Physica A 418 (2015) 65–77

Contents lists available at ScienceDirect

Physica A

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

An introduction to the physics of active matter

G. De Magistris, D. Marenduzzo [*]

SUPA, School of Physics and Astronomy, University of Edinburgh, JCMB King's Buildings, Mayfield Road, Edinburgh EH9 3JZ, Scotland, United Kingdom

HIGHLIGHTS

- We review some introductory features of active matter physics.
- We show how to model growing microbial colonies.
- We discuss the physics of self-motile systems.
- We provide an introduction to the physics of active gels.

ARTICLE INFO

Article history:
Available online 27 July 2014

Keywords:
Active matter
Nonequilibrium physics

ABSTRACT

In these notes we provide an introductory description of the physics of active matter, focusing on theoretical aspects, and on some methods which are often used in the field. We discuss a selection of active systems, where activity comes from different microscopic sources (mainly self-replication, self-propulsion, non-thermal forces), and in all cases we focus on their statistical physics and emergent collective behaviour, which is often linked to underlying nonequilibrium phase transitions. We hope to convey the idea that this field is a fascinating growing area of research at the interphase between statistical, soft matter and biological physics, and that active matter systems can possess, in general, a much richer physics than their passive counterparts.

1. Introduction

In these notes we provide a simple introduction to the physics of active matter, or of active systems. For our purposes, *active matter* is a collection of active particles; these are "particles which absorb energy from their surroundings or from an internal fuel tank and dissipate it to engage in a variety of non-equilibrium activities, usually, but not solely, connected to motility, growth or replication" (this definition is an adaptation from those in Refs. [1,2], which are respectively one of the first papers on soft active materials and an experimentally-oriented review of active colloidal systems).

Examples of systems which are traditionally considered as active matter are: suspensions of swimming bacteria, or of other motile microorganisms, cell suspensions, and collections of cytoskeletal filaments, such as filamentous actin fibres or microtubules, and molecular motors, such as myosin or kinesin. Activity is linked to either self-replication (or growth) and self-motility in bacterial and microbial suspensions, while it arises from actin and microtubule polymerisation (or treadmilling) and from motor-exerted (non-thermal) forces for cytoskeletal gels. We will consider all these cases in these notes, but our underlying model system for active matter will be a bacterial suspension (a collection of bacteria, which can move and/or reproduce), as this is a relatively simple system, and has been studied extensively as a paradigm of active matter.

---

[*] Corresponding author. Tel.: +44 0 1316505289.
E-mail address: dmarendu@ph.ed.ac.uk (D. Marenduzzo).

http://dx.doi.org/10.1016/j.physa.2014.06.061
0378-4371/© 2014 Elsevier B.V. All rights reserved.

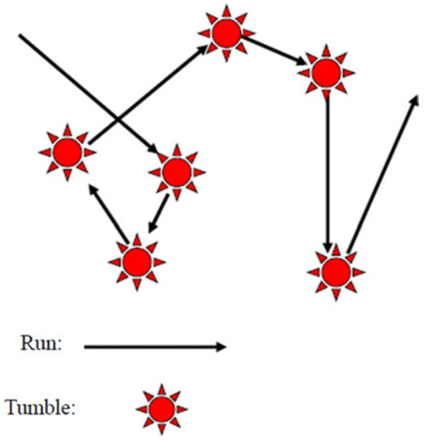

Fig. 1. Sketch of the run and tumble dynamics typical of bacteria; here the tumble rate is constant in time.
Source: Figure taken from Ref. [5], with permission.

Our notes consist in four sections, each covering a distinct aspect of activity. Thus, after an introduction of simple generic properties of active particles, we discuss systems where activity comes from growth (or self-replication), followed by a description of some aspects of the physics of self-motile systems, in the absence or presence of aligning interactions which play a major role in determining their behaviour. Finally, we provide a short description of the hydrodynamics of active gels, where activity comes from the "stirring", or non-thermal forces exerted on the external fluid by active particles, e.g. when they move (in the case of bacteria). We should also stress that there are a number of excellent reviews on the topic of active matter, and we mention here [2–5], which all provide a comprehensive, and research-oriented, complement to these notes. These also provide a more comprehensive list of references.

2. Active particles as "hot colloids"

Let us begin by considering a solution of swimming bacteria (*E. coli* for concreteness). The way bacteria such as *E. coli* move is via a characteristic run-and-tumble dynamics (Fig. 1). Essentially, these bacteria move in a straight line during a "run", at a velocity $v \sim 10\text{–}30\ \mu\text{m/s}$, then change direction (to a first approximation randomly) in a "tumble", after which they move straight for another "run", etc. The duration of each run, τ (which also equals the time lapse between two successive tumbles) is on average about 1 s, while the "tumble" is much faster (about an order of magnitude), hence it can be modelled, to begin with, as instantaneous.[1]

It is intuitively apparent that, after many tumbles, the motion of a single swimming bacterium is effectively diffusive, and the diffusion coefficient can be estimated quite simply as,

$$6D_{\text{eff}}t = \langle \boldsymbol{r}^2 \rangle \tag{2.1}$$

where $\boldsymbol{r}$ is the distance covered after N runs

$$\boldsymbol{r} = \sum_{i=1}^{N} \Delta \boldsymbol{x}_i. \tag{2.2}$$

Assuming that the run length, $l_{\text{run}} = v\tau$, is constant, and that the directions of the runs are completely uncorrelated with each other, we obtain

$$6D_{\text{eff}} = \sum_{i,j=1}^{N} \langle \Delta \boldsymbol{x}_i \Delta \boldsymbol{x}_j \rangle / (N\tau) = \sum_{i,j=1}^{N} \delta_{ij} l_{\text{run}}^2 / (N\tau) = l_{\text{run}}^2 / \tau. \tag{2.3}$$

Note that a better approximation is to say that there is a constant probability to tumble (so that the run length is not constant but fluctuates), this Poissonian assumption leads to $D_{\text{eff}} = v^2\tau/3$ instead of $D_{\text{eff}} = v^2\tau/6$, but the order of magnitude is the same.

It is useful to compare and contrast a suspension of (non-interacting) run-and-tumble bacterial swimmers to a dilute solution of colloids, or hard spheres, which is a well known thermodynamic (passive) system, to which our bacterial suspension

---

[1] The microscopic mechanisms leading to the switch between run and tumble "modes" are intriguing and non-trivial, we are not concerned with them here, the interested reader is referred, for instance, to Ref. [2] and Refs. therein.