Physica A 498 (2018) 96–101

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Transitions induced by speed in self-propelled particles system with attractive interactions

Dorilson. S. Cambui [a,b], Alexandre Rosas [c,*]

[a] Secretaria de Estado de Educação de Mato Grosso, 78049-909, Cuiabá, Mato Grosso, Brazil
[b] Universidade do Estado de Mato Grosso, UNEMAT, Departamento de Matemática, Barra do Bugres, Mato Grosso, Brazil
[c] Departamento de Física, Universidade Federal da Paraíba, Caixa Postal 5008, 58059-970, João Pessoa, PB, Brazil

HIGHLIGHTS

- We study the order–disorder transition in a self-propelled particles model.
- We find that the speed induced transition can be continuous or discontinuous depending on the intensity of the noise.
- For weak noise the transition is discontinuous while for strong noise it is continuous.

ARTICLE INFO

Article history:
Received 4 October 2017
Received in revised form 28 November 2017

Keywords:
Biological systems
Collective motion
Self-propelled particles
Phase transitions
Collective behavior rules

ABSTRACT

In this work, we consider a system of self-propelled particles with attractive interactions in two dimensions. The model presents an order–disorder transition with the speed playing the role of the control parameter. In order to characterize the transition, we investigate the behavior of the order parameter and the Binder cumulant as a function of the speed. Our main finding is that the transition can be either continuous or discontinuous depending on two parameter of the model: the strength of the noise and the radius of attraction.

1. Introduction

Biological systems, such as flocks of birds [1], herds of mammals [2], insect swarms [3], bacterial populations [4], and schools of fish [5], are examples of organized animal groups observed in nature. Such behavior is a natural phenomenon widely observed in the nature. In animal aggregates, collective motion may emerge through numerous interactions between individuals near each other, and a variety of spacial–temporal patterns might be generated. Some well-known patterns, which occur in fish schools [6], for instance, are milling (individuals constantly rotate around an empty core), schooling (individuals move aligned with each other), and swarming (aggregate without any correlation between the velocities). There are many potential benefits from this gregarious behavior, including defense against predators, increase in the reproduction rate and so on [7]. Collective motion patterns observed in nature can be simulated using different models. This is the case of agent-based models of animal grouping used to investigate systems like schools, flocks, and swarms. Agent-based models present different collective states depending on some particular parameters, such as the strength of the noise [6,8]. In real animal groups, it is well known that the speed plays an important role in the emergence of collective states, and as a natural

* Corresponding author.
E-mail address: arosas@fisica.ufpb.br (A. Rosas).

https://doi.org/10.1016/j.physa.2018.01.021
0378-4371/

consequence, transitions between these states or "phases" can occur. In such systems, high velocities can speed up the interactions and transitions were found to be speed dependent [9].

Several models have been developed in order to capture the collective behavior of animal groups [10–15]. In this context, self-propelled particle models have become an important tool in various studies involving collective motion of biological aggregates [1,6,12,14]. In order to study some aspects of the emergence of collective motion, Vicsek et al. [12] proposed a minimal model which mainly focused on emergence of directional alignment in self-propelled particle systems. In their model, each individual moves at the same speed in the average direction of motion of its neighbors, and a noise term is considered to take into account possible measurement errors in the direction of the neighbor's movement. The model exhibits a non-equilibrium phase transition from a disordered motion phase (strong noise/low density, with no orientation order) to ordered phase (weak noise levels and large density, with velocities alignment). That is, the ordered motion phase can occur either by decreasing the noise level or by increasing the density [16,17], with a transition occurring when the noise or density reaches a critical value. From a biological perspective, similar transitions have been observed in fish [18,19], in the collective dynamics of crawling cells [20] and marching locusts [21].

In their original paper, Vicsek et al. claimed that the order–disorder phase transition exhibited by the model corresponds to a continuous phase transition, when the noise (typified by some authors as angular noise [22]) is introduced (only) after the alignment interactions, from which the particles may decide which direction to take up. Although it is still under discussion, the character of this transition was confirmed by later works of the same group [23–25], and later results obtained by other authors are consistent with a continuous transition [16,26–28]. However, the nature of the transition has been questioned. In the physics literature, phase transitions in the Vicsek system have been widely studied, and much controversy has surrounded its nature resulting in a number of studies, which has debated in details whether it is continuous or discontinuous [22,29–31]. Within this framework, the authors of Ref. [32] introduced the so-called vectorial noise model (where the noise arises from each interaction), and showed, using numerical simulations, that the phase transition appears to be discontinuous. On the other hand, Aldana et al. [28] concluded that nature of the transition depends on the different noise implementations into the system (if angular or vectorial). However, other factors can also affect the nature of the transition. Effects of the vision angle on the phase transition behavior has been investigated [33,34]. In [27] the transition character seems to depend on particle velocities, and in [35] the discontinuous nature arises, with phase coexistence and hysteresis, for a system of sufficiently large size. For small velocity regime [36] the order–disorder transition was found to be of continuous.

Phase transitions of systems consisting of self-propelled particles as a function of the noise intensity has been extensively studied in recent years [27,36–40]. However, the analysis of the phase transition as a function of the speed of the self-propelled particles is still lacking in the literature. The speed is a preponderant factor for the formation and maintenance of behavioral patterns in groups of animals in motion. In fact, recent results have shown that transitions between collective behavior states in fish schools occur through the gradual increase of the speed [41]. Therefore, in this paper we study the velocity induced phase transition in an agent-based self-propelled particle model. It has already been shown in the literature that a continuous phase transition occurs for a small speed regime, while in the large speed regime there is a discontinuous phase transition as a function of the strength of the noise [36]. Here we adopt a complementary strategy, that is, we focus on the effects of speed variation on the phase transition. We investigated the behavior of the order parameter as a function of the speed at different values of noise and attraction radius.

The remainder of this paper is organized as follows. In Section 2 we describe the self-propelled particles model. In Section 3, we present and discuss the results and brief conclusions are given in Section 4.

2. Model description and simulation parameters

The system is represented by N identical particles. Each particle i is characterized, in time, by its position $\mathbf{r}_i$ and velocity $\mathbf{v}_i$ in a square lattice of side L. Interaction takes place at discrete time steps of length $\tau = 1$ and, at each time step, new positions are updated according to,

$$\mathbf{r}_i(t+\tau) = \mathbf{r}_i(t) + \mathbf{v}_i(t)\tau. \tag{1}$$

The model is composed for two interaction regions called attraction zone, with radius r_a, and orientation zone, with radius r_o, as illustrated in Fig. 1. These zones are used to define behavioral rules of motion of the individuals. In addition, the model also contain a "neutral" zone, in which the individuals continue to move without being disturbed by any other individual. This neutral behavior only takes place, for a given individual, if there is no other individual either in its attraction or in its orientation zone.

When the individual finds itself far, but not too far, apart from the group, it will try to reach the others to get together, adding cohesiveness to the group. This is the behavior characteristic of the agents in the attraction zone. It is important to emphasize that the individuals interact with their neighbors according to the distance d_{ij} between them. If there are individuals in the attraction zone (but not in the orientation zone) of the ith individual $r_o < d_{ij} < r_a$, there is a tendency of the ith individuals to move toward them. This attractive behavior is modeled by redirecting its velocity to the average position of the neighbors (see Ref. [6]),

$$\mathbf{d}_i^{(att)} = \frac{\sum_{j\in A} \mathbf{r}_{ij}}{\left|\sum_{j\in A} \mathbf{r}_{ij}\right|}, \tag{2}$$