BP 14: Focus Session: From Inter-individual Variability to Heterogeneous Group Dynamics and Disorder in Active Matter (joint session DY/BP/CPP)

The study of active particle dynamics has developed into a vibrant field of multidisciplinary research, including such diverse systems as bacterial colonies, cellular self-organization, synthetic colloids and microrobots as well as macroscopic systems like locusts, flocks of birds, schools of fish or pedestrians. Whereas many studies in the past focused either on the random transport of individual particles or on the interplay of temporal fluctuations (noise) and interactions (velocity alignment or attraction/repulsion), there is now an increasing interest in the question how structural disorder and inter-individual variability, i.e., different motility characteristics of individuals, shape the active particle dynamics and emergent pattern formation of groups. The presence of structural or quenched disorder raises furthermore the immediate question how to bridge data and models based on (short time) tracking data, given the simultaneous presence of temporal fluctuations. With this focus session, we aim at bringing researchers from statistical physics and biophysics together to discuss this interdisciplinary topic and exchange ideas on common challenges arising in different application areas.

Organized by Robert Großmann (Potsdam)

Time: Wednesday 9:30–13:00 Location: ZEU 160

Invited Talk BP 14.1 Wed 9:30 ZEU 160

More is different: High-throughput 3D tracking reveals bacterial navigation strategies — •Katja Taute — Rowland Institute at Harvard, Harvard University, Cambridge, MA, USA — Department of Biology, Microbiology, LMU München, 82152 Martinsried, Germany

How microbes navigate environmental chemical gradients has implications that range from health to climate. The behavioral mechanisms underlying chemotaxis are unknown for most species because of a lack of techniques capable of bridging scales from individual navigation behavior to the resulting population-level performance. We present a multiscale 3D chemotaxis assay that combines high-throughput 3D bacterial tracking with microfluidically created chemical gradients. Large datasets of 3D trajectories yield the statistical power required to assess chemotactic performance at the population scale, while simultaneously resolving the underlying 3D navigation behavior for every individual. Applying this technique to the well-studied model bacterium Escherichia coli, we uncover dramatic, previously unknown heterogeneity in chemotactic performance. We investigate the underlying behavioral mechanisms and discuss potential implications at the population level.

Invited Talk BP 14.2 Wed 10:00 ZEU 160

Variability and heterogeneity in natural swarms — •Gil Ariel — Bar Ilan University, Ramat Gan, Israel

Collective motion of large-scale natural swarms, such as moving animal groups or expanding bacterial colonies, have been described as self-organized phenomena. Thus, it is clear that the observed macroscopic, coarse-grained swarm dynamics depend on the properties of the individuals of which it is composed. In nature, individuals are never identical, and may differ in practically every parameter. Hence, intra-group variability and its effect on the ability to form coordinated motion is of interest, both from theoretical and a biological points of view. In this talk, I will review and examine some of the fundamental properties of heterogeneous collectives in nature, with an emphasis on two widely-used model organisms - swarming bacteria and locusts. Theoretical attempts to explain the observed phenomena will be discussed in view of laboratory experiments, highlighting their successes and failures. While heterogeneity typically discourages collectivity, there are several natural examples where it has an opposite effect.

BP 14.3 Wed 10:30 ZEU 160

Effect of individual differences on the jamming transition in traffic flow — •Yi-Chieh Lai and Kuo-An Wu — Department of Physics, National Tsing Hua University, 30013 Hsinchu, Taiwan

The individual difference, particularly in drivers' distance perception, is introduced in the microscopic one-dimensional optimal velocity model to investigate its effect on the onset of the jamming instability seen in traffic systems. We show analytically and numerically that the individual difference helps to inhibit the traffic jam at high vehicle densities while it promotes jamming transition at low vehicle densities. In addition, the jamming mechanism is further investigated by tracking how the spatial disturbance travels through traffics. We find that the jamming instability is uniquely determined by the overall distribution of drivers' distance perception rather than the spatial ordering of vehicles. Finally, a generalized form of the optimal velocity function is considered to show the universality of the effect of the individual difference.

