Cooperative excitations in the quenched dusty plasma liquid

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Microscopically, a cold liquid around the melting point is not completely disorder. The strong mutual interaction generates ordered structure and correlated motion, which can be deteriorated by stochastic thermal agitation. Namely, the competition of the above two key factors causes the formation of a heterogeneous network, in which crystalline ordered domains coexist with defect clusters [1, 2]. A single particle exhibits alternate small amplitude rattling in the cage formed by the nearest neighbors and hopping (cage jumping) over the caging barrier after accumulating sufficient constructive perturbation from the thermal agitation and neighboring particles[1, 2, 3, 4, 5]. The strong mutual coupling, on one hand, makes hopping cooperative in the form of avalanched type clusters with different number of particles. On the other hand, it terminates hopping through transferring energy to the surrounding network. Cooling the system enhances the spatial correlation lengths of the microstructure and of the cooperative motion. The previous studies indicate that particles cooperative hopping changes from more string like to more band like [6, 7, 8].

In this work, using steady state quasi-2D dusty plasma liquid (DPL) after quenching, for the first time, we further classify the cooperative excitation into: A) the static 2D patch with cage rattling, B) the rotating 2D patch, C) the drifting 2D patch, D) the 1D hopping string, and E) the 1D strip with strong shear and bond-breaking. From the scaling behavior of the mean square coarse grained displacement from a region in the circle with radius *r* centered around a particle, the quasi-particle demonstrates the similar 3-stage anomalous diffusion governed by the similar cage rattling/hopping dynamics.

The experiment is conducted in a cylindrical symmetric rf dusty plasma system, similarly to those used elsewhere [1, 2].The weakly ionized glow discharge ($n_e \sim 10^9\ cm^{-3}$) is generated in 250 mTorr Ar gas using a 14-MHz rf power system quenched from 2.3 to 1.6 W. Polystyrene particles ($7 \pm 0.4\ \mu$m in diameter) are confined by the sheath field adjacent to the trap wall of a center trap with 4.1 cm inner diameter. The estimated Debye length and the charges on the dust are in the order of $10^{-1} mm$ and a few to ten thousand e/dust, respectively. The wake field effect of the downward ion wind toward the bottom electrode lines up dusts into vertical chains, with about 14 dusts in each chain. Dusts along the same chain move together horizontally, without vertical dust flipping. It makes the system a quasi-2D system. The inter-chain distance *a* is

