BP 10: Focus Session: Nonlinear Dynamics in Biological Systems I (joint session DY/BP)

Nonlinear dynamics play a central role for biological systems to achieve remarkable complexity and adaptability. They underlie processes where small changes cascade into large effects, critical thresholds drive transitions, and feedback mechanisms maintain intricate balances. Biological systems are often far from equilibrium, exhibiting behaviors shaped by competing forces, stochastic fluctuations and emergent behavior. From the amplification of sensory signals near bifurcation points to the development of turbulence, concepts from nonlinear dynamics provide a unifying framework for studying patterns, stability, and collective behavior in living systems. This focus session explores the richness of nonlinear dynamics across biological scales, from molecular circuits to population-level phenomena, spanning vastly different fields from cardiac dynamics, embryogenesis and cell motility to active fluids, condensates and origin of life. Through theoretical models, experimental insights, and computational approaches, the talks illustrate how nonlinear-dynamics principles unravel the mechanisms driving function and complexity in biology, offering new perspectives across disciplines.

Organized by Philip Bittihn (Göttingen), Stefan Klumpp (Göttingen), and Carsten Beta (Potsdam)

Time: Tuesday 9:30–12:30 Location: H43

Invited Talk BP 10.1 Tue 9:30 H43

Robust signal amplification and information integration via self-tuned proximity to bifurcation points — •Isabella Graf — Developmental Biology Unit & Theory Transversal Theme, EMBL Heidelberg, Germany

Many living systems demonstrate exquisite sensitivity to small input signals. A tempting hypothesis is that these systems operate close to bifurcation or critical points, where the system's response exhibits a diverging susceptibility to the control parameter and small signals are amplified into a large collective response. A common concern, however, is that proximity to such points requires fine-tuning of parameters, which seems impossible for noisy biological systems. Based on several distinct sensory systems, we have investigated a feedback motif that robustly maintains these systems close to their respective bifurcation point. The key ingredient is that the collective response feeds back onto the control parameter. To illustrate this idea, I will mention several examples ranging from snake thermosensing to mammalian hearing and discuss the functional benefits associated with being near-critical.

BP 10.2 Tue 10:00 H43

Exceptional Points and Stability in Nonlinear Models of Population Dynamics having PT symmetry — •Alexander Felski — Max Planck Institute for the Science of Light, Erlangen, Germany

Nonlinearity and non-Hermiticity, for example due to environmental gain-loss processes, are a common occurrence throughout numerous areas of science. For the latter, parity-time-reflection (PT) symmetry has played an eminent role in understanding exceptional-point structures and phase transitions in these systems. Yet their interplay has remained by-and-large unexplored. We analyze models governed by the replicator equation of evolutionary game theory and related Lotka-Volterra systems of population dynamics. These foundational nonlinear models offer a broad platform for non-Hermitian theory beyond physics. In this context we study the emergence of exceptional points in two cases: (a) when the governing symmetry properties are tied to global properties of the models, and, in contrast, (b) when these symmetries emerge locally around stationary states–in which case the connection between the linear non-Hermitian model and an underlying nonlinear system becomes tenuous. We outline further that when the relevant symmetries are related to global properties, the location of exceptional points in the linearization around coexistence equilibria coincides with abrupt global changes in the stability of the nonlinear dynamics. Exceptional points may thus offer a new local characteristic for the understanding of these systems.

BP 10.3 Tue 10:15 H43

Pattern selection and the route to turbulence in polar active fluids — Henning Reinken[1], Sebastian Heidenreich[2], •Markus Bär[2,3], and Sabine Klapp[3] — [1]OVGU Magdeburg, Germany — [2]Physikalisch-Technische Bundesanstalt, Germany — [3]TU Berlin, Germany

Active fluids, such as suspensions of microswimmers, are well known to self-organize into complex spatio-temporal flow patterns. An intriguing example is mesoscale turbulence, a state of dynamic vortex structures exhibiting a characteristic length scale. Here, we employ a minimal model for the effective microswimmer velocity field to explore how the turbulent state develops from regular, stationary vortex patterns when activity is increased. First, we demonstrate analytically that the system develops a stationary square vortex lattice in the absence of nonlinear advection. Subsequently, we perform an extended stability analysis and uncover a linear instability, above which the square vortex lattice becomes unstable. In numerical simulations, we confirm that this instability is predictive for the unset of turbulence. In addition, an extended region of hysteresis where turbulence and a stable vortex lattice coexist, is found Reference: H. Reinken, S. Heidenreich, M. Bär, S. Klapp, New J. Phys. 26 063026 (2024).

