Charge-fluctuation-induced heating of dust particles in a plasma

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Random charge fluctuations are always present in dusty plasmas due to the discrete nature of currents charging the dust particle. These fluctuations can be a reason for the heating of the dust particle system. Such unexpected heating leading to the melting of the dust crystals was observed recently in several experiments. In this paper we show by analytical evaluations and numerical simulation that charge fluctuations provide an effective source of energy and can heat the dust particles up to several eV, in conditions close to experimental ones. [S1063-651X(99)12110-X]

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I. INTRODUCTION

A dust particle immersed in a plasma acquires electric charge by collecting electrons and ions, and sometimes by emitting electrons [1]. When emission processes are unimportant the equilibrium charge is negative in order to equate electron and positive ion fluxes to the particle surface. The dust particle charge is of the order $Z_d \sim aT_e/e^2$ (where a is the particle radius and T_e is the electron temperature) and can be extremely high (for example, $Z_d \sim 10^3$ for $a = 1\ \mu$m and $T_e \sim 1$ eV). If the ratio of the energy of the intergrain interaction to the grain kinetic energy that is measured by the coupling parameter $\Gamma = Z_d^2 e^2/lT_d$ (where T_d is the dust temperature and $l \sim n_d^{-1/3}$ is the intergrain distance) is sufficiently large, formation of ordered structures of dust particles can occur, as was predicted by Ikezi [2]. The formation of Coulomb lattices in plasmas has been recently found in a number of experiments [3–8], including rf plasma devices [3–6], thermal dusty plasma under atmospheric pressure [7], and dc glow discharge plasma [8]. These special regular systems have been called plasma crystals or dust crystals. Due to the small relaxation times and the easy observability, dust crystals are an effective tool for investigating the properties of nonideal plasmas, the fundamental properties of crystals, and phase transitions.

Recently, during an investigation of the melting transition of dust crystals it was observed that the dust particle temperature associated with their chaotic translational motion can be unexpectedly high [8–10]. In view of the effective dissipation of dust particle kinetic energy through friction with the neutral gas it was always assumed that the dust particles attain the kinetic energy close to room temperature. However, measurements of the velocity distribution function of the dust particles in a rf discharge showed that as the pressure in the discharge decreases or the discharge power increases the enormous increase of the dust particle kinetic energy takes place. For example, in [10] the highest observed random kinetic energy was approximately 50 eV. This increase of the dust particles temperature forces the system from the solid to a fluid or even gaslike state by reducing dramatically the coupling parameter Γ.

The processes leading to the observed high particle temperature are discussed. In [10] it was assumed that dust particles forming a crystal in the sheath region of rf discharge gain energy from the supersonic ion flux directed toward the electrode. This idea was further developed in [11]. It was shown here that the special bilayer crystal with vertically aligned particles becomes unstable below a certain threshold of the neutral gas pressure. This instability is induced by ion streaming motion in the sheath and leads to the heating of dust particles. Another possible reason for dust particle heating was proposed in [12]. In this paper the heating is attributed to collective effects in the presence of the dependence of the dust particle charge on spatial coordinates.

In this paper we address another possible reason of particle heating—random grain charge fluctuations. These fluctuations are always present in dusty plasmas due to the discrete nature of currents, which charge the particles. Since the surface charge determines the interparticle Coulomb forces and external forces acting on the particles in a plasma (electric force and ion drag), its fluctuations lead to particles motion, i.e., they can gain kinetic energy via this process. To analyze the role of this effect we consider the conditions common for experiments in rf dusty plasma [3–5,9,10]. Namely, we assume that the dust particles are trapped in the sheath edge region (see Fig. 1), where there is balance between the gravitational and the electric forces acting on the negatively charged dust particles (thus neglecting ion drag, which is important for sufficiently small particles [13]). We first consider particle charging and the properties of random charge fluctuations in these conditions (Sec. II). Then we discuss the physics of particles heating by random charge fluctuations and evaluate the magnitude of the effect (Sec. III). The numerical simulation method used to model a system of particles with fluctuating charges is described in Sec. IV. The results of numerical simulations are discussed in Sec. V. Finally, we evaluate numerically the magnitude of heating in Sec. VI.

