Ant collectives and their fluctuations

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Abstract: We know a lot about the behaviour of matter on equilibrium. In particular, we know fluctuations follow the central limit theorem. In contrast, only recently have we began to really understand how out of equilibrium active matter behaves. Here, we use fire ants and explore the relationship between ant number fluctuations and system size. We do this for two distinct ant states: a collective active state and a preferentially non-active state. We find that while fluctuations in the predominantly non-active state are similar to fluctuations in equilibrium systems, in the collective active there are giant number fluctuations

I. INTRODUCTION

Active matter is a term used to describe sets of particles, formed by a large number of individuals that can generate movement by themselves. Some examples of active matter are flocks of birds, school of fish or actin filaments propelled by molecular motors. Interesting behaviour of active matter can be self-healing materials or synchronous dynamics. One of the most classic examples is a flock of birds. It is interesting to see how the flock acts like a coherent and compact behaviour despite each bird's fly is independent from the others. The cilia of a paramecium or the ciliar fields in our trachea works in a similar way: they show a collective behaviour [1].

It has been observed that density fluctuations in active matter grow faster than linearly with system size, which is the situation in equilibrium systems [2]. In thermal equilibrium, a region of volume V, with an average number of particles $\langle N \rangle$, has $\langle (\Delta N)^2 \rangle \sim \langle N \rangle \sim V$. In contrast, for active matter systems this does not need to hold. In fact, $\langle (\Delta N)^2 \rangle \sim \langle N \rangle^\alpha$ with $\alpha > 1$; this is referred as Giant Number Fluctuations (GNF) [3]. Values for this exponent have been reported to be $\alpha = 1.6$ for point polar particle models or polar rods and $\alpha = 2.0$ for apolar rods or active nematics [2]. The physics of GNF relates to the ability to easily fluctuate along the direction of motion of the flock. In fact, the system is free to move collectively along any given direction. Hence regions in the system with aligned particles and thus net velocity, as schematically illustrated by the bottom blobs in Fig. 1, can easily change direction a time later, as schematically illustrated by the top blobs in the same figure, illustrating how this mode enhances fluctuations.

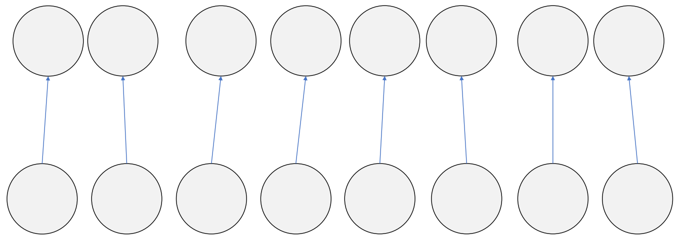

FIG. 1: Aligned regions in the system with non-zero net velocity ($|\vec{v}| \neq 0$. as represented by the bottom blobs, and their position a time Δt later (upper blobs).

An interesting example of active matter is ant collectives. In this work, I will be interested in studying the collective behavior of a colony of Fire ants, *Solenopsis invicta* [4]. Fire ants are well-known for their ability to self-assemble in structures such as waterproof rafts [5], hanging columns and towers [6]. Following research done in the group I have worked within, I we will explore number fluctuations of dense collectives of fire ants as a function of system size to address whether there are GNF. Since ant collectives are known to exhibit activity cycles whereby the system transitions between an essentially stalled and stationary state to an essentially all-moving collective state, we will analyze number fluctuations in either situation.

The work is organized as follows. The experimental setup and the ants as an experimental system are presented in Sec. II. The data analysis will be presented in Sec. III. Experimental results are presented in Sec. IV, and Sec. V consist of the conclusions.

II. EXPERIMENTAL SET UP AND SYSTEM

Our experimental setup consists of a closed Petri dish of (4.50 ± 0.02) cm where we introduce 0.5 g of ants corresponding approximately to 400 ants. The height of this closed Petri dish is approximately the height of an ant, restricting the movement of the ants in a 2D plane. Using a CCD camera, with a spatial resolution of 0.06 mm/px and acquisition rate of 3.75 fps, a grad student Caleb Anderson recorded the behavior of the ants a function of

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time, see Fig. 2.

Fire ants, the subject of our study, present some interesting characteristics. The average length and mass of the ants are $\ell \approx 2$ mm and $m \approx 1.3$ mg [7] (See Fig. 2). They are well known for their ability to arrange in structures. Another interesting aspect about is that they can change their mechanical properties like a liquid or resist deformations as a solid. On the one hand, if a coin is dropped in a 2D column of Fire Ants, they will move around to let it drop slowly, as if it was dropped in honey. On the other hand, if compressed they spring back [4]. Hence, fire ants collectives are viscoelastic.

