VELOCITY DISPERSION OF DUST PARTICLES CONFINED IN A SHEATH

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Velocity distribution of dust particles localized in a plasma sheath near an electrode was found in a number of experiments. Velocity dispersion indicated that the kinetic temperature of dust grains significantly exceeds the temperature of plasma environment. Consequently, the question arose about the stochastic mechanisms of anomalous heating of grains. We propose the model in which the kinetic energy is due to the significant potential energy that grains have at the moment of their release from the crystalline structure on melting. Stochastic processes only modify the regular motion of dust grains, forming a velocity distribution similar to a Gaussian.

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INTRODUCTION

Already in the first experiments on melting of plasma crystals [1-4] it was observed that dust grains released from the crystalline structure move with considerable velocities. The motion of particles was recorded with high-speed cameras, and by processing shots a velocity of the grains was calculated. A velocity distribution function was built, and its form turned out to be close to a Gaussian [1, 2]. Quite unexpected was the fact that the "kinetic temperature", as a characteristic of this motion, could exceed the temperature of the surrounding plasma more than a thousand times.

From the first experiments, various statistical processes that could lead to dust particle heating in the transition from crystalline to gaseous phase were proposed. Among the most typical processes are electrostatic fluctuations of plasma environment, which were studied on a basis of the Langevin equation [5], and fluctuations of dust particle charge [6]. A discussion of various models of random processes is given in the recent paper [7]. The instability of dust grains due to modification of an ion flux by their neighbors, and the effects of negative friction caused by plasma particle absorbtion [8-11] were considered as well. These and other works show the complexity and versatility of physical processes in dusty plasma. Nevertheless, the consideration of various mechanisms did not distinguish the dominant process, which would explain the occurrence of anomalous "kinetic temperature" of grains.

In our paper, we draw attention to the fact that the considerable kinetic energy of particles can be caused not by stochastic processes but due to significant potential energy of grains in sheath and gravity fields at the moment of their release from a crystalline structure during melting. Stochastic processes only partially modify dust particle motion. The experimental evaluation of the fields [2] showed that a grain can gain significant kinetic energy. As well in the works [1, 2], it was not argued that high kinetic energy was obtained as a result of stochastic heating.

The potential energy that leads to the intense movement of particles can occur for two reasons. First, in the state of a crystal, when it as a whole occupies the lowest position in the potential well, each grain is in a position that does not correspond to equilibrium state of a free dust particle. Because of strong interaction with neighbors it is shifted from the position of the local equilibrium in sheath and gravity fields; and when melting, it begins to oscillate around this position. Secondly, the initial displacement from the state of the local equilibrium of a free dust particle is determined not only by neighbor particles but also by charge variation of a grain. Grain charges differ by a few percent [4], which means that their equilibrium positions are shifted to each other.

Estimation of grain kinetic energy can be obtained from the following considerations. For DC sheath the floating potential is of the order of

$$\varphi \sim \frac{1}{2}\frac{T_e}{e}\ln\frac{m_e}{m_i},$$

where T_e is an electron temperature, e-elementary charge, m_e and m_i are masses of an electron and ion; here we neglect the effect of grains on the floating potential. A depth of a potential well in which grains are confined is of the order of this magnitude. A charge of dust particle is four orders of magnitude higher than the elementary charge. Thus a grain with kinetic energy five orders of magnitude higher than electron temperature still is confined in a sheath. Kinetic energy of grain oscillations in RF sheath could be even greater. A particular magnitude of grain energy depends on an initial displacement of a grain from a position of its local equilibrium. In general, it looks reasonable that a kinetic energy of grain oscillations could be three orders higher than the electron temperature.

Thus, we suppose that grain intense motion could be caused by a potential energy of displacement from the position of its local equilibrium at the moment of crystalline structure melting. Along with this regular oscillations are modified by effects of various stochastic forces.