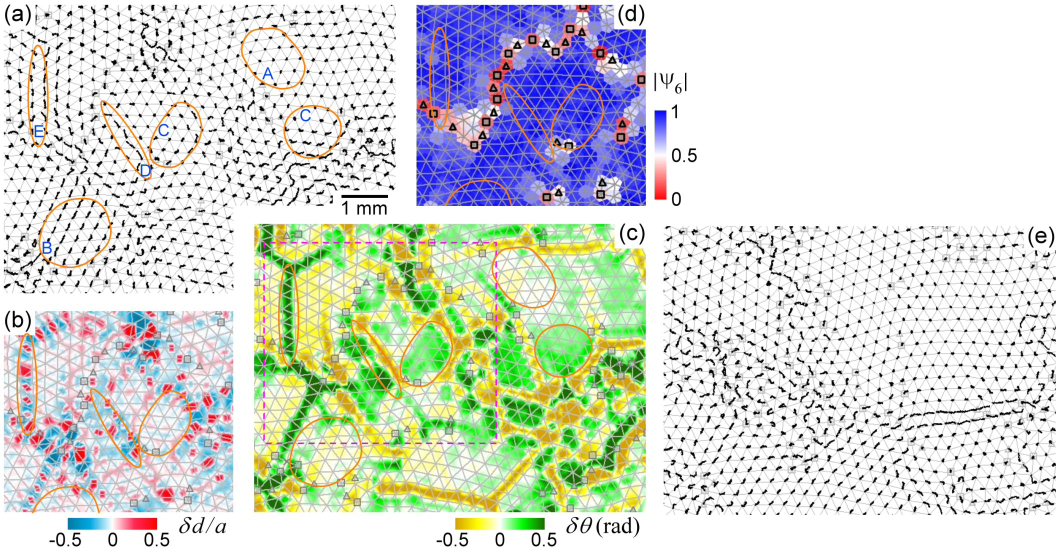

Figure 1: (a) to (c) The plots of dust trajectories, the bond length variation δd, the bond angle variation $\delta\theta$ in 7 s interval. The background triangulated grids show the initial dust configuration of the 7 s interval. The squares and the triangles correspond to the 7- and 5-fold defects respectively. The green (yellow) regions in (c) represent the counterclockwise (clockwise) rotations of the patches and the bonds in the narrow shear strips with one a in width. The connected shear strips with various lengths form a fractal skeleton through the liquid. The circled regions show the examples of different types of cooperative motions. (d) The corresponding $|\Psi_6|$ plot. (b) and (d) are from the region in the dashed rectangle of (c). (e) The plot of the 7s particle trajectory starting 7s later than that of (a). It shows the dynamical heterogeneity with the stick-slip cooperative rattling-hopping in different regions as time changes.

about 0.3 mm. The dust images illuminated by a thin laser sheet are recorded by a CCD through a microscope.

Figure 1 shows the typical 7s dust trajectories in the steady state after quench. The background triangulated grids indicate the initial particle configuration of each plot. The squares and triangles indicate 7- and 5-fold defects respectively. At first glance, the motion can be roughly classified into small amplitude cage rattling and cooperative hopping. Obviously, cooling leads to the transition from the string-dominated hopping to the band-dominated hopping. Single particle hopping only persists less than 1 a in length. By plotting the length variation δd and the angle variation $\delta\theta$ of the bonds connecting the adjacent particle pairs in 7 s (the structural relaxation time scale) in Fig. 1(b) and (c) respectively, the cooperative excitation can be further classified into: A) the static 2D patch with cage rattling, B) the rotating 2D patch, C) the drifting 2D patch, D) the 1D hopping string, and E) the 1D strip with strong shear and bond-breaking.

The bonds in the cooperative clusters from type A to D excitations all keep the same small δd. The strong relative shear motion of the adjacent cooperative clusters causes the formation of the type E excitation with large $\delta\theta$ and alternate bond-stretching and compression in the narrow strip with 1 a in width and various lengths along the cluster interface. Figure 1(e) depicts the 7s particle trajectory starting 7s later than that of Fig. 1(a). It shows the dynamical heterogeneity with the stick-slip cooperative rattling-hopping in different regions as time changes.

The skeleton composed of shear strips forms a time varying fractal network with fractal dimension about 1.61 [8]. The sizes of the cooperative clusters follow the power law distribution [7]. It manifests that the system exhibits multi-scale dynamics. Namely, the system can be viewed as many interacting and evolving cooperative patches with a wide range of spatial scales. Similarly to the single particle caging, each patch is caged by the surrounding patches. It is thereby interesting to know whether the motion of a coarse grained quasi-particle, i.e. the averaged motion of particles in a circle with radius r centered around certain single particle, also exhibits the similar anomalous diffusion governed by the caging dynamics? Figures 2(a) and 2(b) show the τ dependence of $\text{MSCD}_{r,\tau}$ at various r, and the n_r dependence of $\text{MSCD}_{r,\tau}$, where n_r is the number of the dust in the circle with radius r. The single particle MSD exhibits three different regimes: a) the cage rattling dominated sub-diffusion with scaling exponent $\beta <$ 1, at small τ, b) the hopping dominated super diffusion with $\beta > 1$, for the intermediate τ, and c) the random phase normal diffusion with $\beta \sim 1$ for τ greater than the averaged persistent time of a single hopping, which washes out the memory of persistent motion. The nearly parallel curves in Fig. 2(a) (especially for $r > 2$ a) and the power law scaling of $\text{MSCD}_{r,\tau}$ versus n_r in Fig. 2(b) manifest that the motion of the quasi-particle also follows the 3-stage anomalous diffusion governed by the cage rattling-hopping dynamics, similar to the single particle anomalous diffusion. With increasing r, the slightly increased scaling exponent β for the intermediate τ regime manifests the more persistent cooperative hopping. Note that, the scaling exponent γ = -1 if the motions of dusts are uncorrelated spatially, according to the central limit theory; and $\gamma = 0$ if the motions of all the dusts in the circle are the same. The deviation of the power law scaling from the descending tail in Fig. 2(b) implies the loss of self-similarity of the dynamics over certain spatial scales due to the loss of the spatial correlation of the cooperative motion.

