Microdynamics of dusty plasma liquids in narrow channel: from disorder to order

2003 J. Phys. A: Math. Gen. 36 6103

(http://iopscience.iop.org/0305-4470/36/22/336)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS A: MATHEMATICAL AND GENERAL

J. Phys. A: Math. Gen. **36** (2003) 6103–6107 PII: S0305-4470(03)54965-4

Microdynamics of dusty plasma liquids in narrow channel: from disorder to order

Wei-Yen Woon, Pei-Shan Du, Li-Wen Deng and Lin I

Department of Physics and Center for Complex Systems, National Central Universiy, Chungli, Taiwan 32054, Republic of China

E-mail: lini@phy.ncu.edu.tw

Received 18 October 2002, in final form 4 December 2002
Published 22 May 2003
Online at stacks.iop.org/JPhysA/36/6103

Abstract
We report direct observations on the microscopic dynamics of dusty plasma liquid confined in a narrow gap. We measure the horizontal and transverse displacement histograms as well as the transverse particle density distributions from particle trajectories. Under confinement, the liquid forms a layer structure. The dust particle motion at boundaries show anisotropy and three outermost layers is found due to the pinching effect of the boundaries. When the gap width is reduced to below $7d$ ($d =$ inter-layer width), the dust particle motion in the central region shows a transition from isotropic motion to anisotropic discrete hopping motion, leading to a slower dynamics and layer structure through the whole liquid.

PACS numbers: 52.27.Lw, 05.40.−a, 64.60.Cn

When pouring liquid into a container, it fills up the volume according to the shape of the container as the relative orientation angles between the liquid molecules can be altered freely. However, when the temperature of the liquid is lowered down to the freezing point, the liquid becomes solid as the relative positions of the liquid molecules are fixed due to the reduction in the kinetic energy. A similar effect can also occur when reducing the entropy of the system. The fact that the molecules are allowed to visit fewer accessible states induces a transition from disorder to order and results in a slower dynamics. In particular, when liquids are confined in gaps with width comparable to the molecular scale, they can no longer be treated as bulk liquids [1]. The dynamics of the system slows down and the viscosities of liquids are found to diverge from bulk liquid when the gaps are reduced down to molecular scale. The early measurement by surface force apparatus shows signatures of order phase in confined liquids [2]. However, no direct real-time observation on the micro-dynamics is available due to the limitation of the instrument and experimental approach.

By suspending negatively charged micrometre size polystyrene particles in a low pressure glow discharge background, a dusty plasma liquid (DPL) with low viscous damping can be formed [3]. The Coulomb repulsive forces between the particles along with the ever-present stochastic noises result in sub-mm separations and wiggling caged motion accompanied by occasional hopping. With a proper system design, the polystyrene particles can be aligned into vertical chains by the wake field attraction [4] induced by the downward vertical ion flow. The quasi-2D system allows long-term tracking of the chain position in the 2D viewing plane. The system is therefore a novel platform for direct 2D observation for microscopic dynamics of strongly coupled Coulomb system (SCCS) by video rate optical microscopy.

When DPL are confined in relatively large circular confinement, it has been reported that the relative position of a particle in the whole cluster is rearranged through collective hopping [5]. The particle can only fluctuate around the potential minimum of the caging well before gathering high enough constructive superposition of the stresses from external stochastic noises and internal stresses from the displaced neighbouring particles in one site. When the combined superposition of the external and internal stresses exceeds the local barrier of the caging potential, the particles hop collectively for a lattice constant before rest at a new site, releasing the stresses. Clusters of hopping strings can be identified as the process repeats itself throughout the observation. Typically, the strings surround temporarily ordered domains with diameters of about a few d, where d is the distance between the adjacent density peaks. The hopping excitations of the particles are isotropic since the excitation sources are stochastic in nature. What difference would it make when the size of the confinement is reduced? Moreover, when forcing the boundary particles to align in straight lines with the confinement edges, how would the transport properties of the particles change in the transverse and longitudinal directions respectively? In this work, we show the trajectories of the particles in the centre and boundary regions respectively and measure the transverse (y) particle density distribution and the displacement histograms in both horizontal ($\triangle x$) and transverse ($\triangle y$) directions. The measurements show anisotropic hopping excitations in y direction. The above measurements give a dramatically different result when the gap widths are reduced to below $7d$.

