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The interaction potential reconstruction in the dusty plasma and the influence of the trap

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Abstract

The effective pair-wise interaction potential is reconstructed by the Shommers technique on the basis of the measured pair correlation functions in complex plasma. This potential appears to have an attraction branch. We show that the field of the trap cannot be the only reason for this attraction.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

The problem of potential reconstruction for a system with known pair correlation function (PCF) or structure factor is one of the fundamental tasks of statistical physics (the so-called inverse task). There is a hypothesis that the behaviour of dust particles can be considered the same as the behaviour of the statistical microscopic particles system [1]. Thus the determination of the effective interaction potential between dust particles is also an important problem for the physics of complex plasmas.

The study of the inverse task in statistical physics started as soon as the first approximate solution of the direct task was obtained. For example, Percus and Yewick tried to reconstruct the potential in the same article where they obtained their well-known equation (i.e. PY-closure) [1]. Later, Kirkwood and PY approximations were used to reconstruct the effective pair-wise potentials for the metals [3]. But various closure relations appeared to give poor results for the inverse task. Below in figure 1 one can see that one more closure relation (HNC) gives an adequate solution of the direct task for the Yukawa-potential system, while the solution of the inverse task is far from the real potential. Consequently more complicated reconstruction techniques were developed [4, 5]. These algorithms were successfully applied to a number of real and model systems [6]. So it seems interesting to apply one of these techniques to the data of measurements in the dusty plasma.

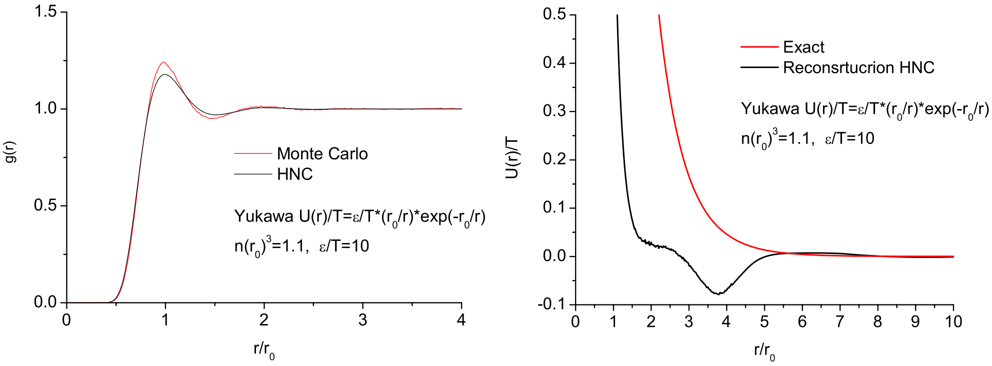

Figure 1. Left: the PCFs of the Yukawa system. Right: the interaction potentials.

Before proceeding with this task we have to make some remarks about the uniqueness of the reconstructed potential. At the gaseous phase the dependence of PCF on the potential generating this function is evident, because $g(r) \to \exp(-\Phi(r)/T)$ when the density approaches zero (here Φ is the potential, T is the temperature). But there are the density–temperature regions where different potentials can result in the same PCFs [7]. These regions as a rule are located in the liquid phase. Below we will consider both gaseous and liquid phases. If the system of dust particles can be described by the pair-wise effective potential, then this potential must be the same in both phases. Otherwise the system cannot be described by such a type of potential.

2. Theoretical relations

The details of the original reconstruction techniques are presented in [4–8]. The interaction potential is obtained by iterations. At first some initial potential must be given. In [4] it was $\Phi_0(r) = -T\ln(g_{\mathrm{exact}}(r))$ where $g_{\mathrm{exact}}(r)$ is the known (experimental) PCF. (Here and below the temperature T is measured in the energy units.) Then one can obtain $g_0(r)$ by Monte Carlo or molecular dynamic simulations with this initial potential. It was shown in [4] that the potential at $n+1$ iteration is

$$\Phi_{n+1}(r) = \Phi_n(r) + T\ln(g_n(r)/g_{\mathrm{exact}}(r)). \tag{1}$$

Every $g_n(r)$ is obtained by corresponding simulation with $\Phi_n(r)$. When $g_n(r)$ coincides with $g_{\mathrm{exact}}(r)$ the required potential is obtained. In [5] a more complicated scheme than (1) was used. The question of which scheme [4] or [5] is better is still open. But the principle is the same for both algorithms: the coincidence of simulated and exact $g(r)$ gives the solution of the inverse task. Scheme (1) was chosen earlier [8] and it is applied in the present work.

The Monte Carlo (MC) or molecular dynamic simulations usually use periodic boundary conditions. The trap allows us to use MC simulation without periodic boundary conditions. The trap field prevents the particles from running away [9]. Let the radius of the trap be R. Then the potential energy of the dust particles system is

$$V(r) = \sum_{i,j}\Phi(\vec{r_i} - \vec{r_j}) + \sum_i U(\vec{r_i}). \tag{2}$$

Here Φ is the pair-wise interaction potential, which must be defined; U is the field of the trap. In general the potential U makes the system inhomogeneous, i.e. $g(\vec{r}, \{U\}) = g(\vec{r_1} - \vec{r_2},$

