RESEARCH ARTICLE | JANUARY 05 2018

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AIP Conf. Proc. 1925, 020027 (2018)
https://doi.org/10.1063/1.5020415

Correlation Function of the Coupling Parameter in Dusty Plasmas

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Abstract. The paper presents a study of the coupling parameter, Γ of ordered structures in the dusty plasma and its dependence on the structural parameter κ. Investigations revealed that this dependence differs in different ranges of κ. If κ < 0.85, a strong interaction of dust grains was observed, whereas it is significantly weaker for κ > 1.4.

INTRODUCTION

The coupling parameter in a dusty plasma is defined as a ratio of the electrostatic energy of the interaction of charged condensed grains to their chaotic motion energy. Generally, calculations of its value depends on the nature of the grain interaction under plasma shielding conditions and for different types of a plasma (for example, collision or collisionless), the expressions for the coupling parameter have different forms. Interest in its properties increased significantly when studying charged particles in dusty plasmas, which are characterized by the presence of large charges. It was found that the nonideal interaction of grains causes a formation of spatially ordered structures [1], which are called "plasma crystals" [2]. The first estimates showed that the value of the coupling parameter can be represented in the form [3]:

$$\Gamma_0 = \frac{(eZ)^2}{4\pi\varepsilon_0 R_W T}, \tag{1}$$

where Z is the charge of grains, $R_W = (3/4\pi N)^{1/3}$ is the Wigner–Seitz radius, N is the grain number density, and T is the temperature of grain thermal motion.

Later, it was obtained that the coupling parameter depends on the structural parameter, which is defined as a ratio of the Wigner–Seitz cell radius to Debye screening radius, and this dependence is nonlinear. Attempts to improve the form of the expression for the parameter led to the equations [4]:

$$\Gamma^* = \frac{(eZ_d)^2}{4\pi\varepsilon_0 R_W T_d}\exp(-\kappa), \tag{2}$$

where $\kappa = R_W / r_D$ is the structural parameter, r_D is the screening length, T_d is the temperature of dust grains.

In order to use formula (2) over a wide range of variations of the parameter κ, corrections were introduced, which led to formulas (3) and (4) [5–9]:

$$\Gamma^* = \Gamma_0 (1+\kappa)\exp(-\kappa), \tag{3}$$

$$\Gamma^* = \Gamma_0 \left(1+\kappa+\kappa^2/2\right)^{1/2}\exp(-\kappa). \tag{4}$$

Nevertheless, the authors do not know the rigorous thermodynamic justification for formulas (3) and (4), as well as the field of their application. However, an analysis of the experimental and theoretical data shows that in different ranges of values of κ, the dependence can be described by various functions. Therefore, the analysis of the

Diverse World of Dusty Plasmas
AIP Conf. Proc. 1925, 020027-1–020027-4; https://doi.org/10.1063/1.5020415
Published by AIP Publishing. 978-0-7354-1617-8/$30.00

dependence of the coupling parameter on the structural parameter is carried out in order to determine the form of the function for different ranges of values of κ.

Of great practical interest in of dusty plasma investigations is the study of the melting curve (crystallization) equation Γ(κ). For a one-component plasma at κ = 0, it was shown that crystallization occurs at Γ = 106. If we measure the distance in units of Wigner–Seitz radius (*R*w), crystallization occurs at Γ = 172 [4].

Previously, an equation for the melting line in a one-dimensional dust grating was proposed [6]:

$$\Gamma e^{-\kappa}\left(1+\kappa+\frac{\kappa^2}{2}\right)=106 \quad . \tag{5}$$

