*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-1.039 (2004)*

The numerical study of quasi 2d- dust structures

O. S. Vaulina, I.E. Drangevski, O. F. Petrov

Institute For High Energy Densities, RAS, Izhorskaya 13/19, 127412, Moscow, Russia

Abstract. Dynamics of macroparticles forming quasi 2d- fluid-like structures is numerically studied for pair potentials of Yukawa type. The parameters responsible for the phase state and mass transfer processes are determined and investigated.

The dusty plasma is an ionized gas containing micron-size charged dust grains (macroparticles). The most of experimental investigations of dusty plasma are performed in plasma of gas discharges. The non-emitted dust particles immersed in plasma acquire negative electric charges $eZ \sim 10^3e$ -10^5e that are responsible for the particle interactions. The best-known model for pair interaction of dust particles in plasma is based on the screened potential of Yukawa type: $U = (eZ)^2 \exp(-l/\lambda)/l$, where l is the distance, λ is the screening length. This model agrees with numerical and experimental results for distances $l < 4\lambda$ between two isolated particles in plasma [1, 2]. The combined effect of the particle interactions with the ambient plasma can lead to formation of three dimensional (3d-) or quasi 2d- strongly coupled dust structures (fluids or crystals). The quasi 2d- structures (which consisted from 1 to 10 dust layers) are typical for plasma of RF-discharge.

The main difficulty in the study of transport processes in strongly coupled systems is connected with the absence of analytic models in a fluid theory [3]. Two dimensionless parameters responsible for the mass transfer and phase state in 3d-dissipative Yukawa systems were found in [4,5] for $\kappa = l_p/\lambda < 6$, where l_p is the mean inter-particle distance. These parameters are: the "screened" coupling parameter $\Gamma^* = (Ze)^2\,(1+\kappa+\kappa^2/2)\,\exp(-\kappa)/(Tl_p)$, and the scaling factor $\xi = \nu_{fr}^{-1}\, eZ\,[(1+\kappa+\kappa^2/2)\,\exp(-\kappa)/(\pi m l_p^3)]^{1/2}$, where ν_{fr} is the friction coefficient, and T is the temperature of particles with the mass m. Thus, it was noticed that the dynamics of 3d- Yukawa systems for $\kappa < 6$ determined by the second derivative of the potential $U(l)$ at the mean interparticle distance l_p. It is thus naturally to expect that this property can be also fulfilled (with some corrections) for quasi 2d- Yukawa systems.

Here we present the numerical study of transport of macro- particles in single dust layer trapped in an external electric field. The calculations were performed by Langevin molecular dynamic method for particles in field of gravity (balanced by linear electric field ***E****(z)* = βz, where β is the value of gradient of electric field) with periodic boundary conditions in two anther directions (***x*** and ***y***) for N_p = 100 independent macro-particles with the cut-off of the pair potential equal to $8l_p$ and $\kappa \equiv l_p/\lambda = 2, 4$ (here $l_p = (N_p/S)^{1/2}$, where S is square of simulated sell). The simulation technique is detailed in [4,6].

The transport characteristics (pair correlation functions $g(l)$, and diffusion coefficients D) were calculated for various values of the effective dimensionless parameters introduced by analogy to 3d- Yukawa systems with some normalized coefficients (taking into account the difference between 3d- and 2d- problems), namely, the effective coupling parameter

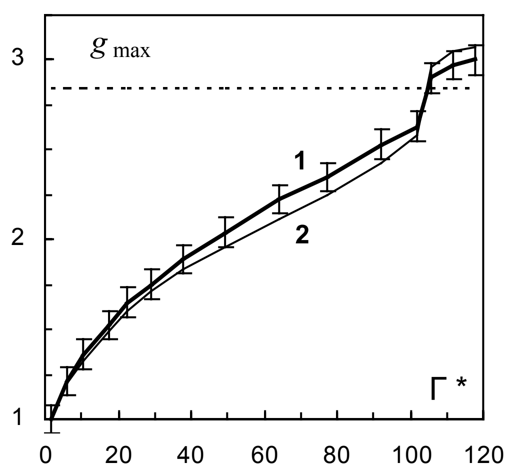
$$\Gamma^* = 1.5\,(eZ)^2\,(1+\kappa+\kappa^2/2)\exp(-\kappa)/T\,l_p, \qquad (1)$$

