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Random charge fluctuation effect on strongly correlated dust particles confined in two dimensions

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ABSTRACT

Random charge fluctuation effect is investigated for positively charged strongly coupled dust particles. The dust particles are moving in two dimensions and are confined by a parabolic potential. Using the Monte Carlo method, the effect of charge fluctuation is investigated for a finite number of *particles* interacting through a screened Yukawa potential. It is found that the charge fluctuation corresponds to an additional heating of the system giving rise to a change on the background configurations as well as on the melting characteristics.

1. Introduction

Understanding the physics of strongly coupled plasmas is one of the fundamental problems in the operation of inertial confinement based *on* thermonuclear reactors, power generating plants, plasma generators and powerful sources of optical and X-ray radiation [1]. Strongly coupled plasma includes ions cooled by laser radiation in electrostatic traps, crystallization of electrons at the surface of liquid helium and massive highly charged particles or dust. The latter are of special interests due *to* the diversity of the charging process. It is possible to have negatively charged strongly coupled systems as well as positively charged [2]. Exposed to *ultraviolet* (UV) radiation larger than the photoelectric work function the dust grains acquire positive charge, the same effect can also be obtained by thermionic emission. As a result dust grains are heated to high temperature and electrons and ions are emitted from the dust surface.

The properties of a finite number of charged particles in a single two-dimensional (2D) layer have been the subject of intensive theoretical and experimental investigations in the last decade [3]. Positively charged dusty plasma structure has gained great importance since the first investigation by Rosenberg et al. [4]. As a consequence of the strong Coulomb interaction between particles, it was shown theoretically and in laboratory experiments that these particles form a well organized structure known as dust Coulomb crystals [5,6]. Many experiences based on levitation in the sheath above a horizontal cathode were conducted to investigate background as well as phase transition in two-dimensional configurations, for both negatively and positively charged dust crystals [7,8]. Such (2D) dust crystals are governed by the type of interaction between particles and the confinement potential. One of the important parameters describing dust crystals is the ratio of the intergrain energy interaction to the grain thermal energy, measured by the coupling parameter $\Gamma = Z_d^2 e^2/(dT_d)$, where d is the inter-particle distance, T_d is the dust temperature and Z_d is the dust charge. Depending on the system dimensionality and for sufficiently large Γ, formation of ordered structures of dust particles can occur. 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.

However, in dusty plasma physics charging processes play a crucial role for the physical properties and for the existence of plasma which must be sustained by an external source to preserve the depletion of charged particles. The dust grains acquire charge by collecting or emitting electrons, positive as well as negative ions giving rise to highly charged particles which can reach $q \sim 10^4 e$. One of the important features which makes a dusty plasma different from other multi-species plasmas is the time dependence

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of the dust charge which is considered as a dynamical variable governed by the charge fluctuation equation. This effect has been widely investigated in different situations in dusty plasma such as expansion and waves [9,10]. The fluctuations are the result of turbulence or spatial and temporal variations due to collective effects responsible for the change of the plasma parameters. In this case, when the discrete nature of the charge is not neglected, the random aspect of the charging process can alter the dust motion by the intergrain potential which depends on the charge fluctuations [11]. This is common in *radio frequency* (RF) dusty plasma where the grains are confined in the sheath region [12]. Two-dimensional systems are observed when the transverse dimension is higher than the Debye screening length. In the *latter* systems, the effect of stochastic heating due to random charge fluctuation has been studied by Vaulina et al. Using molecular dynamics, this effect was associated with an effective source heating of dust crystal. As a result melting can be considerably affected by random collection of electrons and ions [13]. Dusty plasma produced by RF heated can *find* its energy increased up to several eV due *to* random charge fluctuation. The size of the dust is an effective parameter which *determine* the energy gain [14]. Using Langevin approach, Quin et al. investigated the effect of charge fluctuation in the presence of neutral gas. Heating provided by charge fluctuation is balance by cooling effect caused by neutral gas. Hence, particles temperature is subject to change. Such a model gave an explanation to the experimental large temperature observed in plasma crystal [15]. For situations close to RF dusty plasma experiments, the random charge fluctuation can effectively heat the dust particles by the fluctuation of intergrain potential or the external force fluctuation. The dust temperature in this case is higher than the thermal temperature. The temperature varies from 0.1 eV to 0.3 eV for dust particles with radius $a = 5$ μm and from 1.7 eV to 8.3 eV for $a = 25$ μm [16].

Previously, Astrakharchik et al. studied a two-dimensional classical cluster of dust particles. The particles, of constant charge at equilibrium, interact through screened Yukawa potential. Using numerical simulation background as well as melting properties have been studied. *For* such system the interaction is mainly governed by Debye screening length which plays a crucial role in phase transition [17]. The effect of finite temperature of the dust particles on the shell configuration has also be investigated using Monte Carlo simulation. For small clusters, the ground state configuration depends on the screening parameter [18]. Recently an increasing *interest* to the physics of positively charged dusty plasma is taken particular attention [19]. In this Letter the effect of random charge fluctuations on the background configuration is studied for positively charged two-dimensional dust crystals where particles interact through a screened Yukawa potential. Thermal properties of the system are investigated.

