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## Microscopic visco-elastic motions of narrow two-dimensional dust Coulomb liquids under modulated shear stress

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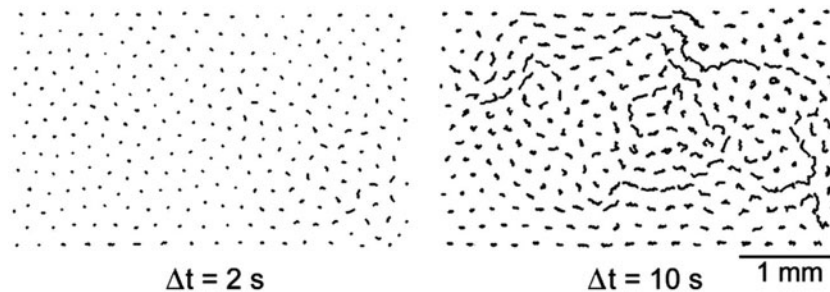
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**Abstract.** The microscopic visco-elastic motion of a quasi-2D dusty plasma liquid confined to a width of about 15 interparticle distances under square stress pulses shorter than thermal relaxation time from a chopped laser beam is investigated experimentally. The stress-enhanced excitations of hopping vortices are responsible for particles in the laser driven zone reaching, after a higher initial velocity, a constant nonzero terminal forward velocity and partial plastic deformation through the loss of the structure memory. The driven particles around domains with caged shear motion still partially keep the structural memory and demonstrate partial elastic backwards motion with exponential relaxation after turning off the laser.

The generic structural and dynamic behaviour of liquids confined in narrow channels is a fundamental problem for mesoscopic systems [1]–[7]. Macroscopic measurements of the relation between the temporal changes of the velocity of and the stress on the boundary plate have been commonly used to investigate the visco-elastic response. The plastic viscous response dominates for liquids under low frequency shears. As the confining size goes down to a few interparticle spacings, the suppression of the lateral degrees of freedom makes the thin liquid film exhibit interesting behaviour [1]–[7]. The system shows a nonlinear visco-elastic response to high frequency shears [1]. Nevertheless, the microscopic origin of the above behaviour has been less well explored experimentally, especially for the case with a shear pulse length comparable to the thermal relaxation time. In this paper, we report our experimental investigation on this issue using a quasi-2D dusty plasma liquid (DPL) confined in a narrow channel and sheared by a periodically chopped laser beam along the centre axis.



**Figure 1.** Typical particle trajectories for the stress-free case at 2 and 10 s exposure time.

The strongly coupled DPL formed by micrometre particles suspended in a low pressure plasma background belongs to the general category of strongly coupled Coulomb systems (SCCS), due to the strong negative charging of the dust particles ( $10^4$  electron/particle). Through optical video-imaging, the generic collective dynamic behaviour at the kinetic level can be directly visualized. In the past few years, many interesting topics such as the microscopic particle motions in the melting or liquid states, waves in crystal states driven by ac biased electric probes and chopped laser beams, micro-vortices induced by shears from CW lasers in a cold liquid and Mach cones induced by fast moving particles or laser forcing, have been studied experimentally [8]–[13]. The visco-elastic response of a sheared liquid has never been explored.

At the kinetic level, the rich dynamic behaviour and the visco-elastic properties for a liquid are mainly determined by particle rearrangement under the interplay of shear force, thermal fluctuations and mutual interaction. Crystals show elastic response to moderate shears because, with good interlocking through strong coupling, each particle exhibits sheared motion in the cage formed by the surrounding particles and no bond-breaking occurs through relative position rearrangement. For a stress-free liquid, the larger thermal fluctuations can assist particle hopping over the caging barrier [14]. On a short timescale, many small (a few interparticle distances) temporarily ordered domains, in which particles show small-amplitude caged motions, coexist with the surrounding hopping vortices or strings (figure 1). The structure memory is lost through hopping induced position rearrangement in timescales longer than the thermal relaxation time. An external shear force can further promote the above hopping process through the mechanical instability [12, 15]. The accumulation of the structure memory loss induces macroscopic plastic deformation. For cold liquids, especially when confined in a small space and under shear pulses shorter than or comparable to the decaging time, temporarily ordered domains which keep the structure memory still exist. They play an important role in the partial elastic response of the system.