In this case, the inverse frequency of oscillations for a one-dimensional dust lattice was used as a characteristic time scale. However, it should be noted that equation (5) applies to Yukawa systems, which do not always correspond to the real situation. First of all, this is due to the fact that vibrations of a one-dimensional dust lattice can be regarded as an approximation. In real systems, due to the nonlinearity of the ion–grain interaction and ion–neutral collision, the absorption of the plasma on the grains can lead to a noticeable deviation of the form of the real electrostatic interaction potential from the Debye–Huckel (DH) potential. In the general case, the deviation of the shape of the potential in the plasma from the DH potential is determined by various types of anisotropy. Especially noticeable are deviations at large distances, where the interaction is not screened exponentially, but decays according to a power law. In this case, it is necessary to distinguish between collisionless and collisional regimes. In a collisionless plasma, the screening dependence on distance is proportional to $1/r^2$, while in a plasma with collisions it is $1/r$. Thus, for example, a smoky plasma [10] should be considered as a Coulomb system of particles with an effective charge several times smaller than the actual one due to partial screening [11]. In this case, it is necessary to change from the potential DH to the long-range asymptotics [12].

RESULTS

In this paper, to study the functional dependence determining the phase diagram, it was suggested to write formulas (3) and (4) in the following form:

$$\Gamma=\Gamma_0\exp(-\kappa)f(\kappa). \tag{6}$$

The analysis of phase diagrams allows us to determine the correlation function *f*(κ) by formula:

$$f(\kappa)=\frac{\Gamma}{\Gamma_0}\exp(\kappa). \tag{7}$$

To determine the correlation function *f*(κ) over a wide range of the parameter κ, the phase diagrams given in [1–4] were used. The phase diagrams are shown in Figs. 1 and 2.

Consider the behavior of the correlation function *f*(κ) for the phase diagram shown in Fig. 1. To do this, we reconstruct Fig. 1 in linear (Fig. 3) and logarithmic (Fig. 4) coordinates.

Figure 3 shows that formula (3) is not applicable to describe the phase diagram. On the other hand, Fig. 4 clearly shows that the correlation function, *f*(κ) can be represented by the sum of two exponentials. As it follows

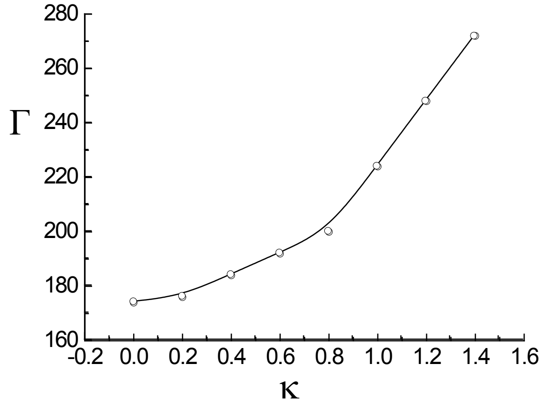

FIGURE 1. A phase diagram of the investigated system.

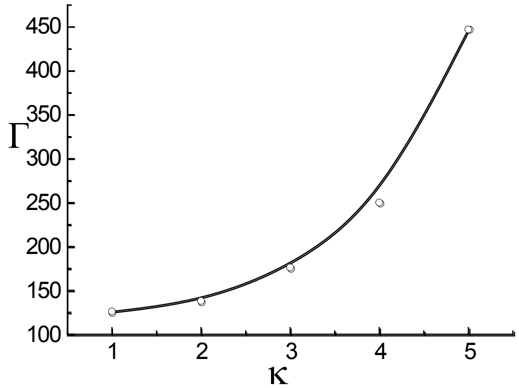

FIGURE 2. Another example of the phase diagram.

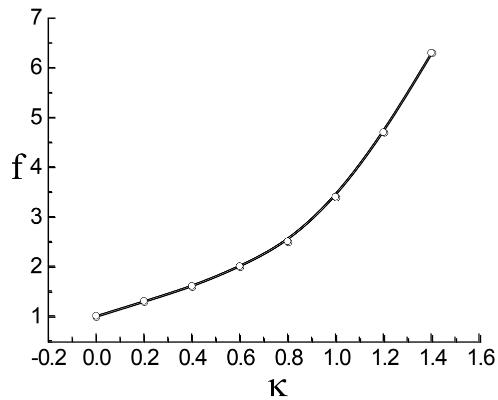

FIGURE 3. Correlation function, $f(\kappa)$ of the system corresponding to Fig. 1.

