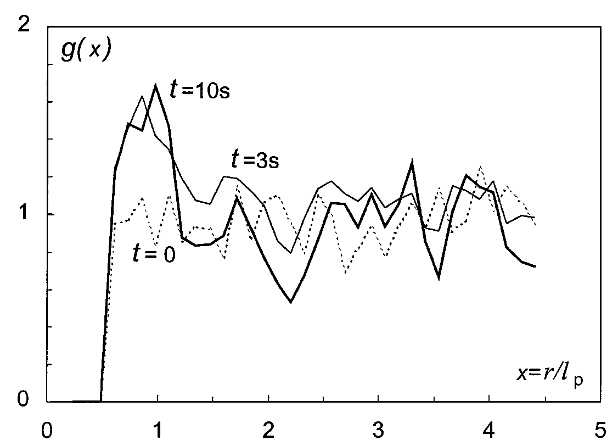

FIG. 3. Pair correlation function $g(x)$ versus $x = r/l_p$ for several observation times t.

m_+ is the mass of dust particle] is close to the time of thermalization of the system $\tau_{\rm Maxw} \cong \nu_+/4\pi\omega_o^2$, which in our case is ~4–6 s [3,9].

Trajectories of 40 particles (for 5 s after the beginning of solar irradiation) are shown in Fig. 1b. Irregular fluctuations of velocity (V_x, V_y) of the separate particles on a background of their total drift motion reflect the dust temperature T, which for Maxwellian distribution can be obtained from

$$T_{x(y)} = m_+\{\langle V_{x(y)}^2\rangle - \langle V_{x(y)}\rangle^2\}, \quad (1)$$

Here, $\langle\,\rangle$ is the averaging of velocities on the time, and $\langle V_{x(y)}\rangle = V_d^{x(y)}$ is the regular drift velocity. Determining the dust temperature from Eq. (1) for the various experiments with the number of identified macroparticles ~20–80 gives $T_x \cong 51$ eV, $T_y \cong 22$ eV, within 5%. The velocity distributions $f(V_x), f(V_y)$, both in the direction of the OX axis and in the OY direction, were close to Maxwellian for different areas of ampoule (Fig. 4). Similar nonuniform distributions of stochastic kinetic energy ($T_x \neq T_y$) and "abnormal heating" were observed in a number of other dusty plasma experiments and can be related to the temporally spatial fluctuations of dust charge, for example, due to the random nature of charging currents, or the spatial inhomogeneity of the system [10–15].

The temperature T_e^s of photoelectrons (which leave the particle's surface) depends on the material properties of the dust and, in most cases, is between 1 and 2 eV [16,17]. The temperature of electrons T_e in the dust cloud is different from their initial temperature T_e^s. So, in the absence of electric fields, an effective relaxation length of electron energy (reducing energy by ~2.72 times) for neon is Λ_u [cm] $\approx 10 - 12/P$[Torr] [3]. This value (~0.3 cm) at a pressure $P = 40$ Torr exceeds the mean distance $l_p \sim 0.15$–0.17 cm between the dust particles, which are background electron sources. Thus, the loss of electron energy on distances $\sim l_p/2$ is about 30% of their initial energy. The presence of electric fields reduces the loss of stochastic energy of electrons [3]. Therefore, for our further estimations, we shall assume that the value of T_e is significantly different from the photoelectron temperature at a dust surface.