BP 10.4 Tue 10:30 H43

Likelihood-based inference for heterogeneous motile particle ensembles — •Jan Albrecht[1], Cristina M. Torres[1], Carsten Beta[1], Manfred Opper[2,3,4], and Robert Grossmann[1] — [1]Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam, Germany — [2]Faculty of Electrical Engineering and Computer Science, Technische Universität Berlin, 10587 Berlin, Germany — [3]Centre for Systems Modelling and Quantitative Biomedicine, University of Birmingham, B15 2TT, United Kingdom — [4]Institute of Mathematics, University of Potsdam, 14476 Potsdam, Germany

The inherent complexity of biological agents often leads to motility behavior that appears to have random components. Robust stochastic inference methods are therefore required to understand and predict the motion patterns from time discrete trajectory data provided by experiments. In many cases second-order Langevin models are needed to adequately capture the motility. Additionally, population heterogeneity needs to be taken into account when analyzing data from multiple individual organisms. We present a maximum likelihood approach to infer stochastic models and, simultaneously, estimate the heterogeneity in a population of motile active particles from discretely sampled trajectories. To this end we propose a new method to approximate the likelihood for nonlinear second order Langevin models. We demonstrate that our approach outperforms alternative methods for heterogeneity estimation, especially for short trajectories, while also providing a measure of uncertainty for the estimates. We use the approach to investigate population heterogeneity in systems of ameboid cells.

BP 10.5 Tue 10:45 H43

Surviving the first "winter": Protocells with polymerization reactions protects against environmental fluctuations — •Xi Chen, Jens-Uwe Sommer, and Tyler Harmon — Leibniz Institute of Polymer Research, Dresden, Germany

The origin of life has been a long standing question with various hypotheses describing the emergence of the first protocells. Phase separated condensates are promising candidates for protocells because they are compartments that enrich specific polymers and host nonequilibrium reactions that leads to growth and division. However, the ability of protocells to survive in an environment that has large fluctuations, such as temperature and composition, is poorly understood. We show with a mean-field model that condensates formed by polymers which undergo nonequilibrium polymerization/depolymerization reactions exhibit significant robustness to large environmental fluctuations.

This robustness occurs when the nonequilibrium polymerization reactions are faster inside condensate phases than outside. The first

condensate does not form until environmental factors lead to strong enough reactions that polymers long enough to phase separate form. The effects of nonequilibrium polymerization is then fully realized because a condensate exists. From here, the condensate does not dissolve until the nonequilibrium reactions are diminished to significantly below when the condensate formed. Altogether, this forms a hysteretic loop with respect to the environmental factors that drive nonequilibrium reactions. We show this hysteretic loop prevents protocells from dying from environmental fluctuations.

BP 10.6 Tue 11:00 H43

How inter-particle interaction affects two species transport in nano-channels — •Wolfgang Bauer — Dept. of Internal Medicine I, UKW, Würzburg, Germany

Channel transport mechanisms of multiple species is essential for cell physiology and nanotechnology. Here, we present a model maintaining spatial correlations of two species, moving away from mean field approaches. The spatial occupations of the channel give the state space, where local flux and entropy production determine channel transport and its thermodynamic efficiency. Optimal transport coupling between species occurs in an attractive empty channel and strong repulsive forces between particles of the same species. This confines state space to a circular topology with concentration gradients of the two species acting as thermodynamic driving forces in series. For opposing gradients, the species with the stronger gradient produces positive entropy, while the other negative entropy. Attenuating the repulsive force within one species and maintaining that of the other adds a bypass path on the circular topology in state space. This enables a leak flow of the less repulsive species parallel to its gradient, generating local positive entropy on the bypass. For a certain range of opposing gradients, both species can produce positive overall entropy simultaneously. However, the rectifying potential of the concentration gradient of the species with bypass option is diminished, i.e. it cannot rectify flow of the other species above a threshold of the latter's opposing gradient. Vice versa the flow of the species with bypass option may always be rectified parallel to the concentration gradient of the other.