II. DUST CHARGING AND RANDOM CHARGE FLUCTUATIONS

In this section we consider an isolated spherical dust particle of radius a with a fixed position within the sheath. The particle is charged by collecting electrons and ions from the

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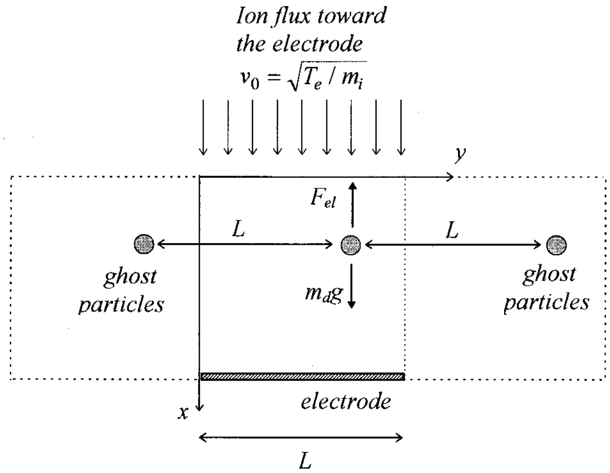

FIG. 1. Sketch of the simulation system showing a single dust particle confined in the sheath above a negatively biased electrode due to the balance between the gravitational and electric forces. Ions enter the sheath with Bohm velocity $v_B = \sqrt{T_e/m_i}$. The electric field grows from the sheath edge $E(x=0) \approx 0$ to $E = E_s$ at the electrode surface. Ghost particles due to periodic boundary conditions simulate a horizontal particle spacing of L.

plasma. Under the condition $a \ll \lambda_d \ll \lambda_{\mathrm{mfp}}$, where λ_d is the screening length and λ_{mfp} is a mean free path for electron–neutral-species or ion–neutral-species collisions, we can use the orbit motion limited theory [14] to describe the charging currents. In this simple theory the conservation of angular momentum and energy for collected electrons and ions is used to find the electron and ion collection cross section. Assuming Maxwellian distribution for electrons and cold ions moving with a velocity v_0 toward the electrode in the sheath region we have for the charging currents

$$I_i = \pi a^2 n_i v_0 \left(1 - \frac{2 Z_d e^2}{a m_i v_0^2} \right) \tag{1}$$

and

$$I_e = \sqrt{8\pi} a^2 n_e v_{Te} \exp\left(\frac{Z_d e^2}{a T_e} \right), \tag{2}$$

where $n_{e(i)}$ is the electron (ion) number densities and $v_{Te} = \sqrt{T_e/m_e}$ is the electron thermal speed. We have also assumed the negative charge Z_d and vacuum capacitance of a dust particle in a plasma $Z_d e = \phi_s a$, where ϕ_s is the particle surface potential with respect to the surrounding plasma. From Eqs. (1) and (2) the equilibrium charge can be found by equating $I_e = I_i$. Introducing the ratio $\tau = T_e/(m_i v_0^2/2)$ and the dimensionless charge $z = -(Z_d e^2/a T_e)$ $(z > 0)$ we arrive at

$$\exp(-z) = \sqrt{\pi/8}(n_i/n_e)(v_0/v_{Te})(1+\tau z), \tag{3}$$

We have treated the charging currents here as if they were continuous in time. This continuous charging model provides information about the equilibrium charge [Eq. (3)]. However, in reality electrons and ions are absorbed by the particle surface at random times and by random sequences. For this reason particle charge exhibits stochastic fluctuations superimposed onto the equilibrium value. Some studies appeared in recent years that addressed various aspects of charge fluctuations that arose from the random nature of the charging process in plasmas [15–18]. In our previous paper [18] we have obtained the useful characteristic of the random charge fluctuations—their temporal autocorrelation function (TAF). It was shown that independently of the charging mechanism, the TAF of random charge fluctuations has the form