2. Theory

Let us consider a confined two-dimensional system of N identical positively charged dust grains. The dust particles of charge $q = Ze$ can be trapped by the background plasma. *They are considered mono-sized with spherical shape of radius a. In real cases, the dust grains have different sizes in space plasma and in laboratory experiments. For space plasma a continuous size spectrum ranges from macromolecules to rock fragments* [20]. *In laboratory dusty plasma, size variations can be eliminated experimentally by introducing monodispersive spherical dust particles* [21]. *To limit the confinement region*, an external parabolic potential V_c, tuned by the frequency ω_o, is applied,

$$V_c = \frac{1}{2} m\omega_o^2 r^2, \tag{1}$$

where m being the dust mass and r is the particle distance measured from the center of the confinement potential. The existence of dusty plasma needs the permanent presence of a neutral beam injection to sustain the system and to yield the quasi-neutrality which is accomplished by the presence of electrons and ions. We assume that the dust grains interact through the Yukawa potential which accounts for the screening effect caused by the background plasma. Thus, the Hamiltonian which gives the total energy is

$$H = \sum_{i=1}^{N} \frac{1}{2} m\omega_o^2 r_i^2 + \frac{e^2}{\epsilon} \sum_{j>i}^{N} Z^2 \frac{e^{-|\mathbf{r_i}-\mathbf{r_j}|/\lambda_D}}{|\mathbf{r_i}-\mathbf{r_j}|}, \tag{2}$$

where ϵ is the dielectric constant of the medium and r_i (r_j) is the distance of the ith (jth) particle measured from the center of the confinement potential.

The dimensionless form of Eq. (2) is obtained by the following normalization (Ref. [3])

$$\tilde{H} = H/E_o, \qquad \tilde{r} = r/r_o, \tag{3}$$

where $E_o = (q_o^2/\epsilon)^{2/3}\gamma^{1/3}$ and $r_o = (q_o^2/\epsilon)^{1/3}\gamma^{-1/3}$. The constant γ represents the one particle confinement energy $\gamma = m\omega_o^2/2$ and $q_o = Z_o e$ is the dust charge at equilibrium.

In reduced form the Hamiltonian of the system is rewritten as follows:

$$H = \sum_{i=1}^{N} r_i^2 + \sum_{j>i}^{N} Z^2 \frac{e^{-\kappa'|r_i-r_j|}}{|r_i-r_j|}, \tag{4}$$

where κ' is the dimensionless screening strength.

One of the interesting characteristics of the dusty plasma is the charge fluctuation. We investigate the effect of random charge fluctuation on particle configuration when the charging process is by emitting photoelectrons from the dust surface and provides a positive charge to the dust grains. Such situation occurs in the presence of strong ultraviolet radiation or fast electrons. The UV radiation provided by mini-arcs or deuterium lamps cannot ionize the background inert gas. The photon energy is above the work function for photoelectronic emission from the grain surface [4,8]. The corresponding emitted current is given by [6]:

$$I_p = \pi a^2 e J_p Q_{ab} Y_p e^{(-e\phi_d/T_{pe})}, \tag{5}$$

where J_p is the photon flux, $Q_{ab} \sim 1$ is the efficiency of the photon absorption, $Y_p = 1/2$ is the yield of photoelectrons, $\phi_d = eZ/a$ is the potential at the dust surface and T_{pe} is the average temperature of the emitted electrons.

Taken in consideration this current and due to the random aspect of the charging process, the instantaneous charge on each particle is different. In order to incorporate the charge fluctuation of the dust particles the Hamiltonian of Eq. (4) has to be modified as follows

$$H = \sum_{i=1}^{N} r_i^2 + \sum_{j>i}^{N} \left(1 + \frac{\Delta Z_j^l}{Z_o}\right)\left(1 + \frac{\Delta Z_i^l}{Z_o}\right) \frac{e^{-\kappa'|r_i-r_j|}}{|r_i-r_j|}. \tag{6}$$

The charge variation of the ith particle at the time step l is given by (Ref. [13]),

$$\Delta Z_i^{l+1} = \left[\Delta Z_i^l + \delta Z \xi\right](1 - \beta\Delta t). \tag{7}$$

The parameter ξ is

$$\xi = \sin(2\pi\chi_1)\sqrt{2\ln(1/\chi_2)}. \tag{8}$$

Where χ_1, χ_2 are random numbers uniformly distributed in the interval $[0,\ 1]$. The amplitude of the random charge fluctuations is $\delta Z = \sqrt{\nu_o \Delta t}$. In the case of photoemission and *using the quasi-neutral condition at equilibrium*, we have

$$\nu_o = 2\pi a^2 \left(\frac{8T_e}{\pi m_e}\right)^{1/2} Z_o n_d (1 + \alpha). \tag{9}$$