The experiment is conducted in a cylindrical rf dusty plasma system described elsewhere [6]. A weakly ionized discharge ($n_e \simeq 10^9$ cm^{-3}) is generated in 250 mtorr Ar gas using a 14 MHz rf power system. Two vertical plates 42 mm in length and 14 mm in height are put on the centre region of the bottom electrode surface to confine polystyrene particles of 7 μm diameter. Particles are negatively charged and confined by the strong electric field in the surrounding dark space (sheath) adjacent to the confining wall. Vertically, the suspended dust particles are aligned with eight particles for each chain by the wake field attraction induced by the downward ion flow. Particles in the same chain move together horizontally. It is a quasi-2D system with smooth slipping boundaries. The chain positions in the horizontal plane are illuminated by a thin laser sheet and monitored through digital optical microscopy at 30 Hz frame rate.

Figure 1 shows typical snapshots and trajectories for DPL in a gap $9d$ in width. Each bright spot in figure 1(a) corresponds to the scattering centre of a dust particle. The position of each bright spot is traced and linked frame by frame throughout the experiment. The transverse particle density distribution is obtained by taking the statistics of the particle position in the y-direction. The densities at the boundaries are higher than at the centre region and two to three layers can be found near the boundaries due to the pinching effect of the boundaries. The central part does not show a clear layer structure in this case.

The trajectories can be explored in detail. As shown in figure 2(a), for DPL in a $9d$ wide gap, the 10 s trajectories show that the particles in the centre region spread in a rather isotropic manner. In contrast, the trajectories at the boundaries show obvious anisotropy. The dust particles stay at the boundaries most of the time and diffuse into the centre region by occasional

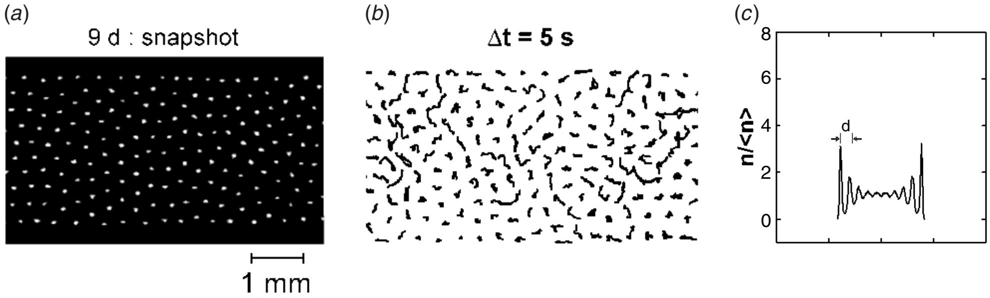

Figure 1. (*a*) Typical snapshots of the particle configuration in gap width = 9*d* (*d* = inter-layer width), (*b*) 5 s trajectories and (*c*) the transverse particle density distribution averaged over 30 000 picture frames.

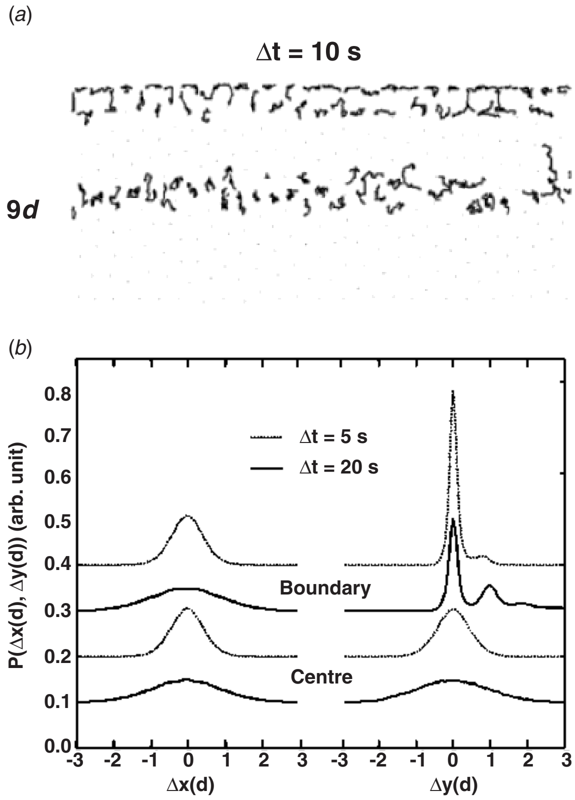

Figure 2. (*a*) 10 s trajectories for gap width = 9*d*. (*b*) The displacement for 5 s (dashed line) and 20 s (solid line) in the *x*- and *y*-directions respectively.

hopping. In the central region, both the transverse and horizontal displacement histograms in figure 2(*b*) show an isotropic distribution. At the boundaries, the transverse displacement histogram is different from the horizontal one. On a short timescale ($\triangle t = 5$ s), the dust particles are caged at the boundaries while on a longer timescale ($\triangle t = 20$ s), a second peak in the histogram appears, indicating hopping motion for $1d$. The distribution is anisotropic as the dust particles can only go into the interior of the liquid. Due to the caging and alignment

