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Active colloids in complex fluids

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ABSTRACT

We review recent work on active colloids or swimmers, such as self-propelled microorganisms, phoretic colloidal particles, and artificial micro-robotic systems, moving in fluid-like environments. These environments can be water-like and Newtonian but can frequently contain macromolecules, flexible polymers, soft cells, or hard particles, which impart complex, nonlinear rheological features to the fluid. While significant progress has been made on understanding how active colloids move and interact in Newtonian fluids, little is known on how active colloids behave in complex and non-Newtonian fluids. An emerging literature is starting to show how fluid rheology can dramatically change the gaits and speeds of individual swimmers. Simultaneously, a moving swimmer induces time dependent, three dimensional fluid flows that can modify the medium (fluid) rheological properties. This two-way, non-linear coupling at microscopic scales has profound implications at meso- and macro-scales: steady state suspension properties, emergent collective behavior, and transport of passive tracer particles. Recent exciting theoretical results and current debate on quantifying these complex active fluids highlight the need for conceptually simple experiments to guide our understanding.

1. Introduction

Active fluids are ubiquitous in nature and permeate an impressive range of length scales, ranging from collectively swimming schools of fish (~km) [1] and motile ants (~mm) [2] to microorganisms (~μm) [3,4•,5,6] and molecular motors within individual cells (~nm) [7,8]. Suspensions of active particles, commonly defined as self-propelling particles that inject energy, generate mechanical stresses, and create flows within the fluid medium, constitute so-called *active* fluids [9•,10•]. This internally-injected energy drives the fluid out of equilibrium (even in the absence of external forcing) and can lead to swirling collective behavior [11] and beautiful pattern formation [12,13], that naively appear unique to life. Indeed, the motility of swimming microorganisms such as nematodes, bacteria, protozoa and algae has been a source of wonder for centuries now. Anton van Leeuwenhoek, upon discovering bacteria in 1676, observed, "*I must say, for my part, that no more pleasant sight has ever yet come before my eye than these many thousands of living creatures, seen all alive in a little drop of water, moving among one another*" [14]. Since then, scientists have observed and classified other collective large-scale patterns in active fluids, such as vortices [15,16], flocks [17•], and plumes [18–20] that form at high concentrations of their organisms and highlight the link between life, fluid motion and complex behavior. Surprisingly, recently developed synthetic materials/particle have also exhibit these life-like complex behaviors. Examples are shaken granular matter [21,22•], phoretic colloidal particles [23•,24•], soft field-responsive gels [25•], and, included in this review, externally-actuated artificial swimmers [26–29•].

These active particles (living or synthetic, hard or soft), as collected in Fig. 1, have sizes that range from a few tenths of a micron to a few hundred microns, spanning colloidal length scales over which thermal noise is important [30•]. The motion of these active colloids allows one to either direct (channel) or extract (harness) the energy injected at one length scale at other scales. For instance, activity can render large, normally athermal spheres diffusive [31] and yield controllable, directed motility of micro-gears [32,33•,34•].

Recently, there has been much interest in the production and dynamics of suspensions of active colloids [10•]. The study of such active suspensions is driven by both practical and scientific relevance. From a technological and engineering standpoint, active suspensions play an integral role in medical, industrial, and geophysical settings. The spread and control of microbial infections [35,36], design of microrobots for drug delivery [37] or non-invasive surgery [27], biofouling of water-treatment systems [38] and biodegradation of environmental pollutants [39] are just a handful of examples. From a scientific standpoint, active suspensions are interesting in their own right because they are non-equilibrium systems that exhibit novel and unique features such as turbulence-like flow in the absence of inertia [40,41•], anomalous shear viscosities [42•,43,44•], enhanced fluid mixing [45•,46•], giant density fluctuations [15,22•] and liquid crystal-like orientational ordering [47]. Because these features are generic to many other active materials