$$\langle \delta Z_d(t) \delta Z_d(t') \rangle = \langle \delta Z_d^2 \rangle \exp\left(-\frac{|t-t'|}{\tau_c} \right), \tag{4}$$

where $\delta Z_d = Z_d(t) - \overline{Z_d}$, $\overline{Z_d}$ is the average particle charge and τ_c is the characteristic time of charge fluctuations. For the charging mechanism considered here,

$$\frac{1}{\tau_c} = \beta = -\frac{\partial}{\partial Z_d}[I_i - I_e]_{Z_d = \overline{Z}_d}, \tag{5}$$

where β is the natural decay rate of small charge variations and

$$\langle \delta Z_d^2 \rangle^{1/2} = [(I_i + I_e)_{Z_d = \overline{Z}_d}/2\beta]^{1/2} = \alpha \sqrt{|\overline{Z_d}|} \tag{6}$$

is the amplitude of random charge fluctuations. With the help of Eqs. (1) and (2) we obtain for charging in the sheath

$$\beta = \pi a^2 n_i v_0 \frac{e^2}{a T_e}[1 + \tau + \tau z], \tag{7}$$

$$\alpha = \left[\frac{1+\tau z}{z(1+\tau+\tau z)} \right]^{1/2}. \tag{8}$$

For numerical estimations we have made some simplifying assumptions about the sheath structure. We assume that the dust particles are trapped near the sheath edge, where ions are accelerated by a presheath potential drop $\Delta\varphi = T_e/2e$ to the ion acoustic velocity $v_0 = v_B = \sqrt{T_e/m_i}$ (Bohm criterion), so that $\tau = 2$. We also assume Ar plasma with parameters typical to the rf plasma experiments $T_e = 1$ eV and $n_i = 10^8\ \mathrm{cm}^{-3}$. Quasineutrality is assumed to hold up to the sheath edge, so that $n_i \approx n_e + |\overline{Z_d}| n_d$. The latter equation takes into account the possible effect of electron depletion in the dust cloud if dust particle concentration is sufficiently high. From Eqs. (3) one can see that the dimensionless charge z (and consequently α and β) is a function of the so-called Havnes parameter

$$P = \frac{a T_e}{e^2} \frac{n_d}{n_e} \cong 695 a T_e n_d / n_e,$$

where a is in μm and T_e in eV, which is roughly the ratio of the charge density of the dust particles to that of the electrons. When $P > 1$ (this can be expected for some experiments on dust ordering) the charge is significantly diminished, while for $P \ll 1$ the dust charge approaches the value for an isolated particle [1]. The values of z, α, and β for different values of P are summarized in Table I.

TABLE I. The values of z, α, and β for different values of P. a is measured in μm.

P	z	α	β (s^{-1})
0	3.9	0.46	$7.5\times 10^3 a$
0.5	3.1	0.50	$6.5\times 10^3 a$
1	2.8	0.52	$6.1\times 10^3 a$
5	2.0	0.59	$4.9\times 10^3 a$

III. PARTICLE HEATING BY RANDOM CHARGE FLUCTUATIONS

As it was mentioned in [16], charge fluctuations lead to a fluctuating intergrain potential that would have an effect similar to the random motion, additional to the thermal one. Thus, random charge fluctuations in a system of strongly interacting particles can heat the particles above neutral gas temperature (in spite of the effective cooling by neutral gas friction). In [19] it was assumed that the kinetic energy provided by charge fluctuations is equal to the fluctuation amplitude of the intergrain interaction energy, so that neglecting screening

$$T_f \sim \frac{|\overline{Z}_d|\sqrt{\langle \delta Z_d^2\rangle}e^2}{l}, \tag{9}$$

