ESPCI PARIS | PSL

Gulliver
UMR 7083 CNRS
ESPCI, PSL

Collective motion in crowded active matter with non-reciprocal interactions

Directeur de thèse :

Ludovic Berthier (Gulliver ESPCI, Paris)
`https://ludovicberthier.github.io/`

Collaboration: J. Klamser (CNRS, Montpellier)

Scientific context: Today we lack a theory for the most fascinating thing that is: life. Life needs transport processes beyond thermal diffusion and relies on the ability of agents on all scales (from molecular motors inside cells to entire organisms) to move autonomously in a systematic fashion. The major success of equilibrium statistical physics is to relate the thermal microscopic particle dynamics to macroscopic collective properties. The field of active matter physics aims to bridge precisely this gap for active particle dynamics that do not move only because of temperature, but because each particle is equipped with a motor producing systematic motion like that of birds, bacteria, or robots.

Without a theory, numerical studies are essential. Intense focus has been on minimal models leaving big gaps on the baffling collective phenomena emerging when persistent particle motion competes with crowding at high densities. Only last year [1] turbulent-like collective motion has been reported in this regime that strikingly resembles the chaotic advective flows observed in dense bacterial assemblies or biological tissues.

More recently non-reciprocal interactions are considered as another mechanism creating systematic particle motion. In the simplest case, consider prey attracting predators, but predators repelling prey, thus creating motion though ‘chase and run’ [2]. Artificial systems have been engineered (like spinning colloids) that interact via non-reciprocal forces mediated by hydrodynamic interactions creating intriguing collective dynamics [3]. Most living systems are not only active but have also non-reciprocal interactions. For instance alignment interactions in bird flocks are non-reciprocal due to blind spots in vision [4].

Description of the thesis: The goal of this thesis is to understand the individual and combined impact of non-reciprocal interactions and activity in collective phenomena emerging when density is high keeping in mind real-world systems like dense human crowds. Building on our existing understanding of active systems, the first objective is to confirm or rule out the emergence of comparable behaviour from non-reciprocity. This requires the identification of appropriate models and the targeted exploration of well-chosen parameter ranges. The goal is then to combine non-reciprocity with activity to quantify the possible impact when non-reciprocity is ignored in active models. While keeping the focus on comparison with real-world systems, fundamental questions will be natural stepping stones as for example on the existence of phase transitions in one dimension and two dimensions (equilibrium theorems do not apply).

Supervision: The project will take place at Gulliver (ESPCI UMR 7083 CNRS) and be supervised by L. Berthier (DR, CNRS). The lab has developed well-known expertise for the study of disordered and non-equilibrium materials, and has a large experience regarding the numerical simulations of these systems [4]. The work will also be performed in close collaboration with J. Klamser (L2C, CNRS, Montpellier). Berthier and Klamser have often collaborated on this topic in the past [1].

Références :

[1] Y.-E. Keta, J. Klamser, R. L. Jack, and L. Berthier, *Emerging mesoscale flows and chaotic advection in dense active matter*, Phys. Rev. Lett. 132, 218301 (2024)

[2] Z. Zhang and R. Garcia-Millan, *Entropy production of nonreciprocal interactions*, Phys. Rev. Res. 5, L022033 (2023).

[3] E. S. Bililign, F. Balboa Usabiaga, Y. A. Ganan, A. Poncet, V. Soni, S. Magkiriadou, M. J. Shelley, D. Bartolo, and W. T. M. Irvine, *Motile dislocations knead odd crystals into whorls*, Nature Physics 18, 212 (2022).

[4] D. Martin, D. Seara, Y. Avni, M. Fruchart, and V. Vitelli, *An exact model for the transition to collective motion in nonreciprocal active matter*, arXiv:2307.08251.