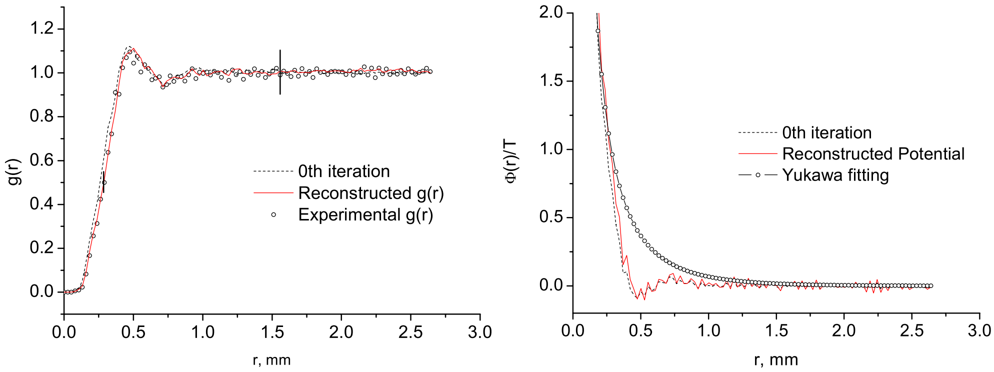

Figure 2. Left: the pair correlation functions for the 2D dust particles system $n = 486$ cm^{-2}. Right: the reconstructed potential for the 2D dust particles system.

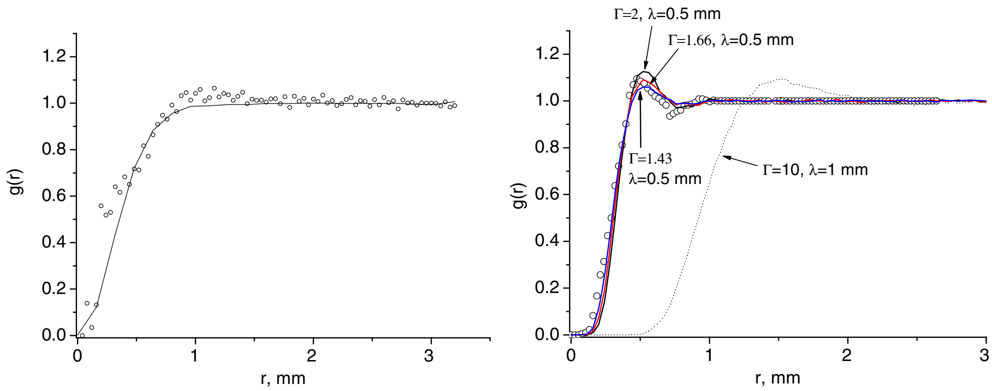

Figure 3. Left: the simulation with the trap at small density $n = 150$ cm^{-2}. Right: the simulation with the trap at high density $n = 486$ cm^{-2}.

$\{U \equiv 0\}) \rightarrow g(\overrightarrow{r_1}, \overrightarrow{r_2}, \{U \neq 0\})$. That is why we set $U = 0$ at $r < R$ and $U = \infty$ at $r > R$ (infinite well trap). As far as $U = 0$ inside the region of experiment we can consider the dust particles as a homogeneous system.

3. Results

In the following we will consider the 2D systems. Recently, the technique [4] has been used to obtain the interparticle potential in dusty plasma [8]. The potentials were extracted from the data of measurements [10]. It was shown that the potentials could have the attraction branch (see figure 2). One possible reason for this attraction is the influence of the trap field, which is always present in experiments with dusty plasma. In [10], the trap was a special ring mounted on the lower electrode. There are two sets of experiments in [10] (relative error 10%). (We denote them cases of 'small densities' and 'high densities'. The particle charge was estimated in [10] as $Z = 3000|e|$ and $3500|e|$ correspondingly.)

The presence of the trap can change the resulting $g(r)$. The analysis made in [8] (without trap) showed that the reconstructed potential for the correlation functions measured in [10] could have the repulsive as well as the attractive branches. The fitting of the repulsive branch in the case of high densities gave rise to the Yukawa potential $\Phi(r)/T = Q^2 \exp(-r/\lambda)/(rT)$, where $Q^2/(\lambda T) = 7.1$ and $\lambda = 0.5$ mm. This form of the potential is in qualitative agreement with the data of the measurements [11]. (It is the only experimental data on the dust particle potential known to the author.) At low densities the repulsive branch could not be fitted by a Yukawa-type potential. Now we will try to take into account the trap, supposing that the potential between the dust particles is of Yukawa type with $\lambda = 0.5$ mm. (Another λ value, for example $\lambda = 1.0$ mm, considerably shifts the PCF peak position, see figure 3.)

For the case of small densities the MC simulations with the trap gave rise to the experimental $g(r)$ at $\Gamma = Q^2/(\lambda T) = 1.1$. This value is close to the theoretical estimates made in [10], i.e. $\Gamma = 1.2$. The corresponding PCFs are presented in figure 3. The circles are the measured $g(r)$ and the lines are the results of our simulation with the trap. For the case of high density the MC simulation with trap could not give rise to the measured $g(r)$. None of the calculated $g(r)$ can reproduce the first maximum of experimental correlation function. The best value of the coupling parameter is $\Gamma = 1.66$.

Thus, the effective attraction between the dust particles cannot be explained by the influence of the trap only. The shadowing effects, the drag forces should be taken into account to obtain the correct effective pair-wise potential between the dust particles. This conclusion is confirmed by a recent 3D calculation [12] where these effects and forces have been taken into account.

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