BP 14.4 Wed 10:45 ZEU 160

Distinct impacts of polar and nematic self-propulsion on active unjamming — Varun Venkatesh[1], •Chandana Mondal[2], and Amin Doostmohammadi[1] — [1]Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark — [2]UGC-DAE CSR, University Campus, Khandwa Road, Indore 452017, India

We explore, by MD simulations, the jamming-unjamming transition in a dense system of active semiflexible filaments. In particular, we characterize the distinct impact of polar vs nematic driving for different filament rigidities and at varying densities. Our results show that high densities of dynamic active filaments can be achieved by only changing the nature of the active force, nematic or polar. Interestingly, while polar driving is more effective at unjamming the system at high densities below confluency, we find that at even higher densities, nematic driving enhances unjamming compared to its polar counterpart. The effect of varying the rigidity of filaments is also significantly different in the two cases: While for nematic driving, lowering the bending rigidity unjams the system, we find an intriguing reentrant jamming-unjamming-jamming transition for polar driving as the filament rigidity is lowered. While the first transition (unjamming) is driven by softening due to reduced rigidity, the second transition (jamming) is a cooperative effect of ordering and coincides with the emergence of nematic order in the system. Together, through a generic model of self-propelled flexible filaments, our results demonstrate how tuning the nature of self-propulsion and flexibility can be employed by active materials to achieve high densities without getting jammed.

15 min. break

Invited Talk BP 14.5 Wed 11:15 ZEU 160

Superstatistical Analysis and Modelling of Complex Dynamical Systems — •Claus Metzner[1,2], Christoph Mark[2], Ben Fabry[2], Patrick Krauss[1], Achim Schilling[1], Maximilian Traxdorf[3], and Holger Schulze[1] — [1]Neuroscience Lab, University Hospital Erlangen, Germany — [2]Biophysics Lab, Friedrich-Alexander Universität Erlangen-Nürnberg — [3]Department of Otorhinolaryngology, Head and Neck Surgery, Paracelsus Medical University, Nuremberg, Germany

On longer time scales, complex systems often pass through different dynamical attractors and thus produce 'anomalous' distributions and correlations when analyzed with conventional statistical tools. We argue that the most appropriate way of describing such systems is by hierarchical multilevel models, in which the lowest level is a relatively simple random walk model that can generate the observed time series on short time scales, but which depends on latent hyper-parameters that are themselves time-dependent and controlled by the higher levels of the model. First, our Bayesian method is introduced for the sequential inference of those gradual or abrupt parameter changes. We then review possible applications of the superstatistical framework in such diverse fields as biophysics, neuroscience, finance, or policy assessment. Finally, we discuss more recent extensions of the method for model selection and the use of machine learning models for estimating complex likelihood functions.

BP 14.6 Wed 11:45 ZEU 160

How to infer parameter distributions in heterogeneous populations of active particles — •Jan Albrecht[1], Robert Grossmann[1], and Manfred Opper[2,3] — [1]Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam, Germany — [2]TU Berlin, Fakultät IV-MAR 4-2, Marchstraße 23, 10587 Berlin, Germany — [3]Centre for Systems Modelling and Quantitative Biomedicine, University of Birmingham, B15 2TT, United Kingdom

Experiments with active particles, e.g., motile microorganisms like bacteria or amebae, provide information about their position at discrete points in time. However, most active particle models, like active Ornstein-Uhlenbeck particles for example, are commonly described by first order stochastic differential equations for the velocity or force. This leads to a second order model in position posing challenges for parameter inference, because there is no general way to obtain a closed form expression for the likelihood of the parameters in terms of those time-sampled trajectories. This would be needed to apply efficient Bayesian parameter estimation techniques. In this talk, we propose a filtering-like sequential method to address this problem. The likelihood is first expressed in terms of integrals over transition probabilities. Approximating the transition probability for small times makes these integrals analytically feasible, leading to a likelihood approximation that allows consistent parameter inference. Using a Bayesian approach, we furthermore show how to extend this framework to estimate the entire distribution of motility parameters in heterogeneous populations of particles efficiently.