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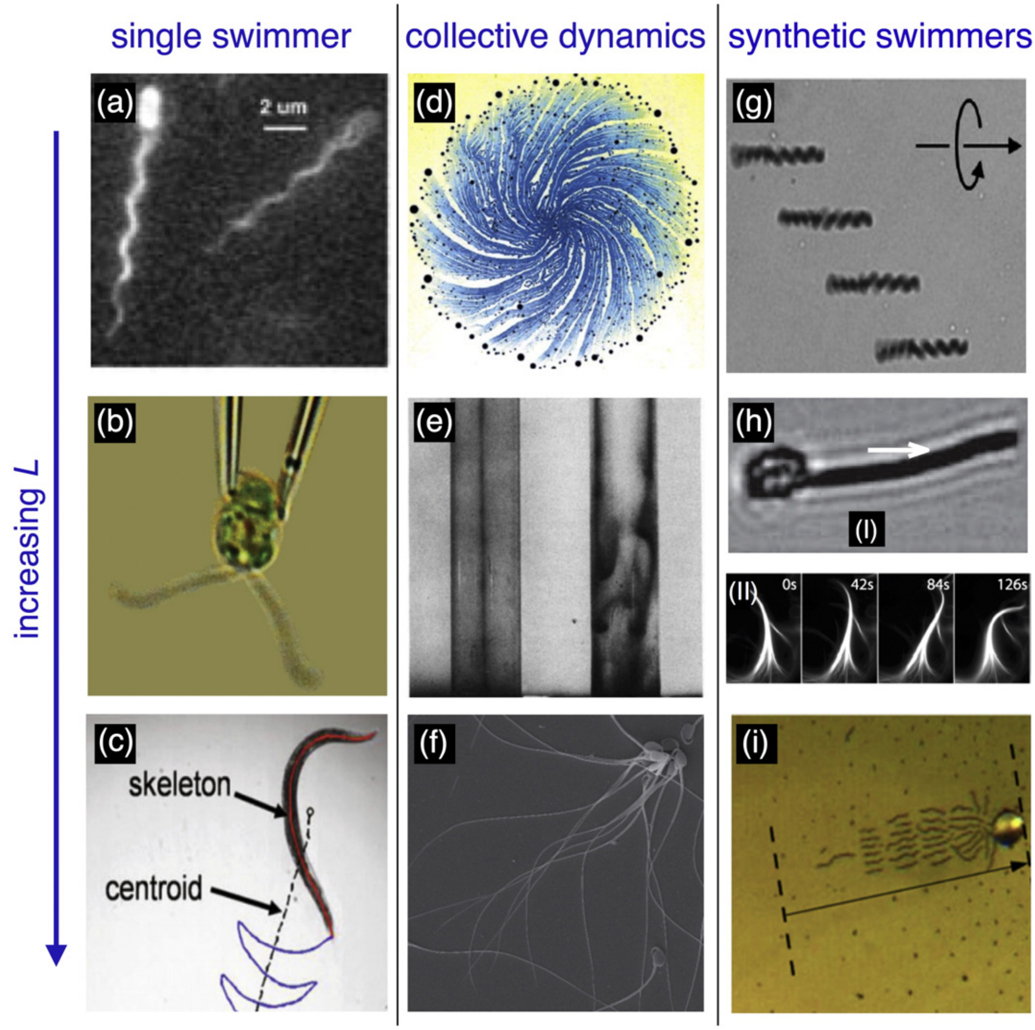

Fig. 1. An overview of active colloidal systems—natural and synthetic. (a)–(c): Individual natural swimming microorganisms arranged in order of increasing size: (a) prokaryotic bacterium *Escherichia coli* with cell body approximately 2 μm [48], (b) eukaryotic unicellular alga *Chlamydomonas reinhardtii* with a cell body that is approximately 8 μm [5], and (c) multi-cellular organism *C. elegans* that is approximately 1 mm long [49]. (d)–(f) Examples of collective behavior of microorganisms: (d) a bacterial colony of *P. vortex* on agar [50], (e) bioconvection of algae under shear [18], and (f) cooperative behavior in sperm [51]. (g)–(i) Synthetic swimmers: (g) field driven translation of helical magnetic robots [52], (h:A) magnetically driven chain comprised of paramagnetic spheres attached via DNA strands [26], (h:B) metachronal waves generated by reconstituted microtubule-motor extracts [53•], and (i) magnetically driven surface snakes comprised of self-assembled 80–100 μm spheres [54].

(e.g. cell, tissues, vibrated granular matter), active suspensions also serve as a toolbox for understanding and deciphering generic features of active materials across many length scales.

The suspending fluid in these active (colloidal) suspensions can be simple and Newtonian (e.g. water) or complex and non-Newtonian. Complex fluids are materials that are usually homogeneous at the macroscopic scale and disordered at the microscopic scale, but possess structure at intermediate scale. Examples include polymeric solutions, dense particle suspensions, foams, and emulsions. These complex fluids often exhibit non-Newtonian fluid properties under an applied deformation (e.g. shear) including viscoelasticity, yield-stress, and shear-thinning viscosity. An overarching goal in the study of complex fluids is to understand the connection between the structure and dynamics of the fluid microstructure to its bulk flow behavior [55,56]. For example, recent experiments by Keim and Arratia [57,58], which visualize a monolayer of dense colloidal particles under cyclic shear at low strains, have shown how local particle re-arrangements connect to the suspension bulk yielding transition. This work highlights how local measures of the microstructure can shed new light on the bulk material response in an amorphous material.

In active fluids, it is even more challenging to link the activity at the microscale to the fluid meso- and macro-scales. For instance, living tissues are continuously exposed to stimuli, which can lead to growth and remodeling of their structure. This remodeling in the tissue microstructure is often implicated in medical conditions such as asthma. Recent work by Park et al. [59] has shown how tissue microstructural details, such as cell shape, affect bulk properties, such as fluidity and rigidity. In a similar vein, recent experiments have shown that the interplay between the motion of active particles and the complex fluid rheology of the suspending medium leads to a number of intricate and often unexpected results. In particular, the local mechanical stresses exerted by microorganisms in an active colloidal suspension can alter the local properties of its environment [60,61]; while simultaneously, the complex fluid rheology modifies the swimming gaits and diffusion of individual organisms [62,63•]. It is essential to understand this two-way coupling in order to uncover the universal principles underlying these active complex materials and in order to design and engineer new active materials.

In this paper, we review recent work on active colloids moving in fluidic environments and show how recent theory and experiments can elucidate the connections between microscale descriptions and the resulting macroscale collective response. We begin in Section 2 at the level of individually swimming colloids and how their motion couples to the suspending Newtonian (Section 2.1) and non-Newtonian