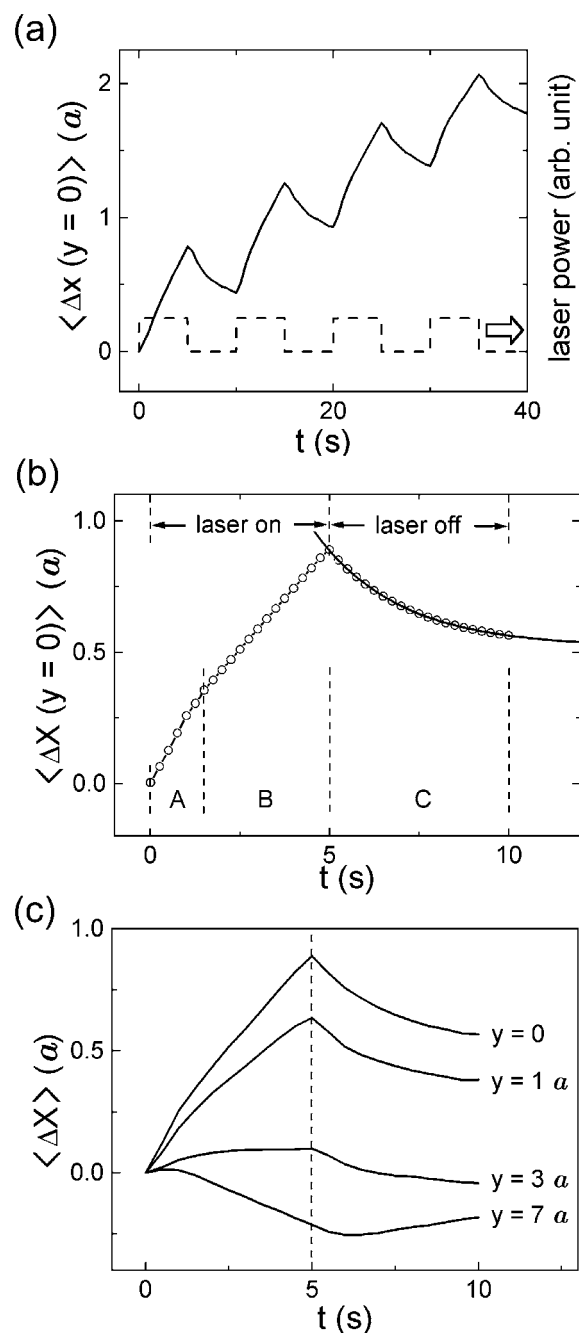
In this paper, we provide experimentally a microscopic dynamic picture of how a quasi-2D dust Coulomb liquid in a narrow channel responds to short shear pulses comparable to the decaging time. A narrow DPL can be confined by the strong sheath field in a narrow plasma trap. The liquid state is created by melting a triangular cylindrical crystal structure with vertical particle alignment. Particles along the same vertical chain move together horizontally under thermal fluctuations. It resembles a confined ultra-thin quasi-2D liquid. The DPL is pushed by a periodically chopped narrow laser beam along the centre longitudinal axis. The averaged displacement shows a nonlinear visco-elastic response. The driven particles exhibit a high average forward velocity ( $0.22 a \text{ s}^{-1}$ , where  $a$  is the mean particle spacing = 0.3 mm) in the

initial stage after turning on the laser. After that the mean forward velocity of the driven particles gradually reaches a lower constant value ( $0.17 a s^{-1}$ ) due to the excitation of hopping vortices and small-amplitude sheared motion in ordered domains away from the laser zone. Turning off the laser causes an exponential type particle position relaxation with the mean backwards displacement less than  $0.5 a$ . The excitation of hopping vortices is the main source for the plastic deformation (a net nonzero forward drift) in a complete laser cycle. The ordered domains are responsible for the partial elastic restoring after turning off the laser.

The experiment is conducted in a cylindrical, symmetric rf dusty plasma system described elsewhere [12]. A weakly ionized discharge ( $n_e \sim 10^9 \text{ cm}^{-3}$ ) is generated in 250 mTorr Ar gas using a 14 MHz rf power system at 2.1 W. A rectangular cell 12 mm in width, 40 mm in length and 14 mm in height is put on the centre of the bottom electrode to trap polystyrene particles of  $7 \mu\text{m}$  diameter. The 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 vertical ion flow. In the horizontal plane, the length of the elongated cluster is about  $60 a$ . The cluster width is fixed at  $14 a$ . A narrow laser sheet (488 nm  $\text{Ar}^+$  laser) with 0.4 mm half-width and 2.5 mm height (covering the entire vertical chain) passing along the centre major axis is used to push the particles. The laser power inside the confining cell is fixed at 70 mW. The particle (vertical chain) positions in the horizontal mono-layer are monitored through digital video optical microscopy.