BP 14.7 Wed 12:00 ZEU 160

Derivation and analysis of a phase field crystal model for a mixture of active and passive particles* — •Michael te Vrugt[1,2], Max Philipp Holl[1], Aron Koch[1], Raphael Wittkowski[1,2,3], and Uwe Thiele[1,3,4] — [1]Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster, 48149 Münster, Germany — [2]Center for Soft Nanoscience — [3]Center for Nonlinear Science — [4]Center for Multiscale Theory and Computation

We discuss an active phase field crystal (PFC) model that describes a mixture of active and passive particles [1]. First, a microscopic derivation from dynamical density functional theory is presented that includes a systematic treatment of the relevant orientational degrees of freedom. Of particular interest is the construction of the nonlinear and coupling terms. This allows for interesting insights into the microscopic justification of phenomenological constructions used in PFC models, the approximations required for obtaining them, and possible generalizations. Second, the derived model is investigated using linear stability analysis and nonlinear methods. It is found that the model allows for a rich nonlinear behavior with states ranging from steady periodic and localized states to various time-periodic states. The latter include standing, traveling, and modulated waves corresponding to spatially periodic and localized traveling, wiggling, and alternating peak patterns and their combinations.

[1] MtV et al., Modelling Simul. Mater. Sci. Eng. 30, 084001 (2022)

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BP 14.8 Wed 12:15 ZEU 160

Active Brownian Particles in a disordered motility environment — Gianni Jacucci[1], •Davide Breoni[2], Sandrine Heijnen[3], Hartmut Löwen[2], Giorgio Volpe[3], and Sylvain Gigan[1] — [1]Laboratoire Kastler-Brossel, Paris, France — [2]HHU Universität, Düsseldorf, Germany — [3]University College London, London, United Kingdom

The study of active matter, i.e. matter that consumes energy to perform actions, is fundamental to deepen the knowledge of living systems, as for example bacterial colonies or flocks of birds, and their collective behaviors. Complex environments, like the internal structure of a cell or a blood vessel, are of particular relevance in this field, as they provide a better description of the real-life settings typical of living matter.

In this work we study the effects of a disordered motility field on active Brownian particles, both in experiments and simulations. Experimentally, the motility field is generated by applying a speckle light field to thermophoretic Janus particles, in our case silica colloids half-coated with a carbon layer, suspended in a critical mixture of water and 2,6-lutidine. We focus on the differences between the effects of respectively a homogeneous and a disordered motility field on the dynamics of the particles.

BP 14.9 Wed 12:30 ZEU 160

Characterization of spatial heterogeneities as influencing factors on the dynamics of confluent endothelial cell migration — •Anselm Hohlstamm, Andreas Deussen, Stephan Speier, and Peter Dieterich — Institut für Physiologie, TU Dresden

Confluent endothelial cells are in perpetual movement. Their collective dynamics arises from the interplay of self-propelled motility and various distance-related cell interactions. However, an understanding of collective cell dynamics is complicated by large spatial heterogeneities and local cluster formations. It is the aim of this work to quantify and characterize their influence on the dynamics of cell migration. We used human umbilical vein endothelial cells, which were stained with a fluorescent dye and observed for 48 hours via time-lapse microscopy. With automated image segmentation we could track several 10.000 cells. Cell densities and mean squared velocities showed a heterogeneous spatial distribution with an inverse relation to each other. Higher cell densities also affected the strength of the velocity autocorrelation, whereas correlation times remained mostly stable during experiments. However, cell division increased the mean squared velocity without changing temporal correlations. In parallel, the mean squared displacement characterized regions with short superdiffusive phases in an aging, highly non-stationary system. In addition, local dynamics are coupled by long range spatial correlations. In summary, the dynamics of an entire endothelial layer is influenced by interactions of small heterogenous regions. Next, we will use this approach to compare different endothelial cells.

BP 14.10 Wed 12:45 ZEU 160

Exploiting the unknown - Smart nutrient collection surpassing the run and tumble strategy — •Mahdi Nasiri, Edwin Loran, and Benno Liebchen — Institut für Physik kondensierter Materie, Technische Universität Darmstadt, Hochschulstraße 8, D-64289 Darmstadt, Germany

Throughout evolution, microorganisms have developed efficient strategies for locating nutrients and avoiding toxins in complex environments. Understanding their adaptive policies can provide new key insights for the development of smart artificial active particles. In this talk, we will present a novel method that uses deep reinforcement learning (DRL) to develop smart nutrient collection strategies for chemotactic active particles. Our method is complementary to our previous work which used DRL to explore optimal navigation [1] and is able to devise efficient survival strategies inside unknown and complex environments while only having access to local sensory data. We were also able to extract an interpretable model from the learned strategies which resemble striking similarities with the classical run and tumble motion.

[1] M. Nasiri, B. Liebchen, New J. Phys. 24, 073042 (2022).