Bacterial Dynamics in Curved Spaces

Zhengyang Liu,[1,2] Cristian Villalobos Concha,[3] Maria Luisa Cordero,[3]
Rodrigo Soto,[3] Anke Lindner,[1] Eric Clément,[1] and Teresa Lopez-Leon[2]

[1]*Laboratoire PMMH, UMR 7636 CNRS-ESPCI-Sorbonne Université-Université Paris Diderot, 7-9 quai Saint-Bernard, 75005 Paris, France.*
[2]*Laboratoire Gulliver, UMR 7083 CNRS, ESPCI Paris, PSL Research University, 75005 Paris, France.*
[3]*Departamento de Física, FCFM, Universidad de Chile, Santiago, Chile.*

(Dated: November 28, 2022)

The interplay between complex environments and active matter suggests a possibility to control and engineer active matter by carefully designing the confinement structures. It is now well established that confinement may influence transport, rheology, pressure, spatial distribution and collective motion of active matter. Curved confining walls, which are ubiquitous in biological systems, show their own, specific rich and intriguing effects on active matter. Here, using a double emulsion system, where the inner and outer droplet sizes can be independently controlled, we experimentally investigate the influence of curved confinement on an active bath of *Escherichia coli* bacteria. In particular, we analyze the fluctuations of the inner droplet using the framework of a stochastic "active noise" model, and show that the strength of active noise is not an intrinsic property of an active bath, but depends on the confinement curvature. Our numerical simulations revealed the origin of this dependence on confinement. Our results pose new challenge to active matter theory and suggest new methods to control active matter.

The interactions between active and passive objects are always intriguing. On the one hand, passive objects are often used as a probe to assess the properties, in particular activity, which are sometimes challenging to measure directly. On the other hand, the capabilities of activity to ehance mixing of fluids and transport of nutrients show great ecological significance and can potentially enable important biomedical applications [1–4].

On the most elementary level, the interaction between an active particle and a passive particle can be described as "scattering". In this process, the active particle swims by the passive particle results in a closed-loop trajectory, due to the hydrodynamic head-rear symmetry of the model swimmer [5]. In the presence of a confining wall, the flow field generated by an active swimmer is modified, as if there is a mirror image of the swimmer, with force singularities pointing in opposite directions [6]. The head-rear symmetry is broken in the modified flow field, leading to net displacement of passive object in a single scattering event. Based on this picture, Mino et al. successfully modeled the confinement effect on the diffusivity of passive particles in active bath [7, 8]. Lagarde et al. focused their experiment more on the single scattering event, and found far field hydrodynamic interactions to be irrelevant compared to direct collisions [9]. The experiments mentioned above all revealed an important aspect of active baths: the effect on passive tracer diffusivity is stochastic and additive. This discovery has led to efforts to model active baths as a stochastic noise [10–13].

Confinement is known to have dramatic impact on active matter, with examples of pattern formation, directed flow and unusual mechanical properties [14–16].

[1] H. Kurtuldu, J. S. Guasto, K. A. Johnson, and J. P. Gollub, Enhancement of biomixing by swimming algal cells in two-dimensional films, Proceedings of the National Academy of Sciences **108**, 10391 (2011).
[2] D. O. Pushkin and J. M. Yeomans, Fluid Mixing by Curved Trajectories of Microswimmers, Physical Review Letters **111**, 188101 (2013).
[3] D. Saintillan and M. J. Shelley, Instabilities, pattern formation, and mixing in active suspensions, Physics of Fluids **20**, 123304 (2008).
[4] A. Sokolov, R. E. Goldstein, F. I. Feldchtein, and I. S. Aranson, Enhanced mixing and spatial instability in concentrated bacterial suspensions, Physical Review E **80**, 031903 (2009).
[5] J. Dunkel, V. B. Putz, I. M. Zaid, and J. M. Yeomans, Swimmer-tracer scattering at low Reynolds number, Soft Matter **6**, 4268 (2010).
[6] J. R. Blake and A. T. Chwang, Fundamental singularities of viscous flow, Journal of Engineering Mathematics **8**, 23 (1974).
[7] G. Miño, T. E. Mallouk, T. Darnige, M. Hoyos, J. Dauchet, J. Dunstan, R. Soto, Y. Wang, A. Rousselet, and E. Clement, Enhanced Diffusion due to Active Swimmers at a Solid Surface, Physical Review Letters **106**, 048102 (2011).
[8] G. L. Miño, J. Dunstan, A. Rousselet, E. Clément, and R. Soto, Induced diffusion of tracers in a bacterial suspension: Theory and experiments, Journal of Fluid Mechanics **729**, 423 (2013).

[9] A. Lagarde, N. Dagès, T. Nemoto, V. Démery, D. Bartolo, and T. Gibaud, Colloidal transport in bacteria suspensions: From bacteria scattering to anomalous and enhanced diffusion, Soft Matter **16**, 7503 (2020), arXiv:2002.10144.
[10] G. Grégoire, H. Chaté, and Y. Tu, Active and passive particles: Modeling beads in a bacterial bath, Physical Review E **64**, 011902 (2001).
[11] C. Maggi, M. Paoluzzi, N. Pellicciotta, A. Lepore, L. Angelani, and R. Di Leonardo, Generalized Energy Equipartition in Harmonic Oscillators Driven by Active Baths, Physical Review Letters **113**, 238303 (2014).
[12] X.-L. Wu and A. Libchaber, Particle Diffusion in a Quasi-Two-Dimensional Bacterial Bath, Physical Review Letters **84**, 3017 (2000).
[13] S. Ye, P. Liu, F. Ye, K. Chen, and M. Yang, Active noise experienced by a passive particle trapped in an active bath, Soft Matter **16**, 4655 (2020).
[14] H. Wioland, F. G. Woodhouse, J. Dunkel, J. O. Kessler, and R. E. Goldstein, Confinement Stabilizes a Bacterial Suspension into a Spiral Vortex, Physical Review Letters **110**, 268102 (2013).
[15] K.-T. Wu, J. B. Hishamunda, D. T. N. Chen, S. J. DeCamp, Y.-W. Chang, A. Fernández-Nieves, S. Fraden, and Z. Dogic, Transition from turbulent to coherent flows in confined three-dimensional active fluids, Science **355**, eaal1979 (2017).
[16] Z. Liu, K. Zhang, and X. Cheng, Rheology of bacterial suspensions under confinement, Rheologica Acta **58**, 439 (2019).