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Transport in strongly coupled 2D complex plasmas: Role of the interaction potential

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The qualitative changes observed in the macroscopic behavior and properties of complex (dusty) plasmas are often a manifestation of critical processes occurring on the ``microscopic level'' due to modification of the interaction potential between the charged grains. In this Letter, we report on new experiments suggesting that the critical changes in the interaction potential can have a major effect on the transport in strongly coupled 2D complex plasmas.

The experimental observations of dust dynamics in a monolayer configuration presented here reveal anomalous dependence on neutral gas pressure. We find an ``immobile'' system at high gas pressures, then, decreasing the pressure, a state with dramatically enhanced transport, followed again by an ordered state. The intermediate state is found only in a *narrow* neutral gas pressure range where high grain mobility and large scale vortex flows coexist with partial preservation of the global hexagonal lattice. The dynamics of a such a state can be treated as viscoelastic [1]. Mechanisms responsible for the energy source driving vortical flows against the neutral gas friction must be due to nonpotential forces. The inhibited transport at higher pressures can, therefore, be explained simply by a threshold where dissipation on neutrals exceeds work done by these forces. However, the transition of the system back to an ordered state at *lower* pressures is intriguing indeed, since this contradicts ``conventional wisdom'' of dissipation on neutrals. The existence of such a threshold in the system can be explained by an increase of the *viscous* dissipation due to significant modifications of the interaction potential between the particles.

The experiment is performed in a capacitively coupled rf discharge operated in argon in a pressure range 2-5 Pa and rf power of 19 W. Injected 600 monodispersive Melamine-Formaldehyde spheres levitate as a monolayer in the sheath above the lower electrode. The grains are confined radially by the potential created by a cavity of 6 cm radius machined into the lower electrode. The particles are illuminated by a horizontal laser sheet and 30000 images are taken by a video camera at a sampling rate of 30 Hz. The cluster diameter is 16 mm with interparticle distance 0.6 mm.

At p=5 Pa the cluster is in an ordered state and particles hardly move. Decreasing the pressure by just 1 Pa we find an ordered state allowing large scale vortex flows as documented by Fig.1 in Ref.[1]. This state can be described as a viscoelastic fluid, which behaves like an elastic body on the short time and spatial scales and as a viscous liquid on larger scales [1]. Lowering the pressure even more results in a suppression of grain mobility and, finally, at p=2 Pa the state is ``immobile'' again and similar to that at p=5 Pa. Thus, the highly mobile state is found only in a very narrow pressure range around p~4 Pa. As mentioned in the introduction, in the following we attempt to explain the transition from 4 to 2 Pa. We stress that the *hydrodynamic* motion shown in Fig. 1 in Ref.[1] is not accompanied by noticeable changes in the kinetic energy of the particles and thus differs from conventional melting arising from increased temperature of caged particles (see e.g. Fig.1 of Ref.[2]). In our experiment such a phase transition has been observed at pressures below 2 Pa.

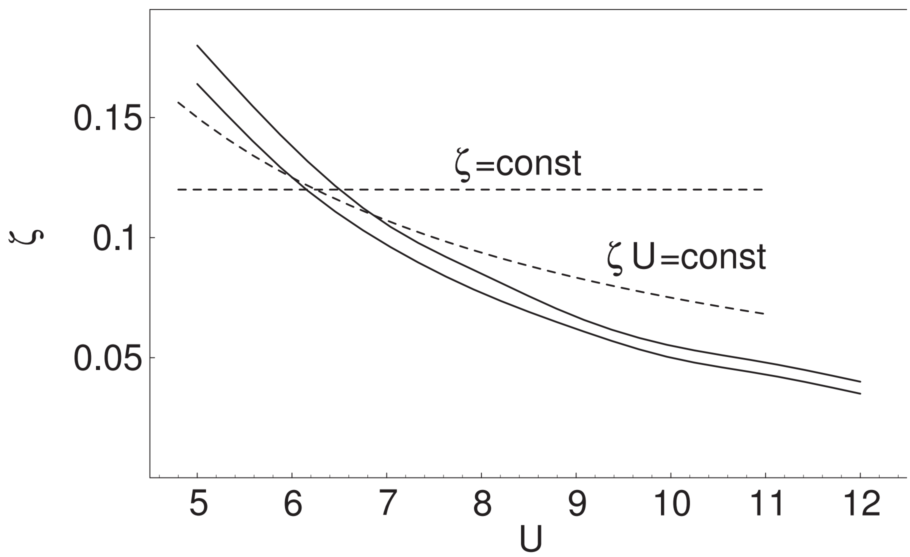

Fig. 1: *Regions of different shapes of the dust potential for τ = 0.012. When U and ζ are above the upper solid curve the potential is monotonic (repulsive). For U and ζ in the narrow region between the two solid curves the potential is nonmonotonic with attractive well but still positive. For U and ζ below the lower solid curve the potential is nonmonotonic and has a negative attractive well. Typical shapes of the potential corresponding to ζ U=const line are shown on Fig.3.*

