

Summary of thesis: Collective Mesoscale Dynamics in Dense Suspensions of Ciliated Microswimmers

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Active matter, composed of self-propelled particles that consume energy to generate motion, offers a comprehensive framework for understanding collective motion we can observe in nature. This thesis explores the emergent dynamics of dense suspensions of the ciliated microorganism *Tetrahymena pyriformis*, which serve as an experimental minimal model of dense living matter. Through a combination of high-resolution capturing, image-based data analysis, theoretical analysis, we investigate how local motility and interactions give rise to unknown large-scale structures in such systems.

Chapter 1 begins by defining active matter within the broader context of nonequilibrium physics and biological systems. We emphasize the central role of collective behavior in living systems—from microbial colonies and animal groups to cellular tissues. Standard theoretical models, such as the Vicsek model and ABP, are reviewed alongside concepts like orientational order and topological defects. We propose a classification of active matter systems based on three key features: alignment symmetry (polar vs. apolar), hydrodynamic interaction (wet vs. dry), and particle density (dilute vs. dense). While dry, dilute systems have been studied extensively, dense wet systems—such as swimming microorganisms—remain poorly understood. *Tetrahymena*, with its cilia-driven propulsion and established culture methods, provides an ideal system to explore this regime systematically.

In Chapter 2, we study the behavior of dilute *Tetrahymena* suspensions near air–liquid interfaces. Despite being classified as hydrodynamically neutral swimmers, the cells tend to accumulate at the interface. This is interpreted using a modified diffusion equation that includes a phenomenological accumulation coefficient. The model quantitatively captures the observed steady-state distribution and highlights the role confinement in shaping spatial organization such bioconvection, even in dilute conditions.

In Chapter 3, we examine the behavior of *Tetrahymena* in dense suspensions, where crowded effects become dominant. Using machine-learning-based

segmentation, we can detect cell positions, orientations, and shapes at single-cell resolution. Tracking analyses reveal persistent motility at the individual level but a moderate increase of relaxation time, suggesting a transition into a glassy active fluid state. Spatial and temporal correlations show dynamic heterogeneity, vortex-like mesoscale structures, and intermittent alignment, all without global order. These observations bridge the conceptual gap between active turbulence and glassy dynamics.

We further analyze clustering behavior and polarity correlations, finding that collective alignment is confined to transient, mesoscale domains. The emergence of these structures is not simply a result of crowding but reflects a nontrivial balance between activity, noise, and hydrodynamic interactions. Our findings indicate that dense active systems may exhibit novel states that lie outside the scope of known reporting.

In summary, this thesis provides an experimental characterization of the complex behaviors that emerge in dense suspensions of living microswimmers. By integrating concepts from nonequilibrium physics, biological experiments and cell-level data acquisition methods, we reveal how local motility, shape, and interaction give rise to emergent structure. The work contributes to bridging the gap between theoretical results on particulate active systems and real biological phenomena in cell tissue, such as tumor metastasis and morphogenesis.