1. MODEL EQUATIONS

Based on these considerations, we shall take a simple model of oscillations of grains with slightly different charges in a parabolic potential well formed by superposition of potentials of homogeneous gravitational field and linearly increasing electric field of a sheath. In addition, we assume that motion of grains is influenced by either electrostatic fluctuations of plasma environment, or fluctuations of grain charge, and friction caused mainly by collisions with neutrals. Pair interaction with neighboring grains is neglected.

The equations of one-dimensional motion of a grain are of the form

$$\partial_t x = v,$$
$$\partial_t v = -g\cdot\delta - (1+\delta)\cdot E_0' \cdot x - \gamma \cdot v + E(x,t), \qquad (1)$$

where x is a displacement from a position that corresponds to the equilibrium of the grain with the average charge, v is a grain velocity; g is the gravitational acceleration, δ is a relative fluctuation of a grain charge from the mean value, γ is a friction coefficient. Acceleration of a dust particle is caused by the electric field of a sheath which linearly depends on grain displacement $E_0' \cdot x$. Electrostatic fluctuations $E(x,t)$ have the form of a superposition of harmonics with random phases α_i [12, 13], which propagate along the axis *x* with velocity *c*

$$E(x,t) = \sum_{i=1}^{N} E_i \cos(k_i(x-ct)+\alpha_i). \qquad (2)$$

We assume that initially grains are placed on the *x*-segment (-0.5, 0.5) and have zero velocity.

Our purpose is to find the velocity distribution function of grains in a potential well under influence of random force: either electrostatic fluctuations (2) or charge fluctuation δ. Our consideration is qualitative, and physical quantities are given in arbitrary units.

2. DISTRIBUTION FUNCTION OF GRAIN VELOCITIES

We start this section with illustrations of the individual motion of grains in absence of friction and electrostatic fluctuations. Phase space trajectories of arbitrarily ten particles with different initial charges are shown in Fig. 1 during the half-period of oscillation in the potential well (*t*=0, 10); the initial stage is represented by black solid lines. Grains move with different velocities, mainly to the center *x* = 0. But one of particles moves in the opposite direction. Another one, whose initial position turned out to be close to equilibrium point determined by its charge, is hardly moving.

The velocity distribution function of grains in the potential well for *t*=2 is shown in Fig. 2. We shall trace a change of its shape caused by turning on various effects. The velocity distribution function of grains with friction and equal charges is shown with gray points, line 1. The distribution function of grains with different initial charges is of triangular form (solid gray line 3), the friction makes its narrower (solid black line 2). Accounting for the electrostatic fluctuations (2) makes this distribution closer to a Gaussian, Fig. 3.

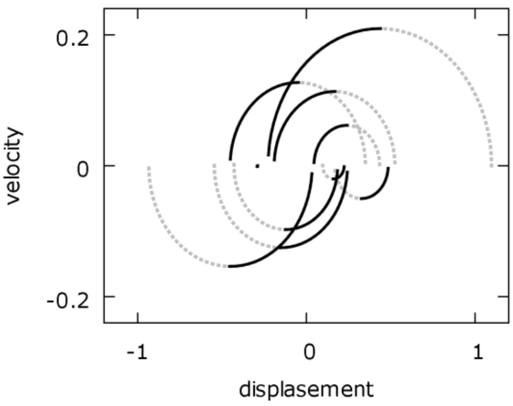

Fig. 1. Ten particle orbits in phase space during a half period of oscillation in the potential well, t = (0, 10). Particles in the potential well with initial charge variation (no electrostatic fluctuation, no friction). Initial stage is shown with solid lines

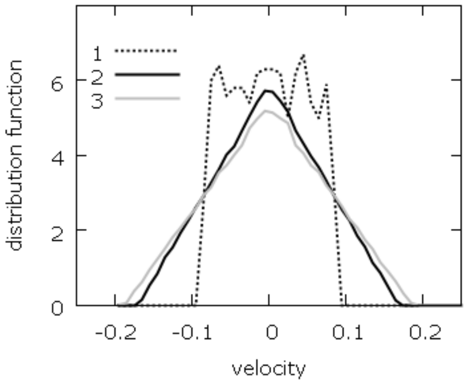

Fig. 2. Distribution functions at t =2. Grains with equal charges and friction (gray dot line 1); grains with different charges and friction (black solid line 2); grains with different charges without friction (gray solid line 3). Electrostatic fluctuations are absent

