Comment on "Long-Lived Giant Number Fluctuations in a Swarming Granular Nematic"

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Narayan et al. (Reports, 6 July 2007, p. 105) reported giant number fluctuations attributed to curvature-driven active currents specific for nonequilibrium nematic systems. We present data demonstrating that similar results can be found in systems of spherical particles due either to inelastic clustering or persistent density inhomogeneity, suggesting two alternative explanations for their results.

Narayan et al. (1) presented experimental evidence that a fluidized monolayer of macroscopic granular rods in the active nematic phase exhibits giant number fluctuations consistent with a standard deviation growing linearly with the mean, in contrast to the behavior expected for any situation in which the central limit theorem applies. These giant number fluctuations were attributed to curvature-driven active currents specific for nonequilibrium nematic systems.

Granular systems often exhibit statistical properties sharply distinct from their equilibrium counterparts, for example, non-Gaussian velocity distributions in dissipative gases (2, 3). Giant number fluctuations were predicted on the basis of perturbation analysis of a nearly spatially uniform state of a generic phenomenological model for active nematics (4). Although we do not question the possibility that giant fluctuations associated with nematic ordering may be present in the system analyzed by Narayan et al., on the basis of two complementary experiments with spherical particles we demonstrate that the linear growth of the standard deviation ΔN with the mean N can arise either from dynamic inelastic clustering or from persistent density inhomogeneity.

We performed experiments with monolayers of spherical grains energized either by mechanical vertical vibration (5) or by an alternating vertical electric field (6). Although the driving mechanisms are very different, the observed behavior is similar: a transition from the uniform gas state for high amplitude driving (vibration or electric field amplitude) to inhomogeneous phase-separated states at lower amplitudes of the driving. We analyzed ΔN versus N using two different coarse-graining procedures. The first procedure (P1, temporal averaging first) is identical to that

used by Narayan et al. (1). We partitioned the experimental system into M small subsystems of equal size L and measured the number of particles N_i in each subsystem. The fluctuation in a given subsystem was calculated from the series of N_i versus time by measuring the mean square deviation from the average N for that subsystem. The values of ΔN for all of the subsystems in the frame were then averaged and plotted against the average N for the experiment.

The results of our analyses (Fig. 1) are notably similar to that shown in Fig. 1B in Narayan et al. Namely, for the homogeneous gas-like states, we observed normal fluctuations $\Delta N/N^{1/2} \sim 1$ (Fig. 1, circles). When N approaches N_0, the value of $\Delta N/N^{1/2}$ goes to 0, approximately as $\Delta N/N^{1/2} = (1 - N/N_0)^{1/2}$. This dependence follows from the bimodal probability distribution. For intermediate values of the driving amplitude, the vibrated system shows localized transient high-density clusters that arise from the inelastic interparticle collisions and the interactions with the vibrating plate (5). In this regime, we find $\Delta N/N^{1/2}$ increases roughly as $N^{1/2}$, which implies that the standard deviation $\Delta N \sim N$ (Fig. 1, top panel, plus symbols). For even lower values of the driving amplitude, when our systems show phase separation and formation of dense clusters, we find that $\Delta N/N^{1/2}$ increases roughly as $N^{1/2}$, which implies that the standard deviation $\Delta N \sim N$ (Fig. 1, triangles). However, the fluctuations appear to be normal ($\Delta N/N^{1/2} \sim 1$) in the dilute regions of phase-separated states (Fig. 1, squares).

To highlight the importance of spatial heterogeneity, we also employed a second procedure (P2, spatial averaging first). The fluctuations in a single image were calculated as the root mean square deviation of the number of particles N_i in each subsystem from the global mean $N = N_0/M$ for that image (N_0 is the total number of particles in all of the subsystems). Then, the standard deviation extracted from a single image was averaged over all images and plotted versus the average of the global mean. For a homogeneous system with spatial and temporal correlations that are small compared with the system size and experiment duration, respectively, the two procedures should give the same result. For those conditions in which the data analyzed included only a single phase (Fig. 1, circles, squares, and plus symbols), the two averaging procedures produced identical results. For the systems exhibiting phase separation, procedure P2 produced $\Delta N/N^{1/2} \sim N^{1/2}$ (diamonds), as observed with procedure P1. However, the values of $\Delta N/N^{1/2}$ are considerably different between P1 and P2 in this case, highlighting