and the scaling factor $\xi = \omega^* / \nu_{fr}$, where

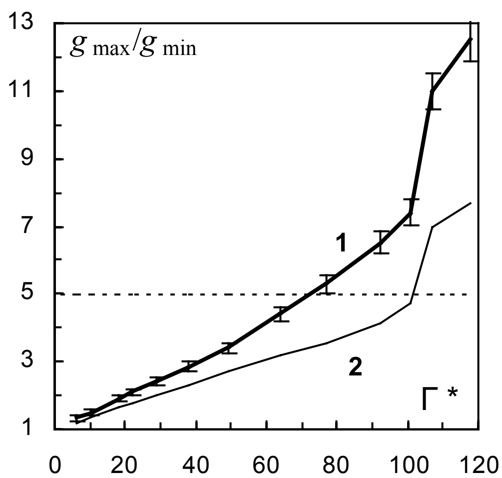
$$\omega^* = l_p^{-1} eZ\,[2(1+\kappa+\kappa^2/2)\exp(-\kappa)/(\pi m)]^{1/2}. \qquad (2)$$

The coupling parameter Γ^* is changed from 8 to 110, and the scaling factor is varied from $\xi \approx 0.04$ to $\xi \approx 3.6$, typical for conditions of complex plasma experiments.

The calculations show that the order in the system of macro-particles is practically independent on the friction (ν_{fr}) and on the value of gradient of electric field (β) and is determined by Γ^* for weakly correlated systems (Γ^*~10), as well as for stronger coupled structures up to the crystallization point Γ^*~102-104, where formation of hexagonal type lattice occurs for all cases investigated. In contrast to the phase state, the processes of the mass transfer in fluid systems are determined by two parameters: Γ^* and ξ (see Figs.1-3).



(a)



(b)

Fig. 1. Maximum g_{max} (**a**) of correlation functions and the ratio g_{max}/g_{min}. (**b**) vs Γ^*:
1- 2d- problem with deviations for different calculations; **2** - 3d- problem

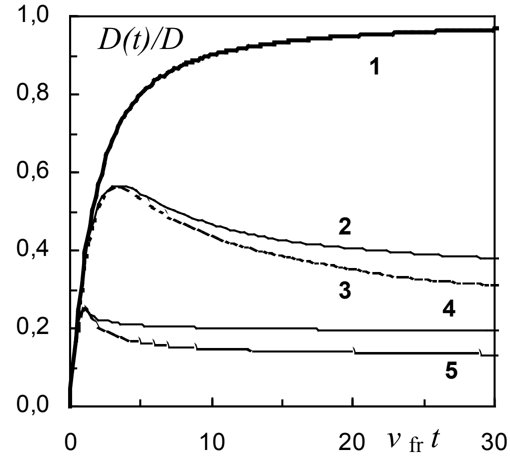


Fig. 2. Ratio $D(t)/D_o$ vs $t\nu_{fr}$ for:
1 - non-interacting particles;
2 - $\Gamma^* = 27$, $\xi = 0.93$; **3** - $\Gamma^* = 56$, $\xi = 0.93$;
4 - $\Gamma^* = 27$, $\xi = 0.23$; **5** - $\Gamma^* = 56$, $\xi = 0.23$

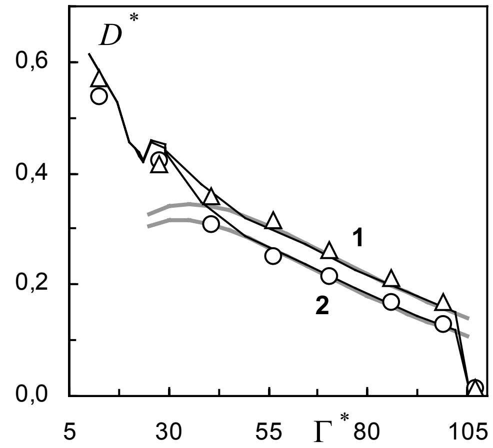


Fig. 3. Function D^* vs Γ^* for 2-d problem (Δ; O), (black lines) - D^* for 3d- systems [4], and an approximation of D^* (gray lines) by Eq. (4) for: **1** - $\xi \geq 1.86$; **2** - $\xi \leq 0.93$,