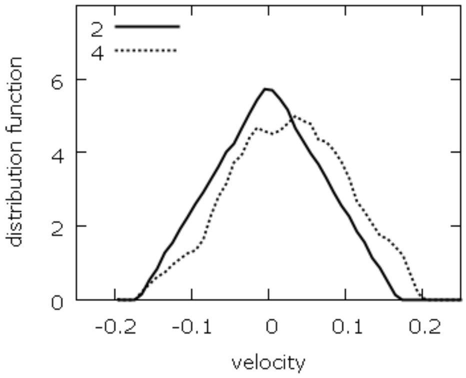

Fig. 3. Distribution functions of grains with different charges and friction. Electrostatic fluctuations are absent (2), present (4)

In this simulation electrostatic fluctuations were assumed to be a superposition of waves with a fixed set of random phases. The averaging was made over particle ensemble but not over random phases – the only one realization of the field was considered. In the next section it is compared with additional averaging over random phases. It can be expected that account for random interaction with neighbors, as well as averaging over random field realizations will further makes a form of a distribution function closer to a Gaussian.

Other process that effects on velocity distribution of grains is permanent fluctuations of their charge. The velocity distribution function with charge fluctuations is shown in Fig. 4 at two moments. Its form is rather close to a Gaussian. Such form of a grain distribution over velocities has been reported in the experimental works [1, 2].

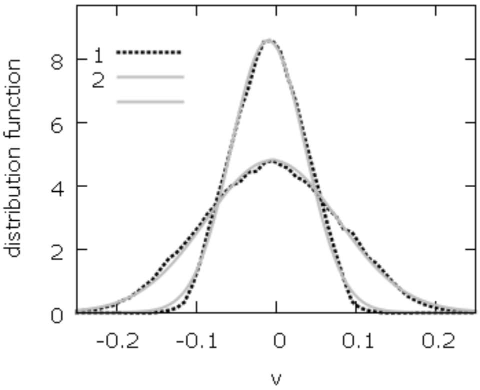

Fig. 4. Velocity distribution functions with charge fluctuations and friction (1), and their approximations with Gaussians (2); t = 1, 2

Thus, in the considered model a kinetic energy of grains is caused mainly by their oscillations in a potential well. Stochastic processes such as electrostatic or charge fluctuations only modify a distribution function bringing it closer to a Gaussian.

3. DIFFERENT ENSEMBLES OF AVERAGING

In the previous section the electrostatic fluctuations (2) were taken as a superposition of harmonics with *a fixed* set of random phases a_i (2). Averaging was made over ensemble of particles which are initially placed in different positions. However additional averaging over various realizations of electrostatic random fields could be done as well. In our model it corresponds to averaging over random phases. Snapshot processing to find the distribution function in experiments may be closer to one or the other method of averaging.

The difference between the results of averaging over ensembles of grains in the electrostatic fields with fixed and different sets of random phases is shown in Figs. 5, 6. The ensemble of random phases leads to a smooth dependence of an average velocity and velocity dispersion on time (black lines in Figs. 5, 6). In this approach, the dispersion of velocities may look like an effective temperature.

For a fixed set of random phases such dependencies (gray lines) are highly irregular. As far as they are not well-defined characteristics, velocity dispersion cannot serve as kinetic temperature of grains at all. Note, that the Langevin approach, which is often applied to a theoretical study of grain heating, is based on averaging over an ensemble of random phases.