The potential of a single dust particle is calculated in the framework of the linear approach [3]. We take the dielectric response function derived in Ref.[4,5] in the framework of the following model: (i) the ion component is described by the kinetic equation with the Bhatnagar-Gross-Krook ion-neutral collision term (i.e., with the ion-neutral collision frequency independent of the velocity), (ii) in the basic (unperturbed) state, we have a homogeneous electric field, which leads to the ion flow, and (iii) for electrons, the Boltzmann response is assumed. A detailed investigation of the test charge potential will be given in Ref.[6]. In the present work, we focus on the potential only in the plane perpendicular to the ion flow (i.e., monolayer plane) and in the parameter regime corresponding to the experiment. Given the three dimensionless parameters, ion drift velocity normalized by ion thermal velocity, U, ion-neutral collisional frequency normalized by ion plasma frequency, ζ, and ratio of ion to electron temperature, τ, one can evaluate the test charge potential in units of e Z / λ as a function of distance R= r / λ from the test charge (λ is the ion Debye length).

For fixed τ =0.012, we summarize the results in the {ζ, U} diagram presented in Fig.1. For U>5, the behavior of both solid curves on the {ζ, U}diagram is close to ζ U^2=const. It can be shown that decreasing the pressure in the experiment corresponds to moving between or along lines ζ U=const or ζ =const on the diagram from left to right, thus, crossing the regions of different potential. The exact path in the {ζ, U} plane is not known due to uncertainties in ζ and U values, but even with large error bars these values strongly suggest that the highly mobile state at p~4 Pa falls somewhere in between the regions of nonmonotonic potential with attractive well and monotonic repulsive potential.

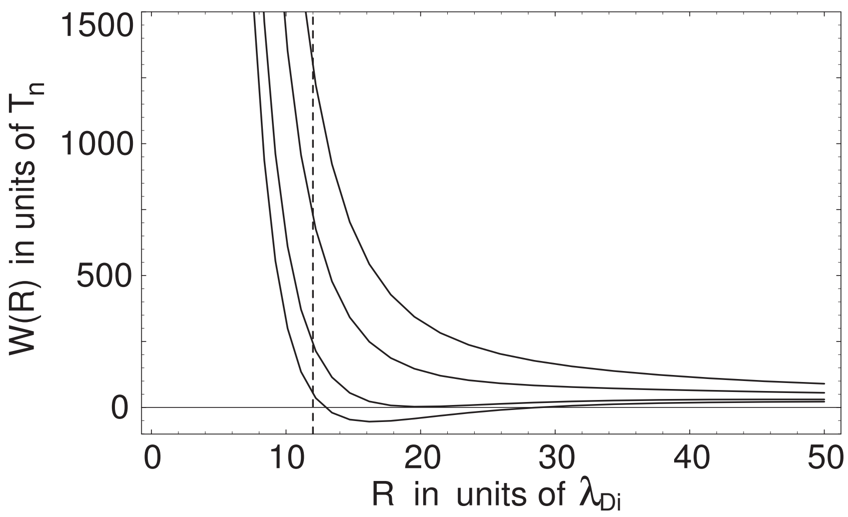

Fig. 2: *Typical shapes of dust-dust interaction potential corresponding to the collisionality parameter and mean velocity at ζ U=const line shown in Fig.2. Upper curve corresponds*

to {0.075, 10}, lower curve to {0.15, 5}. Vertical axis is interaction energy normalized by temperature of neutrals, Z=18000. At large distances R>50 the potential is always repulsive.

We can interpret the results in terms of change of coupling parameter Γ with pressure. Variations in dust temperature cannot explain strongly suppressed transport at lower pressures because the dust temperature is likely to increase with decreasing pressure. Therefore, in the following, we associate the variations of Γ solely with changes in the interaction energy W(r) at $r=\Delta$, since our aim is to find the trend in the variations and not the magnitude of the coupling parameter.

For the actual experiment, Γ is found from the intersection between the potential curves and the vertical line $r=\Delta$ (for the plasma parameters used here this corresponds to R~12) in Fig.2. Moving up this line on the figure we find that Γ increases dramatically as the pressure decreases. In the regime of strong coupling, the dust-dust viscosity is nearly proportional to the coupling coefficient, $\eta \sim \Gamma$ [7]. In turn, the viscous dissipation rate is proportional to η. Thus, the pressure decrease in this regime should be accompanied by a drastic increase of the viscous dissipation, which inhibits the effect of non-potential forces and explains why no vortex (viscous fluid) motion is observed at lower pressures. Of course with change of pressure the Debye length will also vary slightly, as will the units on the horizontal axis in Fig.2. Nevertheless, that does not change the qualitative picture and the quantitative agreement with the experiment is also reasonable.

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