III. IMAGE PROCESSING

Since the goal of this work is to study the fluctuations in the number of ants and how this depends on the system size, we will need to count the ants in the Petri dish. Due to the difficulty in identifying individual ants in dense systems, we will instead count the number of pixels that correspond to the area occupied by the ants. With this in mind we start by converting the original image [see Fig. 3 (a)] into a matrix with 0 value everywhere except for pixels corresponding to ants, which will have value 1. We will then apply a mask that leaves all 0 values out of he Region Of Interest (ROI), so that we only need to sum up the elements within the ROI to obtain the pixels associated to ants [see Fig. 3 (e)].

Fig. 3 shows an example of the complete image analysis process used in this work. First we binarize the original image [Fig. 3 (a)] into a logical image of 1's and 0's [Fig. 3 (c)] where pixels equal to 1 correspond to dark pixels in the original image and pixels equal to 0 to bright pixels. The threshold value to decide which pixels are dark or bright is chosen using the histogram in Fig. 3 (b), which has three differentiated regions: A first peak corresponding to the ants (darkest pixels), A second peak corresponding to the darker pixels of the four corners in the image, and a long shoulder that corresponds to the light grey background. Taking into account that after setting the threshold we apply a mask that will eliminate the corners of the image, we decide to set that threshold level at a value equal to 85. I indicated with an arrow in Fig. 3 (b). Values around this value do not change the final result.

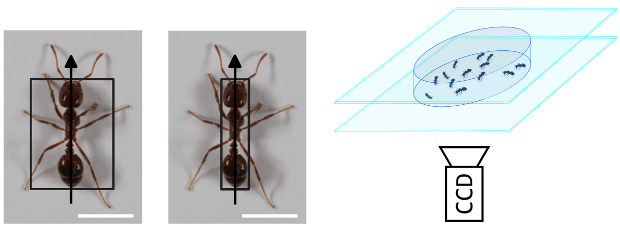

FIG. 2: LEFT: Picture of the fire ants used in the experiment (image extracted from [7]). They can be modelled by cylinders of $\ell = 2$ mm and $w = 1.40$ mm taking into account their legs or by cylinders of $\ell = 2$ mm and $w = 0.74$ mm if we only consider their bodies. Scale bars correspond to 1 mm. RIGHT: Sketch of the experiment conducted in Georgia Tech. Digital camera placed on top records the activity of ants placed in a Petri dish.

To obtain the dependence of between $\langle(\Delta N)^2\rangle$ and $R^2 \sim \langle N\rangle$ we have prepared masks of different radius. From now on, this radius will be taken relative to the Petri dish Radius R_T. Thus $R = R_i/R_T$ where R_i is the mask's radii. To confirm the image analysis procedure we can compare the original image with the binarized one, to see out we did not make appreciable errors.

IV. ACTIVE VS "INACTIVE" PERIODS

Dense collective of fire ants exhibit activity cycles with transitions between an essentially "inactive" and stationary state to an state where most of the collective is active.We study separately this two states of the collective motion. To determine which periods of time correspond to active and which ones to "inactive" we will define a measurement of activity. We note that what we call "inactive" still contains ant that move; in this "inactive" the ant collective have dynamical heterogeneities. We define activity by the amount of pixels that have "changed" their grey scale value between two consecutive images. This can be done straightforwardly by subtracting consecutive images and summing the values of the resultant image. Fig. 4 shows the result. We can see that for the "inactive" case, the sum of all pixels of the subtraction of two consecutive images would be less than if the ants are moving. From Fig. 4 we can determine the period of activity as the interval in which the measurement of activity is larger than a given threshold. For the current experiment the peak of activity is between 3×10^4 and 3.5×10^4 frames, those values correspond to times between 133 min and 156 min respectively (the active period lasts around 23 min).

Once we have identified both states, we proceed to analyze their fluctuations. To study the fluctuations in pixel number for different areas of the Petri dish we have created masks with radii ranging from $R = 0.05$ to $R = 0.8$, which are used to scan the whole picture, discarding those masks whose area falls out of the Petri dish. We do so for each frame inside the temporal range of study. Since we are interested in the standard deviation of the number of pixel (associated with the number of ants) we focus mainly on

$$\langle(\Delta N)^2\rangle = N^2 - \langle N\rangle^2 \,, \tag{1}$$

where $\langle N\rangle = \sum_{Frames} N_i/(\text{Number of frames})$, with N the number of counts or pixels with value 1, and $\Delta N = N - \langle N\rangle$ a fluctuation.