where $T \sim m_d\langle \nu_d^2\rangle/2$ is a temperature characterizing dust particle kinetic energy (m_d and ν_d are the dust particle mass and velocity, respectively). Estimation (9) seems to be insufficiently correct, because it is independent of dynamical properties of random charge fluctuations, and the neutral-gas cooling is not considered. We attempted to develop an analytical approach to this problem, which removes these uncertainties. Let the constant test charge $\overline{Z}_d$ be located inside a stationary system of charged particles with fluctuating charges $Z_{dj}(t) = \overline{Z}_d + \delta Z_{dj}(t)$. The force acting on the test charge (neglecting screening) can be written as

$$f = \overline{Z}_d e^2 \sum_j \frac{Z_{dj}(t)}{l_j^2} = \sum_j \frac{\overline{Z}_d^2 e^2}{l_j^2} + \sum_j \frac{\overline{Z}_d \delta Z_{dj}(t) e^2}{l_j^2}. \tag{10}$$

The first sum on the right-hand side of Eq. (10) is a potential function independent of time and does not result in heating of the system of dust particles, while the second sum can serve as a source of additional heating. The corresponding equation of motion of a test particle (Langevin equation) is

$$d\nu_d/dt = -\eta\nu_d + R(t), \tag{11}$$

where η is the friction frequency of a neutral gas and $R(t) = \sum_j \overline{Z}_d \delta Z_{dj}(t) e^2/m_d l_j^2$ is the random force arising due to charge fluctuations. The solution of Eq. (11) has a form

$$\nu_d(t) = \nu_d(0)e^{-\eta t} + e^{-\eta t}\int_0^t dt\, R(t) e^{\eta t}. \tag{12}$$

Assuming that charge fluctuations on different dust particles are uncorrelated and using Eq. (4) we obtain

$$\langle R(t)\rangle = 0$$

and

$$\langle R(t)R(t')\rangle = \sum_j \frac{Z_d^2 e^4 \langle \delta Z_d^2\rangle}{m_d^2 l_j^4}\exp(-\beta|t-t'|)$$
$$= A\exp(-\beta|t-t'|), \tag{13}$$

where $A \sim |\overline{Z}_d|^3 e^4\alpha^2/m_d^2 l^4$ according to Eq. (6). From Eqs. (12) and (13) the dust particles temperature associated with random charge fluctuations can be determined

$$T_f = \frac{m_d\langle \nu_d^2(t)\rangle_{t\to\infty}}{2} = \frac{m_d A}{2\eta(\eta+\beta)} \sim \frac{|\overline{Z}_d|^3 e^4}{2m_d l^4}\frac{1}{\xi}, \tag{14}$$

where $\xi = \eta(\eta+\beta)/\alpha^2 \approx \eta\beta/\alpha^2$ if $\beta \gg \eta$. Equation (14) seems to be more exact than Eq. (9). For example, for very rapid charge fluctuations ($\beta\to\infty$) we have from Eq. (14) $T_f = 0$, illustrating the fact that the massive dust grains cannot respond to high frequency fluctuations. If the neutral-gas density is high enough ($\eta\to\infty$) we have also $T_f = 0$, because the kinetic energy transferred to the particles is totally dissipated by friction with the neutral gas.

In addition to mutual interactions, dust particles are under the influence of various external forces. For simplicity we assume that they are trapped in the sheath region by the balance between the gravitational $m_d g$ and electric force $Z_d eE$ (see Fig. 1). In a steady state $m_d g + \overline{Z}_d eE = 0$. However, due to random charge fluctuations a random force $f = eE\,\delta Z_d(t)$ acts on the particle. This random force causes the particle to vibrate in the direction of an electric field acquiring an energy from the field and losing energy through neutral-gas friction. Following the procedure outlined above we obtain for this effect

$$T_f \sim \frac{m_d g^2}{2|\overline{Z}_d|}\frac{1}{\xi}. \tag{15}$$

From Eqs. (15) and (14) one can see that the relative contribution of these two mechanisms to the particles heating is determined by $[m_d g/(\overline{Z}_d^2 e^2/l^2)]^2 \sim m_d^2 g^2 (a/l)^{-4} z^{-4}(T_e/e)^{-4}$, e.g., the squared ratio of the gravitational force to the force of Coulomb interaction between neighboring particles. For parameters used in Sec. II, the dust particle material mass density $\rho = 5$ g/cm^3 and $a/l \sim 10^{-2}$, it can be obtained that stochastic grain charge fluctuations in an external electric field [Eq. (15)] provide the basic source of dust particle heating if their radius exceeds approximately 1 μm.