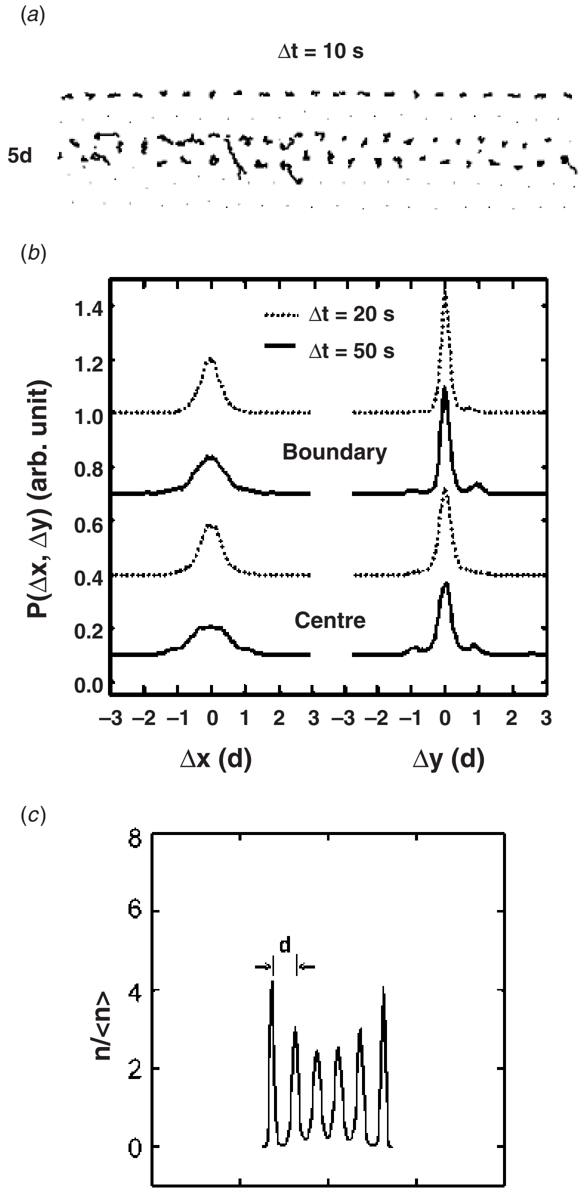

Figure 3. (*a*) 10 s trajectories for gap width = $5d$. (*b*) The displacement for 20 s (dashed line) and 50 s (solid line) in the x- and y-directions respectively. (*c*) The transverse particle density distribution.

by the boundaries, the dust particles at the boundaries are unable to orient themselves as freely as the dust particles in the central region. The argument is further evidenced by the transverse particle density distribution in figure 1(*c*). The confinement effect penetrates for about $3d$, leaving the central region free of any confinement effect.

When the gap width is further reduced to $5d$, the transport properties of the DPL change dramatically, as seen in figure 3. The trajectories in the central region are found to conform more to a straight line as the dust particle begins to spend most of the time staying in the central layer due to the suppression from the three outermost layers pinched by the boundaries. The dynamics slows down and the hopping occurs only on a longer timescale. In figure 3(*b*), the $\triangle y$ displacement histogram (50 s) for the dust particles in the central region shows a similar characteristic to the one at the boundaries, only to allow hopping in both up ($+\triangle y$) and down ($-\triangle y$) directions since there is no confining sheath around. The transverse particle density distribution shows interesting layering. The dust particle motions in the y direction in the central region exhibit a transition from Gaussian-type random motion to non-gaussian discrete hopping motion when the gap width is reduced. The pinching effect of the boundary layers penetrates into the interior of the liquid, resulting in a layering transition throughout the whole liquid.

In conclusion, this direct observation of the micro-dynamics of DPL in a narrow channel evidences the slow dynamics and ordered structure due to a purely entropic effect. Due to the boundary confinement, layers are formed and the transverse particle motion exhibits discrete hopping to the adjacent layer rather than random diffusion. When the boundary layers pinch, the layer transition extends throughout the whole liquid, leading to a much slower dynamics and ordered structure.

Acknowledgment

The research is supported by the National Science Council of the Republic of China under contract number NSC-90-2112-M008-50.

References

[1] Granick S 1999 *Phys. Today* **52** 26
[2] Bhushan B, Israelachvili J N and Landman U 1995 *Nature* **374** 607
[3] Lin I *et al* 1996 *Science* **272** 1626
Juan W T and Lin I 1998 *Phys. Rev. Lett.* **80** 3073
[4] Piel A and Melzer A 2002 *Adv. Space Res.* **29** 1255
[5] Lai Y J and Lin I 2002 *Phys. Rev. Lett.* **89** 155002
[6] Juan W T, Chen M H and Lin I 2001 *Phys. Rev.* E **64** 016402