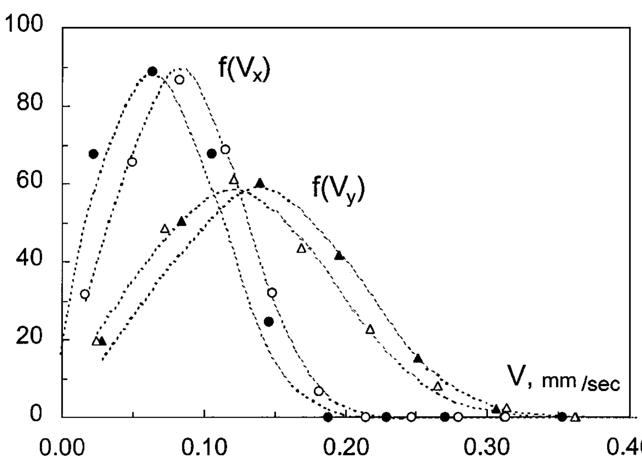

FIG. 4. Velocity spectra $f(V_x)$, $f(V_y)$ for different areas of ampoule which are marked in Fig. 1b: (△) $x1$; (○) $y1$; (▲) $x2$; (●) $y2$. The dotted lines show the approximation of experimental data by Maxwellian functions with $T_x = 51$ eV and $T_y = 22$ eV.

As the considered system consists of the positively charged macroparticles and the photoelectrons with the density $n_e \sim Zn_p$ emitted by them, it is possible to assume that the transport properties of this system will depend on ambipolar diffusion of the particles. Because of the large difference of mobility of electrons μ_e and dust μ_+, a negative surface charge appears on the tube walls. The incipient polarization electric field blocks further partitioning of the charged components. Therefore, the electrons and the heavy dust particles can diffuse "together" with some effective coefficient D_a of ambipolar diffusion [3,5]:

$$D_a = \{D_e\mu_+ + D_+\mu_e\}/\{\mu_+ + \mu_e\}. \quad (2)$$

Here, D_e, D_+ are the free diffusion constants for electrons and particles:

$$D_{e(+)} = T_{e(+)}/\nu_{e(+)}m_{e(+)}, \quad (3)$$

where $T_{e(+)}$, $m_{e(+)}$, and $\nu_{e(+)}$ are the temperature, the mass, and the frequency of collisions with the neutral gas molecules for electrons and dust, respectively. Then, in the case of $\mu_e \gg \mu_+$, the ratio of diffusion constants can be represented in the following form:

$$D_a/D_+ \approx 1 + ZT_e/T_+. \quad (4)$$

With the measured temperatures (T_x, T_y), the ratios of diffusion constants can be estimated as $D_a/D_+^x \approx (0.8–1.6) \times 10^3$, and $D_a/D_+^x \approx (1.8–3.6) \times 10^3$ for $T_e = 1–2$ eV.

The relations (2)–(4) are valid only for the case of a weakly ionized dusty plasma, when the dissipation is determined by collisions with neutrals of the background gas, and the collisions of charged components are negligible. On the other hand, ambipolar diffusion is determined by the polarization effects, which are impossible in a dilute plasma with a low density of charged components. In a plasma with density n, the diffusions have an ambipolar character when $\delta n = |n_e - n_+| \ll n \approx n_e \approx n_+$. For a cylinder with radius R, it is valid for $\delta n/n \approx (\lambda/R)^2 \ll 1$, where $\lambda^2 = T_e/4\pi e^2 n_e$ [3]. Taking into account that $n_e \approx Zn_p$, we have $\delta n/n \approx (2.1–6.4) \times 10^{-2}$ for the considered initial conditions $n_p = n_o$ under the assumption of $T_e \cong 1–2$ eV. The dependencies of λ/R on time are shown in Fig. 2 for $T_e = 2$ eV.

Assuming that for $\delta n/n < 0.1$ the losses of charges in our experiments are connected with their ambipolar diffusion to the ampoule walls, the area of ambipolar diffusion can be determined from the mean velocity of diffusion losses of macroparticles:

$$dn_p/dt = -n_p\nu_d, \quad (5)$$

where $\nu_d = D_a/\Lambda^2$ is the frequency of diffusion losses, and Λ is some diffusion length [3]. For a cylinder with radius R and height $\sim 4R$, the value of $\Lambda \approx R/2$. The value of ν_d can be obtained from the experimental curve $n_p(t)/n_o$ at $t < 10$ s, where the $n_p(t)/n_o$ function agrees well with the solution $n_p = n_o \exp(-\nu_d t)$ of Eq. (5) for $\nu_d \approx 0.035$ s^{-1} (Fig. 2). Then, an estimate of ambipolar diffusion gives $D_a \approx 2 \times 10^{-1}$ cm^2/s.