Fig. 1. $\Delta N/N^{1/2}$ versus N in mechanically vibrated system $N_0 = 1000$, 1-mm steel spheres (top panel) and electrostatically vibrated system $N_0 = 2800$, 0.15-mm bronze balls (bottom panel). The triangles (procedure P1) and diamonds (procedure P2) show fluctuations for the lower value of the driving force when the systems separate into dense and dilute regions (a insets). The solid line indicates $N^{1/2}$ slope. Circles show fluctuations in the uniform state (b insets) corresponding to higher values of the driving. Dashed line shows dependence $\Delta N/N^{1/2} = (1 - N/N_0)^{1/2}$. Squares show $\Delta N/N^{1/2}$ for the dilute regions of two-phase state shown in inset a. Plus symbols display $\Delta N/N^{1/2}$ for intermediate values of driving amplitude when the vibrated system shows localized transient high-density clusters.

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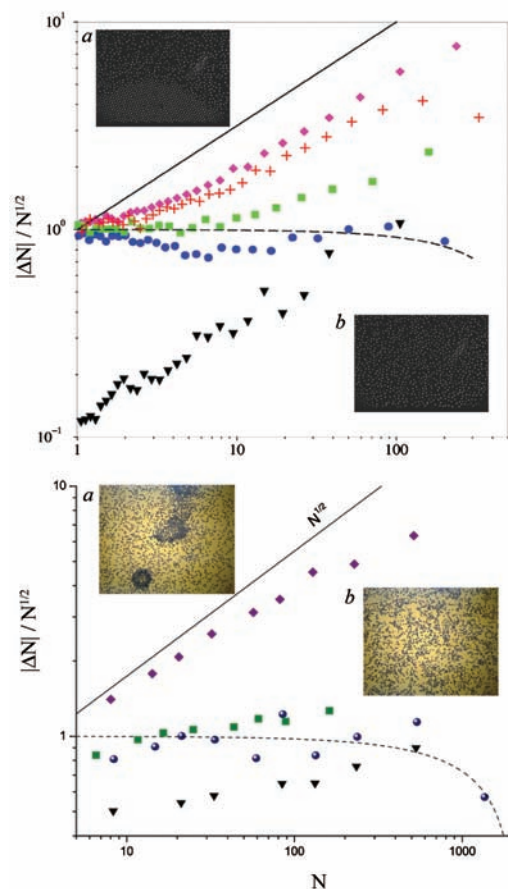*To whom correspondence should be addressed. E-mail: aranson@msd.anl.gov

the ambiguity inherent in performing any kind of spatial averaging in an inhomogeneous system.

These results indicate two distinct possible origins of the behavior reported by Narayan *et al.* in a system that is inelastic but clearly not nematic. One is dynamic inelastic clustering of the sort previously reported (*5*), and the other is static inhomogeneity. To investigate the presence of static inhomogeneity, we processed the data of Narayan *et al.* [movie S2 in (*1*)] over the entire duration of the experiment (45 min total) and calculated the resulting density distribution averaged over the time of the experiment. Figure 2 shows profound inhomogeneity (a density difference of a factor of 2 along the selected slice is shown as the dashed line). Similar, although noisier, curves are produced by averaging shorter segments of the movie. By contrast, the average density in the images for the homogeneous analyses was uniform to within 1%
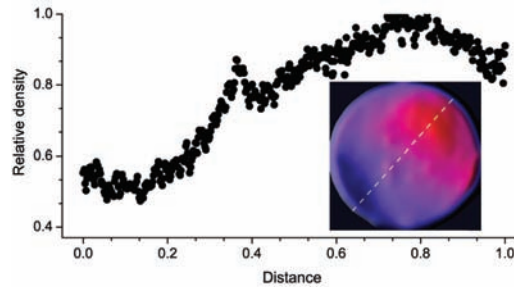

Fig. 2. Density distribution averaged over entire duration of experiment reported by Narayan *et al.* (*1*) and taken along the slice depicted by dashed line in the inset.

for the mechanically shaken experiment and even more uniform for the electrostatic experiment.

Thus, our results demonstrate that systems with spherical grains and persistent or dynamic inhomogeneous density distributions can show apparent giant fluctuations. The density inhomogeneity can appear either spontaneously due to

inelasticity of particles and/or due to imperfection of driving. In either case, the fluctuations will appear anomalous when analyzed with procedures appropriate for spatially homogeneous systems.

References and Notes
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