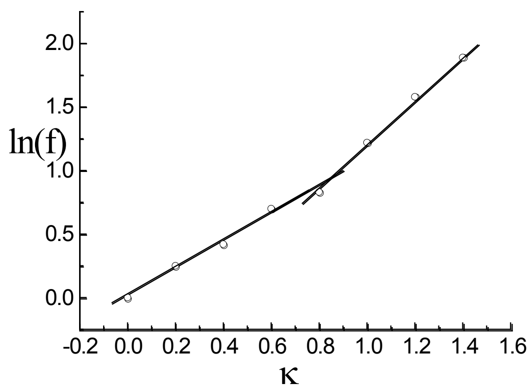

FIGURE 4. Correlation function, $f(\kappa)$ from Fig. 3 in logarithmic coordinates.

from the graph, the value of the parameter $\kappa = 0.85$ demarcates two distinct regions in the phase diagram. It can be shown that for $0 < \kappa < 2$, the exponent can be replaced by expansion in the parameter κ to a quadratic term. Then, in the region $0 < \kappa < 2$, the phase diagram can be represented by formulas:

$$0 < \kappa \leq 0.85 \qquad \Gamma^* = \Gamma_0 \exp(-\kappa)\left(1+\kappa+\kappa^2/2\right)^{1.21} , \tag{8}$$

$$0.85 < \kappa \leq 1.4 \qquad \Gamma^* = 0.85\Gamma_0 \exp(-\kappa)\left(1+\kappa+\kappa^2/2\right)^{1.6} . \tag{9}$$

Using the approach well known in thermodynamics of disordered systems, which makes possible to describe the sum of exponentials by a single exponential, the following formula was obtained.

$$\Gamma = \Gamma_0 \exp\left[(1.25\kappa)^{1.18} - \kappa\right] \tag{10}$$

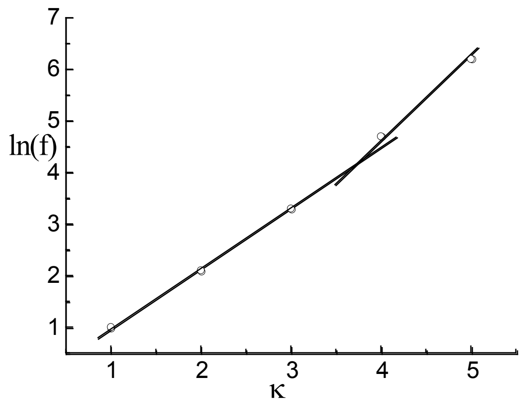

FIGURE 5. Correlation function, $f(\kappa)$ of the system corresponding to Fig. 2.

Next, we considered the phase diagram for κ > 1. In doing so, the phase diagram shown in Fig. 2 was constructed in semilogarithmic coordinates in Fig. 5. The analysis in Fig. 5 makes possible to distinguish the characteristic value of the parameter κ = 3.85. This value separates in the phase diagram two regions with different structural and energy characteristics of the plasma system. To describe the phase diagram over the entire range of variations of the parameter κ (Fig. 2), the following formula was obtained.

$$\Gamma = \Gamma_0 \exp\left[(0{,}92\kappa)^{1{,}21} - \kappa\right] \tag{11}$$

CONCLUSION

The conducted studies show that the nature of the dependence of the coupling parameter on the structural parameter in different ranges of κ values has a different character. This can be explained by a fact that when the parameter κ varies from 0 to 7, the properties of the plasma are significantly different. For example, for κ less than 0.85, the Wigner–Seitz radius takes values less than the Debye screening length. In this case, a strong interaction of charged grains occurs. In the range of values 0.85 < κ < 1.4, the interaction weakens, since the electrostatic potential at the boundary of the Debye sphere decreases. The electrostatic interaction of grains, when distances between grains are greater than the screening length (κ > 1.4) is significantly weakened, and therefore the nature of the dependence of the coupling parameter varies.

Taking into account the fact that the proposed correlation functions are constructed on the basis of processing a considerable number of experimental data, it seems correct to use them for analyzing the states of a dusty plasma.

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