Note that in obtaining Eqs. (14) and (15) we have neglected the so-called Brownian force arising from asymmetric molecular bombardment. Thus T_f represents the kinetic energy additional to the thermal one. The real dust particle temperature is $T_d = T_n + T_f$. In the absence of charge fluctuations the particles are in equilibrium with the neutral gas and $T_d = T_n$. Here after we assume that the effect of particle heating by charge fluctuations is important; $T_f \gg T_n$ thus neglecting Brownian motion. It is necessary to note also that Eq. (15) gives the energy for an isolated dust particle. This energy is concentrated in the direction of the external electric field (charge fluctuations do not change the particle energy in the direction perpendicular to the electric field). To study the effect of strong interaction between dust particles we have performed a molecular dynamic (MD) simulation of a system of particles with fluctuating charges. Moreover, a MD simulation allows us to study the role of confining potential (created by the gravity and electric field) on particle dynamics, as well as to test estimations (14) and (15).

IV. NUMERICAL SIMULATIONS

The numerical simulations have been carried out in two-dimensional (2D) geometry with the number of independent particles ranging from 50 to 300. The computation area was of square form with the side length L equal to about 50 intergrain distances. In order to simulate a system of trapped dust particles we apply a one-dimensional electric field in the direction of the x axis, which is linearly dependent on x: $E(x)=E_s x/L$ (E_s is the electric field at the electrode surface). Thus, the dust particles are trapped in a region near $x=x_0$ where $\overline{Z}_d eE(x_0)=m_d g$. We impose a periodic boundary condition in the y direction, which is perpendicular to the direction of the external electric field E (see Fig. 1). The assumed one-dimensional potential corresponds to real experiments at least in the central part of the experimental apparatus. For each dust particle the two-dimensional equation of motion is solved taking into account the pairwise interaction between dust grains, friction with the neutral gas, electrostatic force in the external electric field, gravitational force, and random fluctuations of a charge on dust grains:

$$m_d \frac{d^2\vec{r}_k}{dt^2}=\sum_j F_{\rm int}(r)\big|_{r=|\vec{r}_k-\vec{r}_j|}\frac{\vec{r}_k-\vec{r}_j}{|\vec{r}_k-\vec{r}_j|}-m_d\eta\frac{d\vec{r}_k}{dt}+\vec{F}_{\rm ext}. \tag{16}$$

The force of the intergrain interaction is taken in the form $F_{\rm int}(r)=-eZ_d(t)\partial\phi_D/\partial r$, where ϕ_D is the screened Coulomb potential with the screening length λ_d:

$$\phi_D=\frac{eZ_d(t)}{r}\exp\left(-\frac{r}{\lambda_d}\right). \tag{17}$$

Note that the interaction force is time-dependent due to charge fluctuations. Potential (17) corresponds to the static response of the surrounding plasma and can be used if $\omega_{pe(i)}\gg\beta$ [where $\omega_{pe(i)}$ is the electron (ion) plasma frequency]. According to Sec. II this condition is well satisfied for micron-sized dust particles. The external force is also time-dependent $F_{\rm ext}(t,x)=m_d g+eZ_d(t)E(x)$. The random fluctuations of a charge on dust particles are assumed to be uncorrelated. Fluctuations of each dust particle charge $Z_d(t)$ are simulated by a random value δZ with the Gaussian distribution, complying Eqs. (4) and (6), so that each time step charge is adjusted as follows:

$$Z_{d,i+1}=\overline{Z}_d+[(Z_{d,i}-\overline{Z}_d)+\delta Z\zeta](1-\beta\Delta t),$$

where $Z_{d,i}=Z_d(t_i)$, $t_{i+1}=t_i+\Delta t$, $\delta Z=\Delta Z_d\sqrt{2\beta\Delta t}$, and $\zeta=\sin(2\pi\chi_1)\sqrt{2\ln(1/\chi_2)}$ with χ_1 and χ_2 being random numbers distributed uniformly in [0, 1]. Initially charged dust grains are situated in random positions inside the computation area after which the process of self-organization starts. Finally, the system of dust particles forms several layers (the number of layers depends on the parameters of our system) parallel to the y direction coming to the quasistationary state. As we have neglected Brownian motion, the temperature of dust particles in a quasistationary state is determined completely by random charge fluctuations. The calculation time step Δt should be less than τ_c to simulate charge fluctuations accurately. We chose $\Delta t=\tau_c/20$. As usual, τ_c is the smallest time characterizing a system of charged dust particles [$\tau_c\ll\eta^{-1}$, $\tau_c\ll\omega_{pd}^{-1}=(4\pi n_d Z_d^2 e^2/m_d)^{-1/2}$]. This means that simulations with fluctuating dust charge require much more computing time than with the fixed one. This is a reason why the 2D approach was utilized with a relatively small number of dust particles.

V. RESULTS OF NUMERICAL SIMULATIONS

We observe the appearance of layers (up to six in our simulations) in a potential trap created by the gravity and electric field. The number of layers is related to the parameters of our system: the number of particles, screening length λ_d, and the value of E_s. For a constant E_s the increase of a number of particles or λ_d results in an increase of the effect of mutual repulsion, and the thickness of particle distribution in an x direction increases. We observe that the increase of the thickness is realized as almost discrete steps of an increase of the number of layers at low temperatures. For example, an addition of a new particle for critical values of E_s and λ_d leads to an increase in the number of layers. The process of dust particle layers formation described here is similar to the experimental findings [3–6] where ~10 layers were observed, and is also similar to the results of three-dimensional numerical simulations of a Yukawa system in a one-dimensional external force field [20].

Two grain sizes, $a=5$ and 25 μm, were used to study the dynamics of dust particles in numerical simulations. The mass density was chosen to be $\rho=5$ g/cm^3. The friction frequency was assumed to be equal to $\eta\sim 25/a_{(\mu{\rm m})}$ (s^{-1}). This dependence corresponds to a pressure $P\sim 0.2$ Torr of a background gas Ar at room temperature. The equilibrium particle charge $\overline{Z}_d$ was assumed to be $\overline{Z}_d\sim 1.7\times 10^4$ for $a=5$ μm and $\overline{Z}_d\sim 8.7\times 10^4$ for $a=25$ μm. The screening length λ_d was taken equal to 450 μm. Variation of the particle kinetic energy was provided by the variation of the parameter ξ [entering into Eqs. (14) and (15)], that is, by variation of the frequency β and relative amplitude α of grain-charge fluctuations, as η has to be fixed to solve equation of motion (16).

We have found that the particle velocity distribution function is the anisotropic Maxwellian function, characterized by two temperatures (corresponding to different directions) $T_{d,x}$ and $T_{d,y}$. It should be noted that $T_{d,y}$ is always less than $T_{d,x}$. This is because the energy is supplied in our system basically in the direction of the external field (x direction). However, due to intergrain interaction (particles collisions) the particle kinetic energy in the y direction is not zero (recall that the Brownian motion was neglected). The dependence of the total particle temperature $T_d\equiv T_{d,x}+T_{d,y}$ obtained in the numerical simulation on the parameter ξ for a different number of layers and two particle sizes is shown in Fig. 2. In addition, analytical results for an isolated particle [Eq. (15)] are plotted. One can see that the total grain tem-