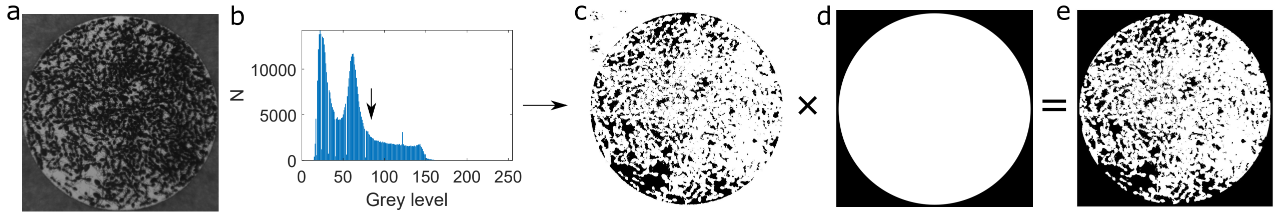

FIG. 3: Flow chart of the image processing. (a) Original image obtained in the laboratory. This is an 8-bit gray-level image. (b) Histogram of the grey levels. N states here for the number of pixels with a given grey level. The vertical arrow points to the chosen threshold to binarize the image in 0's (black pixels) and 1 (white) seen in (c). (d) Shows the mask applied to the binarized image (c) to finally obtained an image with 0's out of the region of interest.

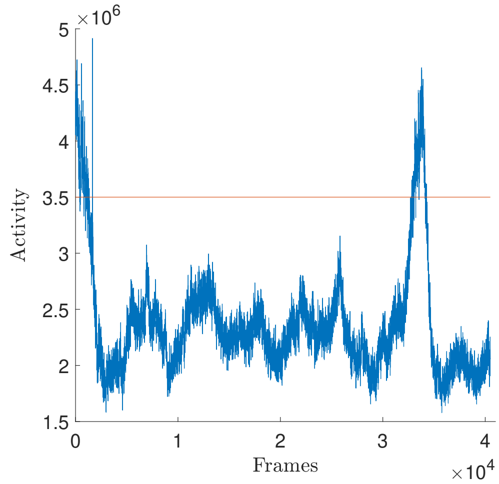

FIG. 4: Estimation of the ant's activity. We define the activity as the sum of all pixels from the matrix resulting from the subtraction of two consecutive images. The larger the difference between the images, the larger the activity. The horizontal line corresponds to the chosen threshold above which we consider the period of activity. In this particular case the activity threshold is set at 3.5×10^6.

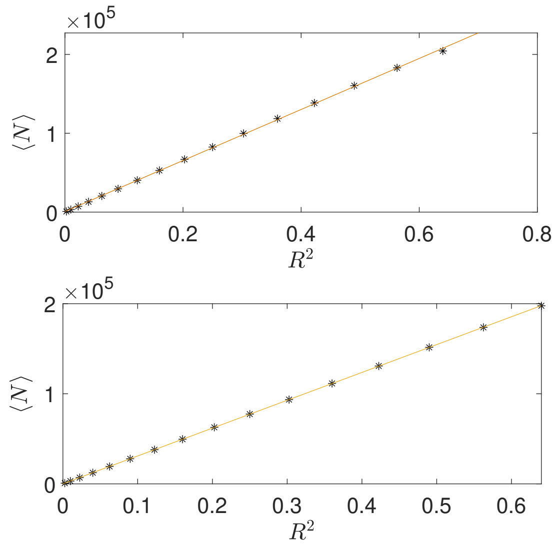

FIG. 5: $\langle N \rangle$ vs R^2. This graphic shows the linear behaviour of $\langle N \rangle$ versus the size of the mask. The top panel corresponds to "inactive" periods and bottom panel to "active" periods. R^2 can be easily related with the area, and so with $\langle N \rangle$ through the density. The straight line in both panels correspond to the linear fit to the data with slopes 3.2×10^5 for "inactive" systems and 3.1×10^5 for active systems.

Before studying the behavior of fluctuations with the system size, we want to verify that $\langle N \rangle \sim R^2$. Fig. 5 shows that $\langle N \rangle$ is indeed proportional to the mask surface, both in the active and "inactive" periods.

A. "Inactive" periods

During the "inactive" period, we can appreciate how many of the ants are still. We can see aggregates that span the whole Petri dish and a few ants that are moving. We never see a state that is motionless. However, compared to the active state this "inactive" is clearly far less active than those labelled as active states.

As we can see in Fig. 6 a power law behaviour is obtained. Making a log-log scale we can find the exponent is close to 1. The fit gives $\alpha_I = 1.14 \pm 0.03$. The values considered in the fit have $R \leq 0.6$ because for larger values, edge effects begin to appear and we see a clear change in behavior. This result implies $\langle (\Delta N)^2 \rangle \sim \langle N \rangle^{1.14}$ not far from the equilibrium result.

B. Active periods

During the active period, we can appreciate how most of the ants are in motion collectively and that they all move around.

