ACTIVE FLUIDS

Rolling sound waves

A quantitative description of sound wave propagation in suspensions of self-propelled colloidal particles is achieved by combining microfluidics, video microscopy and theory.

Jörn Dunkel

From birdsong to human speech, sound is one of the most widely used means of communication among higher life forms. The conceptual foundations for our current theoretical understanding of acoustic signal propagation were laid out in Lord Rayleigh's ground-breaking treatise[1] about one and a half centuries ago. Since then, the transport and manipulation of sounds through passive media, such as gases, liquids and solids, have been investigated extensively, leading to a vast array of technological and biomedical applications. Now, writing in *Nature Materials*, Delphine Geyer and colleagues[2] report a comprehensive experimental and theoretical explanation of sound propagation in an active medium, thereby opening a new window for probing and understanding an exciting class of emergent materials[3].

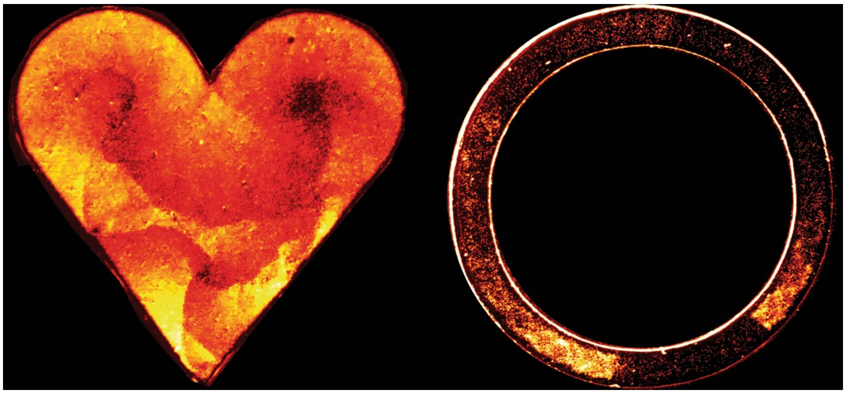

Fig. 1 | Flocking patterns in active fluids. Microscopy images of active Quincke rollers suspensions consisting self-propelled colloidal spheres (diameter ~5 μm) moving in a conducting low dielectric fluid confined to heart-shaped (1 cm wide at the largest point) or circular racetrack (1 mm wide) geometries. The interplay of confinement geometry, self-propulsion and hydrodynamic particle interactions leads to complex self-organized flocking dynamics and sound wave propagation. Credit: courtesy of D. Geyer and D. Bartolo

Active matter comes in many guises, from biological tissues[4] and microbial suspensions[5,6] to chemically driven Janus particles[7] and ATP-powered gels[8]. The unifying aspect of these structurally very different systems lies in their ability to translate small-scale energy input at the level of the individual cells, colloids or molecular motors into coherent large-scale dynamics and collective functions. Solid- and fluid-based active materials promise exciting applications in fields as diverse as soft robotics[9], tissue engineering[10], microfluidics[11–13] and autonomous metamaterials design[14]. The enormous technological potential has stimulated substantial experimental and theoretical research on dry and wet active matter systems over the past decade[3]. However, despite major recent progress in the fabrication of new types of active materials, there still exists a significant gap between experiments and proposed theoretical descriptions. The discrepancy can be largely attributed to the fact that active matter, by its very nature, operates far from thermal equilibrium. More specifically, this means that unlike, for example, the planets and stars in gravitational systems, the dynamics and interactions of the active constituents per se are not bound by the usual conservation laws. The apparent absence or violation of fundamental symmetries, such as time translation invariance (energy conservation), space translation invariance (linear momentum conservation) or rotation invariance (angular momentum conservation), implies that effective continuum theories for active materials typically can have many more terms and parameters than those describing their passive counterparts. Such model complexity makes quantitative comparisons between theory and experiment conceptually, practically and computationally challenging. The results of Geyer and co-workers present an important step towards narrowing the gap between active matter theory and experiment. By investigating the propagation of sound waves in a self-driven colloidal system[15], they were able to estimate quantitatively all the parameters of a continuum theory[16] that generalizes the classical hydrodynamic equations for conventional fluids and gases to the realm of active matter.

The experimental system studied by Geyer et al. consists of self-propelled colloidal spheres (diameter ~5 μm) embedded in a conducting fluid with a low dielectric constant. The underlying self-propulsion mechanism goes back to a discovery made in 1896 by the German physicist Georg Hermann Quincke, who observed that small insulating particles of various shapes begin to rotate spontaneously when placed in a fluid between two oppositely charged capacitor plates. The electric field generated by the plates leads to a redistribution of electric charges on a particle's surface. If the field is sufficiently strong, the direction of the induced electric dipole moment becomes unstable to small fluctuations, which in turn cause the particle to rotate. Once a single isolated sphere has settled at the bottom plate, the rotational instability results in a persistent rolling motion along a randomly chosen direction in the horizontal plane, with typical speeds of a few millimetres per second. When many thousands of such Quincke rollers are tightly confined within a corral, hydrodynamic and electrostatic interactions tend to align their rolling directions[15], resulting in directed collective flocking dynamics (Fig. 1). Related spontaneous ordering phenomena have been observed recently in bacterial[5,6,11] and ATP-driven microtubule[12] suspensions.

Geyer and collaborators use video microscopy to monitor the dynamics of a large number of individual Quincke rollers in a dense suspension confined in a racetrack-shaped microfluidic channel. By analysing the density and velocity correlations of the colloids, the dispersion relations and sound speeds along various directions relative to the average propulsion direction of the flock could be determined. The reported measurements show that active fluids with broken rotational symmetry can support underdamped sound modes, even though the dynamics of their microscopic units is overdamped, thus confirming a longstanding theoretical prediction[3]. Furthermore, a comprehensive spectral fluctuation analysis provided previously inaccessible quantitative estimates for all six material parameters of the linearized Toner–Tu theory[16] of flocking, over a range of distinct roller concentrations. Although the scaling behaviours of the measured parameter values generally agree well with theoretical predictions, certain quantitative deviations also suggest a need for future refinements of the theory.

From both a theoretical and practical perspective, the results of Geyer et al. are highly encouraging, as they provide direct validation of a foundational hydrodynamic theory[16] of active matter. One can therefore be hopeful that predictions obtained within this and related frameworks, such as the recently proposed designs of active metamaterials[14] and autonomous microfluidic devices[13], could also be realizable experimentally in the near future. In this context, the Quincke roller system appears to be a promising candidate for probing the existence of recently predicted[14] topologically protected sound modes in active fluids. If such super-stable active waves can indeed be observed, then this will be another important step towards creating new classes of active matter devices for the robust autonomous detection and transmission of sound and other signals. Until then, exploring how topological protection and similar transport concepts from modern condensed-matter physics can be generalized to active systems remains one of the most exciting interdisciplinary frontiers in materials science. ❐

Jörn Dunkel
Department of Mathematics, Massachusetts Institute of Technology, Cambridge, MA, USA.
e-mail: *dunkel@mit.edu*

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