Physica A 392 (2013) 3240–3247

Contents lists available at SciVerse ScienceDirect

Physica A

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

Gregarious versus individualistic behavior in Vicsek swarms and the onset of first-order phase transitions

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HIGHLIGHTS

- We extend the standard Vicsek model to allow particles with individualistic behavior.
- A relatively small probability of individualistic motion is sufficient to drive the system from order to disorder.
- The new phase transition is discontinuous, as opposed to the Vicsek model's noise-driven continuous phase transition.

ARTICLE INFO

Article history:
Received 14 August 2012
Received in revised form 18 February 2013
Available online 10 April 2013

Keywords:
Self-propelled particles
Vicsek model
Flocking
Swarming

ABSTRACT

The standard Vicsek model (SVM) is a minimal non-equilibrium model of self-propelled particles that appears to capture the essential ingredients of critical flocking phenomena. In the SVM, particles tend to align with each other and form ordered flocks of collective motion; however, perturbations controlled by a noise term lead to a noise-driven continuous order–disorder phase transition. In this work, we extend the SVM by introducing a parameter α that allows particles to be individualistic instead of gregarious, i.e. to choose a direction of motion independently of their neighbors. By focusing on the small-noise regime, we show that a relatively small probability of individualistic motion (around 10%) is sufficient to drive the system from a Vicsek-like ordered phase to a disordered phase. Despite the fact that the α-extended model preserves the $O(n)$ symmetry and the interaction range, as well as the dimensionality of the underlying SVM, this novel phase transition is found to be discontinuous (first order), an intriguing manifestation of the richness of the non-equilibrium flocking/swarming phenomenon.

1. Introduction

Swarming and flocking arise as emergent phenomena of collective motion behavior in a large variety of living and non-living self-propelled particle systems of great interdisciplinary interest. Nature offers a huge variety of collective motion phenomena in self-propelled living systems at all scales, from biomolecular micromotors, migrating cells and growing bacteria colonies, to insect swarms, fish schools, bird flocks, mammal herds, and even human crowds [1]. Moreover, many non-living systems of great practical interest involve collective motion and swarming behavior, particularly in robotics, where swarms of robots are used in terrain exploration, plague control, optimization of telecommunication networks, surveillance and defense, and other tasks without centralized control that appear too challenging to be carried out by an individual agent [1]. Very recently, the novel concept of chemical robots (also known as *chobots*) has been envisioned as

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http://dx.doi.org/10.1016/j.physa.2013.03.036

an army of millions of micrometer-sized robots whose tasks will be to release a chemical payload, or to mix two chemical reactants from different compartments within the chobots when they reach their goal [2].

Instead of focusing on the specific details that make each of these self-propelled systems unique, statistical physicists have been studying the general patterns of collective motion, aiming to identify the general laws and underlying principles that may govern their behavior. From this perspective, one important question to address is the onset of ordered macroscopic phases, i.e. the way in which individuals having short-range interactions are capable of self-organizing into large-scale cooperative patterns in the absence of leaders or other ordering cues from the environment. By analogy with large molecular systems, flocking and swarming phenomena can be associated with phase transitions that depend on a few parameters that characterize the macroscopic states, such as the density of individuals and the flock size. For instance, Buhl et al. [3] investigated the collective motion of locusts, which display a density-driven transition from disordered movement of individuals within the group to highly aligned collective motion. Similar transitions have been observed in the collective motion of zooplankton swarms [4], fish schools [5], and many other self-propelled particle systems (see [1] and the references therein).

On the theoretical side, Vicsek et al. [6] proposed a minimal model to study the onset of order in systems of self-driven individuals, which was later followed by other investigations by means of agent-based modeling [7–9], the Newtonian force-equation approach [10,11], and the hydrodynamic approximation [12–14]. The so-called standard Vicsek model (SVM) [6] assumes that neighboring individuals tend to align their direction of movement when they are placed within a certain interaction range. This alignment rule, which would trivially lead to fully ordered collective motion, is complemented by a second one that introduces noise in the communications among individuals. In their seminal paper, Vicsek et al. show that the noise amplitude drives the system through a continuous second-order transition between an ordered phase of collective motion and a disordered phase.

In this context, the aim of this work is to explore an extension of the SVM, in which an additional parameter α is introduced to control the gregarious versus individualistic behavior of particle motion. That is, an individual has a probability α of adopting its own direction of motion regardless of its neighbors, and a probability $1-\alpha$ of moving according to the SVM's rules. This α-extended model may account for "free-will" behavior in biological systems (i.e. the fact that living organisms are not ruled by fixed decision algorithms and are therefore able to make unforeseen individualistic decisions at any time) as well as for random failures in robotic and other artificial self-propelled particle systems (e.g. the chemically driven *chobots* mentioned above). By focusing on the small-noise regime, we show that a relatively small probability of individualistic motion (around 10%) is sufficient to drive the system from a Vicsek-like ordered phase to a disordered phase. Besides the practical interest of extending the well-studied SVM to novel scenarios of particle behavior, we find a theoretically intriguing manifestation of the richness of the swarming phenomenon, namely that the α-driven phase transition is discontinuous (first order), despite the fact that the α-extended model preserves the $O(n)$ symmetry and the interaction range, as well as the dimensionality of the underlying SVM.

The rest of this paper is organized as follows. In Section 2, we present the definition of the SVM and the α-extended model. Section 3 presents a discussion of our results, while our conclusions are presented in Section 4.

2. The standard Vicsek model (SVM) and the α-extended model

The SVM [6] consists of a fixed number of interacting particles, N, which are moving on a plane. In computer simulations, that plane is typically represented by a square of side L with periodic boundary conditions [6,15]. The particles move off the lattice with constant and common speed $v_0 \equiv |\vec{v}|$. Each particle interacts locally adopting the direction of motion of the subsystem of neighboring particles (within an interaction circle of radius R_0 centered in the particle considered), which is perturbed by the presence of noise. Since the interaction radius is the same for all particles, we adopt the interaction radius as the unit of length throughout, i.e. $R_0 \equiv 1$. The model is implemented as a cellular automaton, i.e. all particles update their states simultaneously in one time step.

The updated direction of motion for the ith particle, θ_i^{t+1}, is given by

$$\theta_i^{t+1} = \mathrm{Arg}\left[\sum_{\langle i,j\rangle} \mathrm{e}^{\mathrm{i}\theta_j^t}\right] + \eta\xi_i^t, \tag{1}$$

where η is the noise amplitude, the summation is carried over all particles within the interaction circle centered at the ith particle, and ξ_i^t is a realization of a δ-correlated white noise uniformly distributed in the range between $-\pi$ and π.

In this work, we implement the model dynamics by adopting the so-called forward update (FU) rule, in which the updated velocities at time $t+1$ determine the new positions according to

$$\vec{x}_i^{\,t+1} = \vec{x}_i^{\,t} + \vec{v}_i^{\,t+1}\Delta t, \tag{2}$$

where $\Delta t \equiv 1$ is the unitary time step of the cellular automaton. This scheme is used for computational convenience, since the transient length is shorter than using the backward update rule that determines the new velocities *after* the positions are updated. In the context of Vicsek model studies, the FU rule was first introduced by Chaté et al. [16,17]. As explained in Ref. [18], the FU scheme requires one to implement an algorithm that ensures the $O(n)$ rotational invariance of the SVM,