Figure 2(a) shows the change of displacement  $\langle \Delta x(y = 0) \rangle$  along the  $x$  axis (laser direction) with time, for a few chopping cycles with 0.1 Hz laser chopping rate (50% duty cycles) averaged over 20 particles in the driven zone ( $y$  axis is normal to the laser direction). Figure 2(b) shows the displacement response curve  $\langle \Delta X(y = 0) \rangle$  after further averaging over 20 chopping cycles. The averaged response after turning on the laser begins with an initial stage A with a large slope  $0.22 a s^{-1}$  (i.e. large mean velocity when the strain is small), and then reaches the stage B with a smaller drift velocity  $0.17 a s^{-1}$  after  $\langle \Delta X(y = 0) \rangle$  reaches about  $0.25 a$ . In the laser-off period (stage C), the mean displacement is bounced backwards with a higher velocity at the beginning and then gradually slows down. The exponential decay curve,  $\langle \Delta X(y = 0) \rangle / a = 0.52 + 0.37 \exp(-(t - 5)/2.3)$ , gives a good fit. The curve exponentially decays to a constant level with total backwards displacement  $0.37 a$  if we extend the laser-off time. The ratio of the backwards displacement in the laser-off period to the forward displacement in the laser on period,  $R = \langle \Delta X_{off} \rangle / \langle \Delta X_{on} \rangle$ , reflects the limitations of elastic restoring. Namely, particles cannot fully return to their initial positions after turning off the laser, even if the laser-off time is long enough. There is a net forward drift,  $\langle \Delta X_d \rangle = \langle \Delta X_{on} \rangle - \langle \Delta X_{off} \rangle$ , in a complete chopping cycle. This evidences the plastic deformation associated with the partial elastic restoring of the liquid for the short shear pulse. The same dissipative origin also causes the overdamped transverse wave. Figure 2(c) shows the averaged temporal response along longitudinal strips at different position  $y$  from the centre strip driven by the laser in one driving cycle starting at  $t = 0$  s. It takes about 1 s for the damped wave to propagate to the two edges. The overdamping is also supported by the absence of the resonant peak when we scan over the laser chopping frequency.

The particle trajectories provide a clear microscopic base to understand the above observations. Figure 1 shows the trajectories in the laser-free case as a reference. The system is in the cold liquid state melted from the triangular lattice. Most particles still have about six nearest neighbours which make them exhibit small-amplitude thermal motions around their caging sites. Assisted by background thermal fluctuations, vortex-like hopping can occur irregularly



**Figure 2.** (a) The change of displacement  $\langle \Delta x(y=0) \rangle$  along the  $x$  axis (laser direction) with time, for four sequential chopping cycles at 0.1 Hz laser chopping rate (50% duty cycles), averaged over 20 particles in the driven zone. The lower curve shows the change in laser power as a reference for the chopping phase. (b) The displacement response curve averaged over 20 chopping cycles of 20 particles in the driven zone. (c) The averaged spatio-temporal response crossing the cluster width in one laser on–off cycle, where  $y$  is the direction transverse to the laser direction and  $y = 0$  at the laser driven zone.

in different areas without external shear [14]. The hopping timescale is in the order of a few seconds. After hopping, the vortex region can switch to a quiet and ordered domain. Introducing stress pulses causes more complicated motions. Figures 3(a) and (b) show the typical trajectories in two complete laser cycles. The trajectories are marked in red and black when the laser is on and off respectively. In general, the external shear enhances the vortex-like hoppings [12]. When the shear is applied, three different types of particle motion region can be identified:

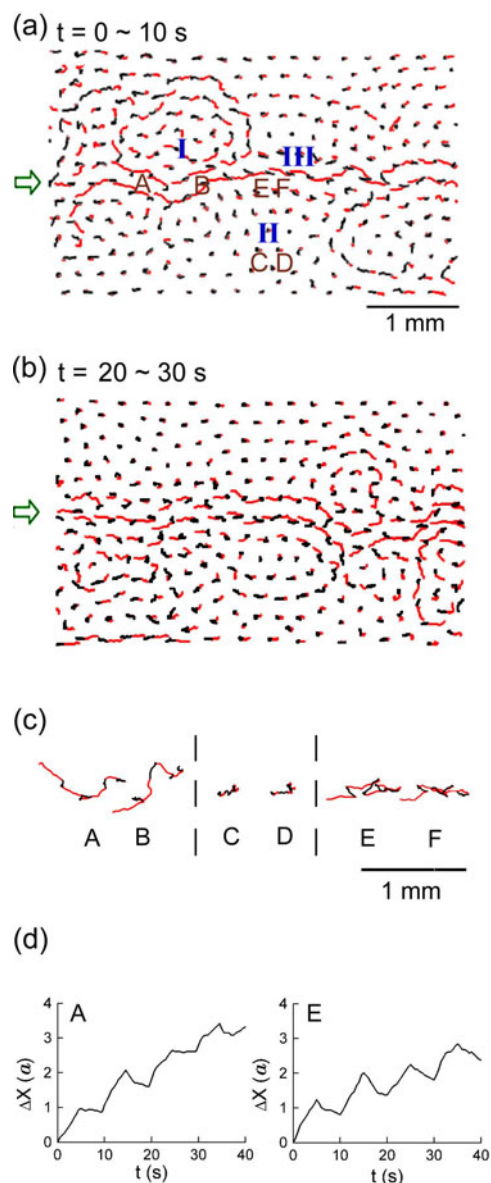
- (I) the hot hopping vortex regions without elastic relaxation,
- (II) the temporarily ordered domains with small-amplitude sheared particle motions around their own caging sites in the entire shear cycle and
- (III) the regions adjacent to region II, which exhibit partial elastic restoring.

The type II regions usually exist in areas away from the laser beam. Those regions swap as time evolves. Figure 3(c) shows the magnified trajectories of the typical particles from the above three regions. Figure 3(d) shows the longitudinal displacements (along the  $x$  direction) of particle A and E in the four laser on–off cycles from  $t = 0$ . Particles are not always bounced backwards when the laser is off.

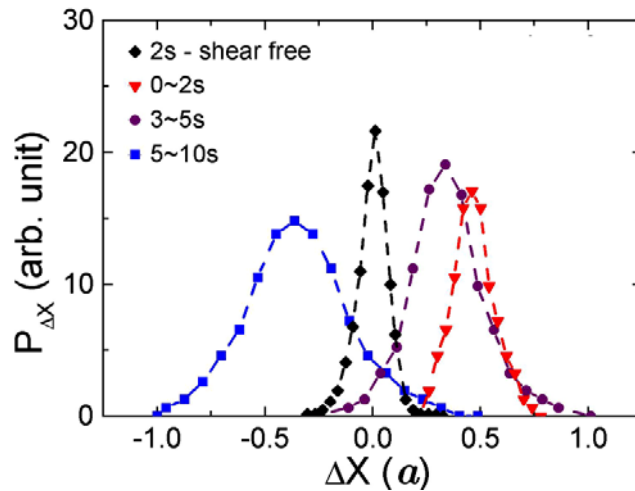
Figure 4 shows the displacement histograms (along the shear direction and averaged over 20 cycles) for the particles in the laser driven strip at three stages A, B and C of the shear-relaxation cycle. The 2 s displacement histogram for the shear-free case is also plotted as a reference. Unlike the symmetric histogram at zero laser power (figure 4), all the particles move rightwards with a slightly broadened distribution in the initial stage A (0–2 s). In the second stage B (3–5 s), the displacement histogram is further broadened. The downshift of the peak position from 0.43–0.33  $a$  indicates that most of the particles are slowed down. Some of them even have quite small displacements of less than 0.2  $a$ . Note that the high displacement tail on the right side extends to 1  $a$ .

In the initial stage, the stressed particles move around the bottom part of their caging wells and the averaged displacement grows almost linearly. This is quite similar to the motion of an overdamped oscillator driven by a constant force. The damping could come from the background thermal fluctuations through the interaction with neutral gas and background plasma. However, unlike a damped oscillator which has zero velocity when the strain grows, the forward averaged velocity is only slowed down in the second stage B. The accumulated strain can induce the cascaded motion of neighbouring particles and gradually propagate the stress to the remote area. The strain energy can only be partially retained in the type II region where particles move in the caging well of the ordered domain without any bond-breaking process. The bond-breaking associated with the thermal and stress-enhanced excitation of vortex type hopping process in type I region can release the strain energy. Therefore, unlike the solid case, particles are not fully held in the second stage B. Their forward motions only slow down through the above dissipative momentum transfer process.