In conclusion, we demonstrate that cooling leads to the formation of a more heterogeneous liquid with more cooperative excitation due to strong coupling in the more solid like crystalline ordered structure. The basic cooperative excitations can be classified into: A) the static 2D patch with cage rattling, B) the rotating 2D patch, C) the drifting 2D patch, D) the 1D hopping string, and E) the 1D strip with strong shear and bond-breaking. The strong shear strips form

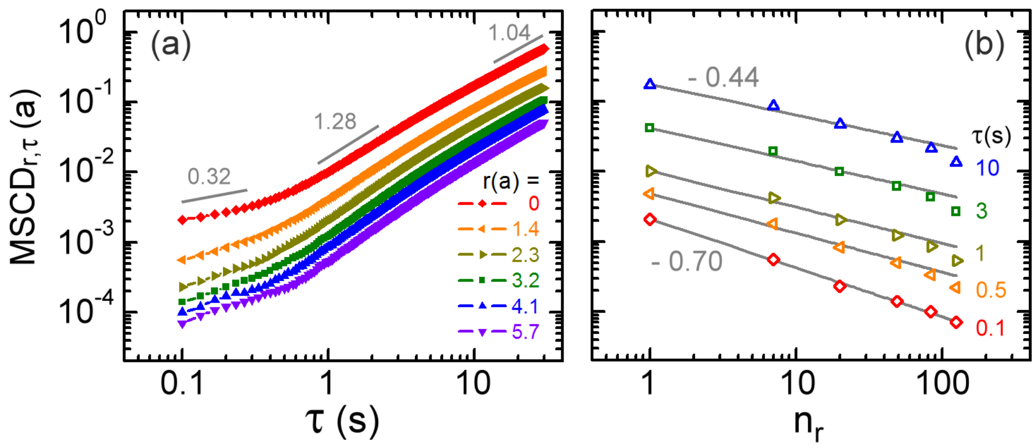

Figure 2: (a) $MSCD_{r,\tau}$ versus τ at different r for the cold liquid. (b) $MSCD_{r,\tau}$ versus n_r at different τ. The numbers by the straight gray line correspond to the scaling exponents.

a time varying fractal network. The cold liquid can be viewed as a time varying patchwork composed of multi-scale interacting and evolving patches. Similar to the cage rattling/hopping dynamics of a single particle, the coarse grained quasi-particle with a wide range of size also exhibits the self-similar three stage anomalous diffusion: sub-diffusion in the rattling dominated small τ, super-diffusion in the hopping dominated intermediate τ, and the random phase motion dominated normal diffusion at large τ.

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References

[1] Y. J. Lai and L. I, Phys. Rev. Lett. **89**, 155002 (2002).

[2] e.g. C.L. Chan, C.W. Io, and L. I, Contrib. Plasma Phys. **49**, 215 (2009), and the references there in.

[3] E. R. Weeks, J. C. Crocker, A. C. Levitt, A. Schofield, and D. A. Weitz, Science **287**, 627 (2000).

[4] M. D. Ediger, C. A. Angell, and S. R. Nagel, J. Chem. Phys. **100**, 13200 (1996).

[5] K. Watanabe and H. Tanaka, Phys. Rev. Lett. **100**, 158002 (2008).

[6] Z. Zhang, P.J. Yunker, P Habdas, and A.G. Yodh. Phys. Rev. Lett. **107**, 208303 (2011)

[7] Y.S. Su, C.W. Io and L. I, to be published in Phys. Rev. E.

[8] C. Yang, C.W. Io, and L. I, submitted to Phys. Rev. Lett.