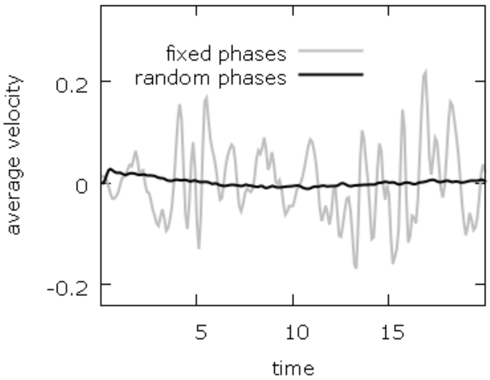

Fig. 5. Average velocity of grains in a potential well with electrostatic field fluctuations and friction. Field with fixed phases (gray line), additional averaging over field realizations, i.e. random phases (black line)

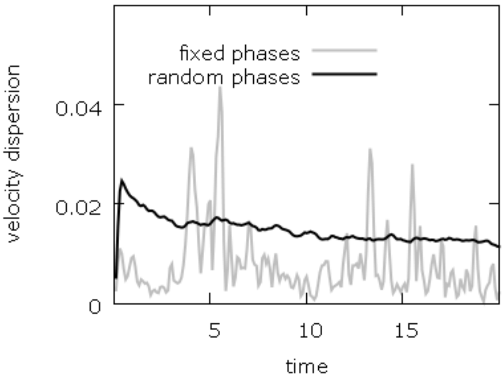

Fig. 6. Velocity dispersion of grains in a potential well with electrostatic field fluctuations and friction. Field with fixed phases (gray line), additional averaging over field realizations, i.e. random phases (black line)

CONCLUSIONS

We suggest that high velocities of dust particles that were observed in a number of experiments on melting of crystals are caused by a substantial initial potential energy of grains. In a crystalline structure a grain interacts strongly with neighbors which determine its location. At the same time a crystal as a whole occupies a position in which the gravitational force is balanced by an electric field of a sheath. On melting, the equilibrium positions of grains are determined by the balance of these forces individually for each particle. Since equilibrium positions of grains in a crystalline structure and after release from it do not coincide, grains start to oscillate. Motion of a grain displaced from an equilibrium position in a potential well is mainly regular. However, it is modified by stochastic processes, such as fluctuations of its charge and electrostatic fluctuations in the plasma environment.

Despite the stochastic forces may not be too strong, grain velocities look somewhat like random. Stochastic interactions make a velocity distribution function closer to a Gaussian. Nevertheless, it is not appropriate to characterize grain motion in terms of kinetic temperature.

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ДИСПЕРСИЯ СКОРОСТИ ПЫЛИНОК В ПРИПОВЕРХНОСТНОМ СЛОЕ

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В ряде экспериментов определялось скоростное распределение пылинок, локализованных в приповерхностном слое плазмы вблизи электрода. Дисперсия скорости указывала на то, что кинетическая температура пылинок значительно превышает температуру плазменного окружения. Соответственно возник вопрос о стохастических механизмах аномального нагрева пылинок. Предложена модель, в которой кинетическая энергия пылинок обусловлена значительной потенциальной энергией, которой частицы обладают в момент высвобождения из кристаллической структуры при плавлении. При этом стохастические процессы только модифицируют регулярное движение частиц, формируя распределение по скоростям, подобное гауссовому.

ДИСПЕРСІЯ ШВИДКОСТІ ПОРОШИНОК У ПРИПОВЕРХНЕВОМУ ШАРІ

В.І. Засенко

У ряді експериментів визначався швидкісний розподіл порошинок, локалізованих в приповерхневому шарі плазми поблизу електрода. Дисперсія швидкості вказувала на те, що кінетична температура порошинок значно перевищує температуру плазмового оточення. Відповідно постало питання про стохастичні механізми аномального нагрівання порошинок. Запропоновано модель, в якій кінетична енергія порошинок обумовлена значною потенціальною енергією, яку частинки мають у момент вивільнення з кристалічної структури при плавленні. При цьому стохастичні процеси тільки модифікують регулярний рух частинок, формуючи розподіл за швидкостями, подібний до гаусового.