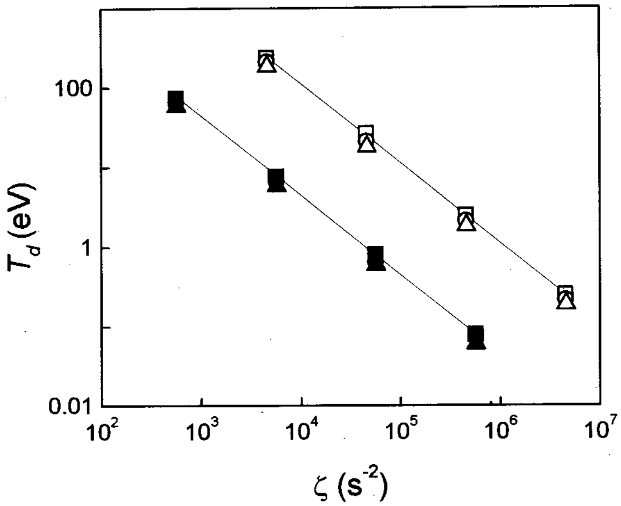

FIG. 2. Total kinetic energy (obtained from numerical simulations) versus ξ. Symbols are □—one layer, ○—three layers, and △—six layers for particles with $a=25\,\mu$m; ■—one layer, ●—three layers, and ▲—six layers for particles with $a=5\,\mu$m. The solid lines are results of calculations [Eq. (15)] for these particles.

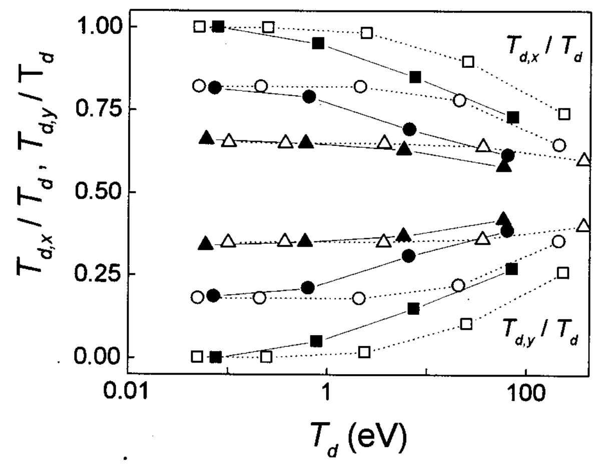

FIG. 3. The ratios of $T_{d,x}/T_d$ and $T_{d,y}/T_d$ versus T_d, showing a fraction of energy transmitted to the y direction due to interparticle interactions. Symbols are the same as in Fig. 2. Solid lines correspond to $a=5\,\mu$m, dashed lines correspond to $a=25\,\mu$m. Note, that in a case of six layers (strong interaction) the total energy is distributed almost equally between directions.

perature is close to the analytical value given by Eq. (15). Thus, Eq. (15) represents the basic source of heating. The deviation from the analytical result is maximum for six layers (strongly interacting system), and is about 25%. The Coulomb coupling parameter Γ can be determined from these simulations. For six layers ($l \approx 330\,\mu$m) Γ is varied from 13 ($\xi \sim 5\times10^2\,\mathrm{s}^{-2}$) to 1.3×10^4 ($\xi \sim 5\times10^5\,\mathrm{s}^{-2}$) for a particle with $a=5\,\mu$m, and from 140 ($\xi \sim 5\times10^3\,\mathrm{s}^{-2}$) to 1.4×10^5 ($\xi \sim 5\times10^6\,\mathrm{s}^{-2}$) for a particle with $a=25\,\mu$m. This allows us to suppose that relationship (15) can be used for a first estimation of the dust kinetic energy provided by random charge fluctuations in an external electric field in the case of strongly coupled particles too.