In the relaxation stage C after the laser is turned off, the 5 s histogram shows a very broad profile from  $-1.0$  to  $0.5 a$ , centred around  $-0.37 a$ . It is interesting to see that particles in or adjacent to the type I hopping vortex have already relaxed their strain energy. They try to settle down in the new caging sites. Some of them can even slightly move forward to look for the new stable position. They belong to the group of particles on the right hand side of the histogram profile around  $0 a$ . They are the main source for the local plastic deformation. Those particles in type III regions are mainly bounced backwards. However, very few of them can fully return to their initial position because type III regions are also coupled to type I regions. Namely, even



**Figure 3.** (a) and (b) The typical trajectories of particles at different starting times under laser driving at 0.1 Hz chopping frequency. The arrow at the left indicates the position and direction of the laser beam. The ordered domains (II) and micro-vortices (I) coexist. Particles in region III between them show partial elastic restoring. (c) The magnified trajectories from the three typical regions I, II and III. The red and black trajectories in (a)–(c) correspond to the trajectories during laser on and off respectively. (d) Typical change of displacement with time along the  $x$  direction in the four laser on–off cycles for particles A and E in (a) and (c).

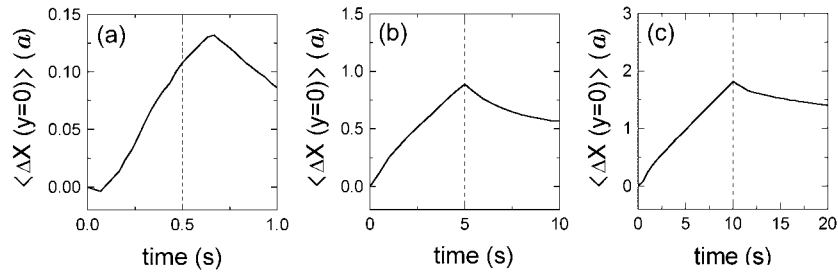


**Figure 4.** The histograms of particle displacement (along the  $x$  direction) in the driven zone at different stages in one laser on–off cycle at 0.1 Hz chopping frequency. The 2 s displacement histogram of the shear-free (laser power = 0 W) case is also plotted as a reference. The lines for each curve are just used for eye guidance.

though a type III region is adjacent to type II region which tends to keep the structural memory, the structural reorganization in the type I region partially adjusts the particle position and partially washes out the structure memory of type III region in a complete shear on–off cycle. The overall effect induces a net forward averaged drift in one laser on–off cycle. The strains are gradually released and the symmetric displacement histogram is recovered to that of the stress-free case after about 20 s, if we extend the laser-off duration. In the next cycle of applying the stress on time, the type I, II and III regions switch to different areas under the thermal fluctuation. Note that, although modes with different scales are involved in the relaxation process after turning off the laser, the simple exponential decay of the averaged displacement reveals a single timescale under an effective relaxation rate.

We also test the responses under different laser chopping rates (figure 5). At 1 Hz laser chopping frequency, the displacement curve shows about 0.1–0.2 s phase lag and a parabolic type nonlinear rise in the initial stage before 0.3 s, which reveals the inertia effect. The 0.05 Hz run shows a very similar initial stage A to that of the 0.1 Hz run, but the latter has a longer second stage B with overall averaged forward displacement longer than  $1 a$ . The total averaged backwards displacement in one relaxation period is still less than  $0.5 a$ . Namely, about 3 s after turning on the stress, the system reaches a state with a steady rate of dissipating energy through excitation of vortex type motion and eventually to the background Ar gas. Particles only keep the structure memory of their last caging sites before turning off the laser. Note also that when we conducted experiments passing two chopped anti-parallel laser beams along the two opposite straight edges of the clusters, similar visco-elastic behaviours with exponential relaxation decay in the laser-off period are observed.

In conclusion, we investigated the microscopic origin and dynamic behaviour of narrow 2D dust Coulomb liquid clusters driven by ac shear forces from a chopped laser beam, with pulse width comparable to the thermal relaxation time. In a chopping cycle, the mean displacement of particles along the driven zone starts with a region of high velocity right after turning on the



**Figure 5.** The averaged displacement response curve (along the laser directions) in one chopping cycle (starting at  $t = 0$  s) for particles in the driven zone in one on-off cycle at 1, 0.1 and 0.05 Hz chopping frequency.

laser and then it gradually reaches a steady level with lower velocity by gradually transferring momentum to various excitations. Turning off the laser causes partial relaxation of the mean displacement toward the initial positions with a net averaged backwards displacement less than  $0.5 a$ . At the microscopic level, external stress, particle mutual interaction and thermal fluctuations are the key factors determining particle motion and rearrangement. Under the shear force, quiet ordered regions due to particle caging coexist with micro-vortices due to thermally assisted hopping. The former regions keep the structure memory and are responsible for the partial local elastic restoring of particle positions in their neighbourhood. The position memory loss due to particle rearrangement caused by the micro-vortex are the main sources for the viscous plastic deformation and the viscous damping of the transverse wave.

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