Microstructure of a liquid complex (dusty) plasma under shear

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The microstructure of a strongly coupled liquid complex plasma undergoing a shear flow was studied experimentally. The liquid was a shear melted two-dimensional plasma crystal, i.e., a single layer suspension of micrometer-size particles in a rf discharge plasma. Trajectories of particles were measured using video microscopy. The resulting microstructure was anisotropic, with compressional and extensional axes at around ±45° to the flow direction. Corresponding ellipticity of the pair correlation function $g(\mathbf{r})$ or static structure factor $S(\mathbf{k})$ gives the (normalized) shear rate of the flow.

Complex, or dusty plasma is a suspension of fine solid particles in a weakly ionized gas [1]. Micron-size particles acquire high electric charge (usually negative), which often makes their suspension strongly coupled. A complex plasma can therefore be in a liquid or solid state. The motion of individual particles - proxy “atoms” - is fully resolved in real time, allowing direct observation of complex plasma dynamics at the “atomistic” level. In two-dimensional (2D) complex plasmas, particles are arranged in a single layer and are therefore easy to observe using video microscopy.

Complex plasmas belong to a broad class of soft condensed matter: Typical shear modulus of a crystalline 2D sample is around 10^{-13} N/mm, so that they can be easily manipulated, e.g., by applying radiation pressure of a laser beam [2]. This allows one to study a broad range of phenomena from nucleation and motion of single dislocations to shear flows. In Ref. [2], the shear viscosity of liquid complex plasma was calculated using a fit of measured particle velocity profiles to a Navier-Stokes model. However, any changes occurring in the microstructure of sheared liquid complex plasma were not studied so far.

In this work [3], we experimentally study the microstructure of a sheared 2D complex plasma at various levels of shear strain rate. We find that the microstructure is distorted, with compressional and extensional axes at around ±45° to the flow direction. The magnitude of distortion is defined by the (normalized) shear flow's strain rate. These findings provide a unique insight into the microstructure of regular liquids sheared to comparable values of normalized strain rate.

Our experimental setup was a modified GEC (Gaseous Electronics Conference) rf reference cell [3]. Plasma was produced using a capacitively-coupled rf discharge in argon at 0.66 Pa. A single layer of dust particles was suspended in the plasma sheath of the lower rf electrode. The microspheres made of melamine formaldehyde had a diameter of 9.19±0.09 μm, a mass m=6.15×10^{-13} kg, and acquired an electric charge of Q=–17000±1700e. The suspension included around 8000 particles and had a diameter of ≈ 60 mm, the mean interparticle distance in the center was Δ=0.55 mm [measured from the first peak of the pair correlation function $g(r)$]. The neutral gas damping rate was ν=0.77 s^{-1}.

At our experimental conditions, the particle suspension self-organized in a highly ordered triangular lattice. We used the method of Ref. [2] to create a shear flow in the 2D complex plasma. Two oppositely directed laser beams were focused down to a fraction of the interparticle spacing and they were rapidly (≈ 300 Hz) scanned to draw rectangular stripes on the suspension. The particles reacted to the averaged radiation pressure. Shear stress was created in the gap between the laser-illuminated stripes, its magnitude was controlled by varying the output laser power.

To facilitate the emergence of shear flow and subsequent analysis, one of the closely packed rows of the triangular lattice was always oriented along the laser beams, before the laser was switched on. Unless otherwise stated, data analysis was performed at the stage of steady-state shear flow (after a waiting time of 3.3 s) in a region of interest indicated by a dashed-line rectangle in Fig. 1. All values reported were averaged over another 3.3 s.

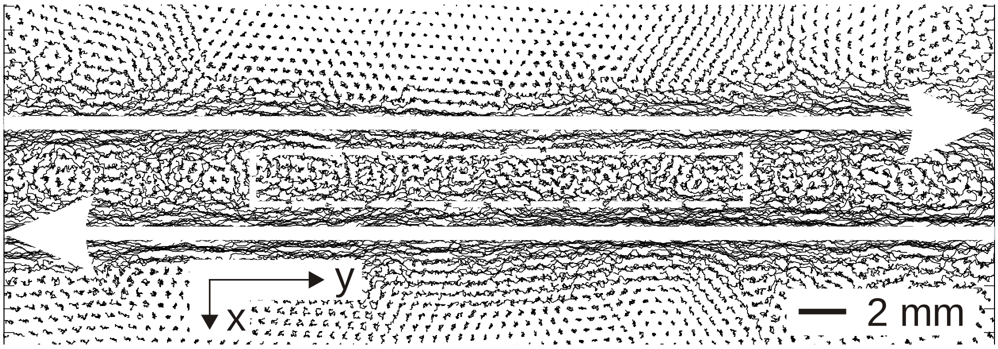

Fig. 1: Shear flow in a planar Couette configuration in a strongly coupled 2D complex plasma is sustained by a pair of counter-propagating laser beams (indicated by arrows). Particle trajectories during 0.83 s of a steady-state flow are shown. The dashed-line box defines the region of interest where the analysis of liquid microstructure was performed. The manipulation laser power was P_{laser} =1.25 W.

We performed standard structure analysis, i.e., calculating the pair correlation function *g(r)* and static structure factor *S(k)* of complex plasma (averaged over azimuthal angle ϕ). Both indicate that complex plasma is in a crystalline state for the laser power $P_{\text{laser}} < 0.9$ W and becomes liquid for $P_{\text{laser}} > 0.9$ W, as evidenced by a sudden decrease in the height of the first peak of *g(r)* and *S(k)* and disappearance of the splitting in their second peak. Although further subtler changes in both functions occur with increasing levels of shear strain rate in the liquid state, these are less prominent and difficult to decipher.

To get a greater insight on the liquid microstructure, we calculated the mean interparticle spacing Δ as a function of the azimuthal angle ϕ. This is equivalent to evaluating the first peak in the angle-resolved pair correlation function $g(\mathbf{r})$, yet provides a very local measure and is also easier to calculate. A complimentary measure is the angular bond density, i.e., the probability to find a near neighbor at a certain angle ϕ from a given particle.

Experimentally measured $\Delta(\phi)$ and angular bond density reveal anisotropic microstructure of sheared liquid complex plasma. The interparticle spacing is larger in a certain direction (extensional axis at $\phi \approx -45°$) and smaller in the orthogonal direction (compressional axis at $\phi \approx 45°$). This constitutes a departure from isotropic distribution in a quiescent liquid. Distorted pair correlation function is given by

$$g(\mathbf{r}) = g_0(r)[1 + \tau\dot{\gamma}(xy/r^2) f(r)], \quad (1)$$

where $g_0(r)$ is for liquid in equilibrium, $\dot{\gamma}$ is shear rate, τ relaxation time, and the function *f(r)* is determined by the particular form of the pair interaction potential for particles. The term proportional to xy/r^2 introduces a $\sin(2\phi)$ component in the angular dependence of $g(\mathbf{r})$.

The observed anisotropy of sheared liquid's microstructure has clear physical meaning. The flow's strain rate (normalized) is given by the degree of anisotropy, i.e., $\tau\dot{\gamma} \approx 2A_2$, where A_2 is the relative amplitude of the $\sin(2\phi)$ contribution in $\Delta(\phi)$. The deviation of directions of compressional and extensional axes from ±45° gives the extent of non-Newtonian behavior of liquid [4].

References

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