The ratios of $T_{d,x}/T_d$ and $T_{d,y}/T_d$ versus T_d are shown in Fig. 3. This figure demonstrates a fraction of the total particle energy transmitted to the y direction in different conditions. This transmission is due only to collisions between dust particles because the additional energy, determined by Eq. (14) is small. It is clear that the strong interaction between particles causes the strong distribution of kinetic energy between directions. For example, in a case of six layers, the total energy is distributed almost equally between x and y directions with an increase in T_d.

VI. CONCLUSION

We have shown that random charge fluctuations can effectively heat the dust particles in plasmas. The heating is attributed to (i) fluctuations of the intergrain potential of interaction in a strongly coupled system and (ii) fluctuations of external forces acting on the particles. We have considered a situation common for experiments in rf dusty plasma. In these experiments the system of strongly interacting dust particles can be trapped in a cathode sheath region where gravity is balanced by the external electric field [3–6]. The analytical results supplemented by numerical simulations show that the second reason for heating prevail in these conditions, if particles are not too small. Numerical evaluations of the magnitude of heating for conditions close to experimental can be made from Eq. (15) and Table I. We obtain that T_d is varied from approximately 0.1–0.3 eV for $a=5\,\mu$m, and from 1.7–8.3 eV for $a=25\,\mu$m with the increase of P from 0 to 5 (we choose ρ and η the same as used in numerical simulations). These energies are significantly higher than the thermal energy (~0.03 eV at room temperature). Thus, random charge fluctuations can be important when considering the reason for dust particle heating, observed experimentally [8–10]. This heating is important because it can lead to the melting of the dust crystals by reducing the coupling parameter Γ. The role of the effect considered increases with the increase of the dust particles size and concentration and with the decrease of the neutral-gas pressure.

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[1] J. Goree, Plasma Sources Sci. Technol. **3**, 400 (1994).
[2] H. Ikezi, Phys. Fluids **29**, 1764 (1986).
[3] J. H. Chu and Lin I, Phys. Rev. Lett. **72**, 4009 (1994).
[4] H. Thomas *et al.*, Phys. Rev. Lett. **73**, 652 (1994).
[5] A. Melzer, T. Trottenberg, and A. Piel, Phys. Lett. A **191**, 301 (1994).
[6] Y. Hayashi and K. Tachibana, Jpn. J. Appl. Phys., Part 1 **33**, 804 (1994).

[7] V. Fortov *et al.*, Phys. Rev. E **54**, R2236 (1996).
[8] V. Fortov *et al.*, Phys. Lett. A **229**, 317 (1997).
[9] H. Thomas and G. E. Morfill, Nature (London) **379**, 806 (1996).
[10] A. Melzer, A. Homann, and A. Piel, Phys. Rev. E **53**, 2757 (1996).
[11] V. A. Schweigert, I. V. Schweigert, A. Melzer, A. Homann, and A. Piel, Phys. Rev. Lett. **80**, 5345 (1998).
[12] V. Zhakhovskii, V. Molotkov, A. Nefedov, V. Torchinskii, A. Khrapak, and V. Fortov, Pis'ma Zh. Eksp. Teor. Fiz. **66**, 392 (1997) [JETP Lett. **66**, 419 (1997)].
[13] M. S. Barnes, J. H. Keller, J. C. Forster, J. A. O'Neil, and K. Coultas, Phys. Rev. Lett. **68**, 313 (1992).
[14] J. Allen, Phys. Scr. **45**, 497 (1992).
[15] G. Morfill, E. Grun, and T. Johnson, Planet. Space Sci. **28**, 1087 (1980).
[16] C. Cui and J. Goree, IEEE Trans. Plasma Sci. **22**, 151 (1994).
[17] T. Matsoukas and M. Russel, J. Appl. Phys. **77**, 4285 (1995).
[18] S. Khrapak, A. Nefedov, O. Petrov, and O. Vaulina, Phys. Rev. E **59**, 6017 (1999).
[19] G. E. Morfill and H. Thomas, J. Vac. Sci. Technol. A **14**, 490 (1996).
[20] H. Totsuji *et al.*, Phys. Lett. A **221**, 215 (1996).