The first maximum g_{max} of pair correlation functions $g(l)$ and the ratio of g_{max} to first minium g_{min} of $g(l\neq 0)$ versus Γ^* are shown in Figs. 1a,b for quasi 2-d and for 3-d systems. In booth cases the melting point of lattices is observed for the effective factor $\Gamma^* \approx 106$, where the values of g_{max}, and g_{max}/g_{min} are abruptly changed and the diffusion coefficients D are rapidly reduced (about in ~ 5-10 times, see Fig. 3).

The diffusion coefficients can be obtained from the relation: $D(t) = \langle\langle(\Delta\mathbf{l}(t))^2\rangle_N\rangle_t/4t$, where $\Delta\mathbf{l}(t)$ is the displacement of an isolated particle from its initial position at the time t, and < > denote the ensemble (N) and time (t) average (the average is for all time intervals t). The $D(t)$ function at small time ($t\nu_{fr} \ll 1$) is close to the function for non-interacting particles: $D(t) = D_o\{1-(1-\exp(-\nu_{fr}\,t))/\nu_{fr}t\}$, where $D_o = T/(\nu_{fr}m)$. Then the $D(t)$ reaches its maximum (see Fig. 2), the magnitude D_{max} and position t_{max} of which are determined by the value of ξ and close to the D_{max} and t_{max} values for 3-d Yukawa systems.

With $t \to \infty$, the function $D(t)$ tends to its constant value D, which corresponds to the standard definition of the diffusion rate. Results of numerical simulation of the diffusion coefficient D for interacting particles are given in Fig. 3, where you can see the normalized function, $D^* = D(\nu_{fr}+\omega^*)m/T \equiv D(1+\xi)/D_o$ (averaged over all $\xi \approx 0.04$-3.65 under study). Deviations of this function for various ξ were within ± 5% for all analysed values of Γ^*. For comparison of our calculation with a diffusion in 3d- Yukawa systems we present in Fig.4 the results of numerical study [4], performed for $\kappa < 6$. Thus normalized D^* function is determined by the effective coupling parameter Γ^* for weakly correlated as well as for strongly coupled systems. In the case of a strongly coupled system (Γ^*> 40-50), the diffusion coefficient can be written by analogy with 3d- Yukawa systems [4]

$$D \cong \frac{T\Gamma^*}{12\pi(\omega^* + \nu_{fr})m} \exp\left(-c\frac{\Gamma^*}{\Gamma^*_c}\right), \tag{3}$$

where Γ^*_c =102 is the crystallization point, $c = 2.9$ for $\xi \geq 1.86$, and $c = 3.15$ for $\xi \leq 1.13$. The accuracy of this approximation, which for Γ^*>50 is just within 5%, decreases to that within 35% with decreasing parameter Γ^* down to the value of $\Gamma^* \approx 30$. Relation (3) allows experimental determination of Γ^* in a strongly coupled system from measurements of the mean interparticle distance l_p, temperature T, and diffusion coefficient D. For diagnostics of a weakly correlated system (Γ^*<50), the numerical calculations of D^*, see Fig. 3, can be used.

To conclude, here we studied the transport of macroparticles in quasi 2-d fluid-like structures. We have introduced generalized dimensionless parameters responsible for the particle correlations, Γ^*, and for the scaling of dynamic processes, ξ, in dissipative Yukawa systems. These parameters, together with the particle temperature, fully determine thermodynamic properties of the modeled quasi 2-d systems since they are responsible for the phase state as well as for the mass transfer processes. Finally, we note that results of the present study can be used to develop new methods of passive diagnostics of complex dusty plasma without disturbing the studied system.

This work was partially supported by the Russian Foundation for Fundamental Research (project no. 04-02- 16362), INTAS (project no. 2001-0391), CRDF (project no. RU-P2-2593-MO-04), by the Program of RAS Presidium and by the Russian Science Support Foundation.

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