As we see in Fig. 7 a power law behavior is obtained. In a log-log scale we can find a linear dependence and from a correspondent fit, we obtain an exponent of $\alpha_A = 1.72 \pm 0.02$. As before, we only consider

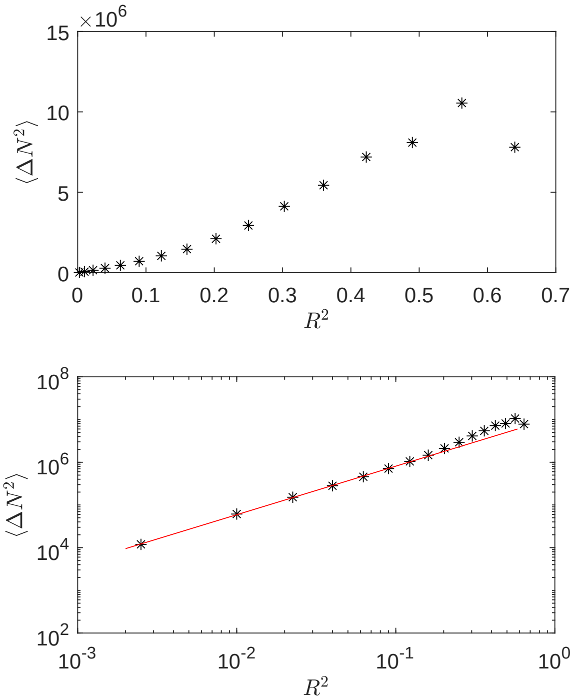

FIG. 6: Fluctuations vs R^2 in Inactivity cycle. This image shows the fluctuations in ant's number for different radius mask. The first graphic show a linear scale while the second graphic shows a logarithmic one. The straight line on the bottom panel is a fit to the data of a power-law, giving an exponent $\alpha_I = 1.14$

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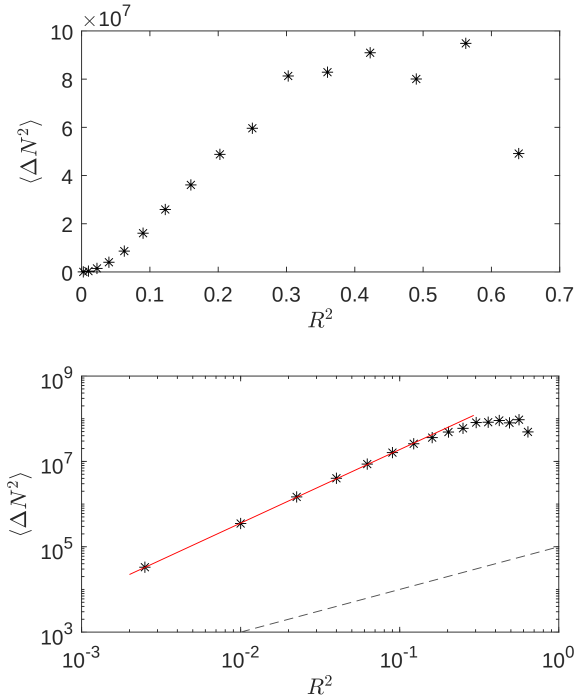

FIG. 7: Fluctuations vs R^2 in Activity cycle. This image shows the fluctuations in ant's number for different radius mask. The first graphic show a linear scale while the second graphic shows a logarithmic one. The straight line on the bottom panel is a fit to the data of a power-law, giving an exponent $\alpha_A = 1.72$. The dashed line is a guide to the eye of a linear relation.

points $R \leq 0.6$ because for greater values, edge effects begin to appear and the behavior changes. This result implies $\langle(\Delta N)^2\rangle \sim \langle N\rangle^{1.72}$, conclusively indicating that ants in the active state exhibit GNF. Furthermore, they fluctuate in a way comparable to polar rods [2]. This is reasonable since ants have a front and an end, and can be associated a vector pointing along their direction of motion (see Fig. 2)

V. CONCLUSION

For "inactive" ant collectives we have found $\alpha \approx 1.14$. This value is close to 1, which is the value expected for systems in equilibrium. The fact that there are fluctuations results from the dynamical heterogeneities in the "inactive" state. The closeness to 1 suggest that the moving ants in these states do so rather independently. For active ant collectives $\alpha \approx 1.72$ which is close to $\alpha = 1.6$ observed for polar rods. This result means there are GNF in collective active state. Furthermore, this indicates that active state are instances of collective motion.

This work is the beginning of other studies. A first step could be analyze other systems with a different $\langle N\rangle$. Once is known there is active and "inactive" states, this implies there is a transition between them. It would be interesting to pursue in that direction and quantify the transition. From the results of "inactive" states and their closeness to equilibrium, would be interesting to quantify the structural properties of the clusters and the dynamics of moving ants. These dynamic heterogeneities observed are also found in other active systems as cell migration [8]. Dynamic heterogeneity is a hallmark of systems approaching the glass transition like supercooled colloidal fluids [9].

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