The free diffusion constants $D_+^{x(y)}$ can be retrieved from the measurements of dust temperature and drift velocity $V_d^{x(y)}$:

$$D_+^{x(y)}(t) = \{\langle \Delta r(t)^2 \rangle - (V_d^{x(y)} t)^2\}/2t\,, \qquad (6)$$

where $\langle \Delta r(t)^2 \rangle$ is the mean-square displacement of separate particles in the direction of axis OX (or OY). Experimental dependencies of $D_+^{x(y)}$ for the same areas of the tube, together with their averages of the different measurements, are presented in Fig. 5. Thus, the values of free diffusion constants can be estimated as $D_+^x \approx 1.3 \times 10^{-5}$ cm^2/s and $D_+^y \approx 5.7 \times 10^{-6}$ cm^2/s. The value of ratio $D_+^x/D_+^y \approx 2.28$ agrees very well with the measured dust temperature, and both measured ratios $D_a/D_+^x \approx 1538$ and $D_a/D_+^x \approx 3509$ are in agreement with the theoretical prediction (4).

Taking into account that, in the case of negligible interparticle interaction, the functions $D_+(t)$ have to reflect Brownian dust motion, the values of $D_+^{x(y)} = D_+^{x(y)}(t \to \infty)$ can be improved. Function $D_+(t)$ for Brownian motion is determined as [8]

$$D_+(t) = D_+\{1 - [1 - \exp(-\nu_+ t)]/\nu_+ t\}\,, \qquad (7)$$

where the value of D_+ corresponds to the relation (3). The best approximation of experimental dependencies $D_+^{x(y)}$ from the curves (7) for $\nu_+ = 3.1$ s^{-1} and $T_+^x \cong 51$ eV, $T_+^y \cong 22$ eV are shown in Fig. 5. Thus, the values of the free diffusion constants can be obtained as $D_+^x \cong 6.2 \times 10^{-6}$ cm^2/s and $D_+^y \cong 1.4 \times 10^{-5}$ cm^2/s. It is easy to see that the behavior of experimental functions is well compounded with dependencies for noninteracting Brownian particles. The difference of these functions for small times of observation can be explained by experimental measurement, or can reflect some small influence of the interparticle interaction on dust dynamics. The behavior of diffusion constants at the small times and at $t \to \infty$ for "liquid" dust systems was studied in [8].

In summary, complex measurements of velocity distributions, temperatures, friction coefficients, and diffusion constants of macroparticles in dusty plasma induced by solar radiation were carried out. The dust system under study represented a weakly correlated fluid with $\Gamma \sim 40$, and an interparticle interaction had a negligible effect on dust transport. The comparison of experimental data and theoretical estimates has shown that the dynamic behavior of macroparticles for $t < 10$–15 s can be determined by ambipolar diffusion. Finally, it should be noted that similar observations of ambipolar diffusion for charged macroparticles are not feasible under usual laboratory conditions because of the presence of gravity.

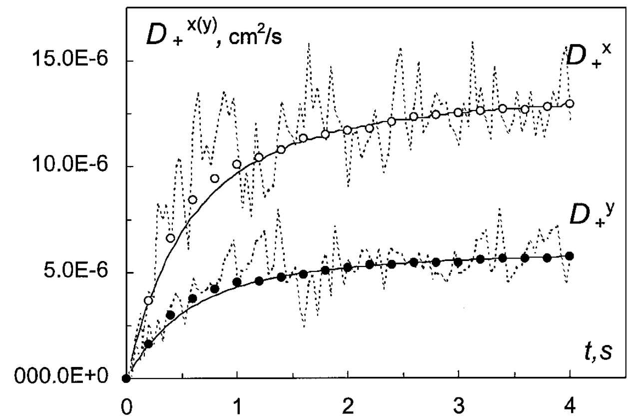

FIG. 5. Experimental dependencies of $D_+^{x(y)}$ (dotted lines) for the areas: $x1$, $y1$ (Fig. 1b), the average of $D_+^{x(y)}$ (○; ●) over the different measurements and their approximations (solid lines) by curves (6) versus time t.

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