Bacteria swimming and the emergence of collective effects

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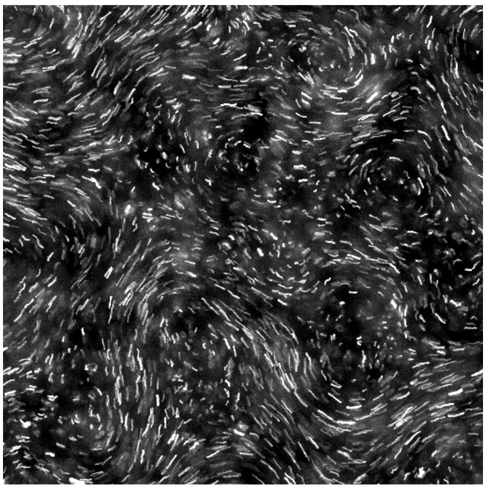
Active matter, the scientific context

Animal's locomotion displays fascinating collective properties originating from an interplay between individual self-propulsion and interactions among individuals in the group [Vicsek et al. Physics Reports 517, 71 (2012)]. The notion of interaction is in itself a complex issue. It involves local ordering through contacts or longer range interactions mediated by the surrounding fluid and also, something more behavioral implying chemical sensing or cognitive decision. In spite of the large lexical variety describing these phenomena (mobs, herds, flocks, shoals, swarms…), that applies to different animals moving in concert at different scales, it is only recently that physicists have elaborated the paradigmatic concept of "active fluids". This notion enforces the statistical physics credo that "more is different" meaning that at some scale will emerge a unified physical entity ruled by macroscopic transport equations associated with constitutive relations. However, the nature of the emergent fields (stress, velocity, density…), usually coupled with order parameters describing the local interaction processes, differs strongly from what is currently known for standard fluids. Theoretically, the phenomenological approaches highlight that due to the intrinsic symmetries of the microscopic interactions as well as the biological activity stemming from self-propulsion, many well-accepted notions describing matter at thermal equilibrium should be deeply revisited [Marchetti et al., Rev.Mod.Phys., 85, 1143 (2013)]. This issue bears some very fundamental and almost philosophical aspects as it provides a (relatively) simple path to evaluate the impact of biological activity on our physical environment and its capacity to organize it.

Fluids loaded with swimming microorganisms are systems of choice to study these problems [Baskaran et al. PNAS, 106, 15567 (2009)]. In recent studies, bacterial fluids were shown to revisit classical properties of matter such as Brownian motion, Fick's law, collective organization, low-Reynolds "turbulence" and viscous response. Experimentally these systems are rather easy to control and the recent advances in microfluidic technologies open the possibilities to fabricate ecological environments where the biological activity of microorganisms can be assessed with great reliability.

Doctoral thesis description



Vortices formed by the collective motion of E. coli in the bulk of the solution.

When fluids are loaded with active motile bacteria at high concentration, it has been recently shown that the cells organize to initiate some spontaneous collective motions. The appearance of some hydrodynamic instabilities in the solution depends on the bacteria concentration and on their ability to move. Although some theories have been developed recently to try to understand how such phenomena can occur, everything is not yet very clear both on the microscopic and on the macroscopic scales. This thesis will start with microscopy experiments (fluorescence, phase contrast, confocal) at different length scales to provide a complete description of both the individual trajectories of bacteria within a population and of the dynamics of the entire population. This will make it possible to obtain the microscopic characteristics of the swimming of each cell and to correlate it with the large-scale behavior of the suspension. Preliminary results have already been obtained and show that when the collective motions appear in the dense suspension of cells, the speed of the carrier fluid can be several times faster than that of the individual swimmers. It becomes then of great importance to careful control the speed of the swimmers. Our collaborators at the University of Edinburgh in the group of Wilson Poon developped a strain the motility of which can be controlled by the light exposure. Switching the light on or off yields the bacteria to swim or not respectively. By playing with the light, the different time scales as well as the length scales of the system, we should be able to control the appearance and the amplitude of the colllective motions, affecting then the overall macroscopic properties of the solution such as the effective viscosity and its reponse to a shear.

The second research axis of this PhD project also concerns the population behavior undergoing hydrodynamic instabilities but this time due to environmental heterogeneities. In nature, the life of bacteria consists of evolving in gradients of the environment in order to find conditions favorable to them. They are thus designed to respond to gradients of oxygen, temperature, food *etc*. The aim here will be to understand to which extend the "active" properties of bacteria will contribute to change the features of the system as we know them for passive fluids. The experiments will consist in using lab-made devices allowing to devise well-controlled gradients (temperature gradient in a Rayleigh-Bénard cell, microfluidic device to control oxygen gradients) and to give rise to the formation of bacteria patterns or accumulations. By using fluorescent microscopy, we will characterize the local parameters of the bacteria trajectories in the flow and we will correlate them to the fluid properties at larger scale. We will study how these patterns for instance destabilize or maybe amplify the flow instabilities.

Environment and context of the LPS and the PMMH

This PhD thesis is proposed in the context of an ongoing collaboration between the Laboratoire de Physique des Solides in Orsay and the PMMH in ESPCI. Thus, most of the experiments will be performed at ESPCI, an engineering "Grande École" and a research campus located in the heart of Paris. This institution hosts many laboratories that develop scientific investigations at the triple point between Physics, Chemistry and Biology. In the last years, under the direction of the Nobel Prize recipient Pierre Gilles de Gennes it has become a reference center for soft matter. The campus laboratories have many connections with the very rich scientific environment of the Paris area (Universities Pierre et Marie Curie and Paris-Diderot, École Normale Supérieure etc.). The LPS and PMMH are laboratories developing a multidisciplinary activity between physics and mechanics with a rich variety of research including soft matter physics, statistical physics, fluid dynamics, solid mechanics and interfaces dynamics.

Both laboratories are currently engaged in many international collaborations and in particular with the Wilson Poon's lab in Edinburgh (Scotland). This thesis proposal is a part of a current scientific collaboration between Pr. Wilson Poon, Dr. Vincent Martinez, Pr. Eric Clément and Dr. Carine Douarche.

Publications of the consortium on active matter and bacterial fluids

Preprint 2017

- B. Vincenti, C. Douarche, E. Clement, Rheology of active magnetic suspensions: emergence of motor and break states, preprint (2017).
- N. Figueroa-Morales, T. Darnige, V. Martinez, C. Douarche, R. Soto, A. Lindner & E. Clement, Large distribution of orientation persistence times relates E. coli motility to motor rotation switching statistics, preprint (2017).
- T. Darnige, N. Figueroa-Morales, P. Bohec, A. Lindner and E. Clément, Lagrangian 3D tracking of fluorescent microscopic objects under flow, preprint (2017).

Publications

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