15 min. break

Invited Talk BP 10.7 Tue 11:30 H43

Beyond the connectionist view: (De-)synchronizing neural networks via cell-intrinsic dynamics — •Susanne Schreiber — Humboldt-Universität zu Berlin, Institute for Theoretical Biology, Berlin, Germany

Neural computation is thought to arise from the connectivity among neurons. Accordingly, we are often more than happy to ignore seemingly unimportant and potentially overwhelming biological detail, for example, related to the properties of the neurons themselves. In this talk, however, I will highlight how cell-intrinsic dynamics, namely the biophysics of action-potential generation, can have a decisive impact on network behaviour. Recent work of my lab shows that, among regularly firing neurons, the somewhat unattended homoclinic type (characterized by a spike onset via a saddle homoclinic orbit bifurcation) particularly stands out: First, spikes of this type foster specific network states - synchronisation in inhibitory and splayed-out/frustrated states in excitatory networks. Second, homoclinic spikes can be easily induced in by changes in a variety of physiological parameters (like temperature, extracellular potassium, or dendritic morphology). As a consequence, small changes in these parameters can suffice to induce drastic switches in network states. I will discuss functional consequences of homoclinic spikes for the design of pattern-generating motor circuits in Drosophila as well as for mammalian pathologies like febrile seizures. Our work predicts an interesting role for homoclinic action potentials as an integral part of brain dynamics in both health and disease.

BP 10.8 Tue 12:00 H43

Transient spatiotemporal chaos in cardiac excitable media — •Melvin Dix[1,2], Thomas Lilienkamp[1,3], Stefan Luther[1,4,5], and Ulrich Parlitz[1,2,5] — [1]Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany — [2]Institute for the Dynamics of Complex Systems, Georg-August-Universität Göttingen, Göttingen, Germany — [3]Faculty for Applied Mathematics, Physics, and General Science, Computational Physics for Life Science, Nuremberg Institute of Technology Georg Simon Ohm, Nürnberg, Germany — [4]Institute of Pharmacology and Toxicology, University Medical Center Göttingen, Göttingen, Germany — [5]German Center for Cardiovascular Research (DZHK), Partner Site Göttingen, Göttingen, Germany

Life-threatening cardiac arrythmia such as ventricular fibrillation have been linked to spatiotemporal chaotic dynamics governed by scroll or spiral waves. It has been observed in vivo and in vitro that these dynamics can be transient, e.g. abruptly stop. Using simulations with different numerical models we investigate the effects of factors such as heterogeneities, motivated by the complexity of the heart. We show that these perturbations can (significantly) prolong the duration of chaotic transients and may also lead to persistent chaos or stable periodic wave patterns [1].

[1] Melvin Dix et al. Physical Review E 110(4), 044207 (2024).

BP 10.9 Tue 12:15 H43

Nonlinear dynamics of heart and brain — •Irene Pellini[1,2], Simon Bauer[1], Johannes Zierenberg[1,3], Philip Bittihn[1,3], and Viola Priesemann[1,3] — [1]Max Planck Institute for Dynamics and Self Organisation, Göttingen, Germany — [2]Max Planck School Matter to Life, Heidelberg, Germany — [3]Institute for the Dynamics of Complex Systems, University of Göttingen, Germany

The core function of the heart and brain arises from the coordinated interaction of their cells. Both organs rely on excitable units – cardiomyocytes and neurons – that propagate electrical signals when a specific threshold is exceeded. Despite this similarity, the two organs exhibit opposed collective behavior due to marked differences in intercellular dynamics and network topology. In the heart, localized electrical connectivity through reciprocal gap junctions generates local synchronization and traveling waves, ensuring efficient pumping function with low entropy. In the brain, long-range connectivity via delayed, non-reciprocal chemical synapses promotes asynchronous dynamics with high entropy, supporting information processing.

Using coupled FitzHugh-Nagumo oscillators, we showcase that characteristic non-linear dynamics for the heart and brain can be related to the network structure, which places both systems on opposite sides of a synchronization phase transition. Crossing this phase transition would lead to pathological conditions, e.g., heart arrhythmia or brain seizures, quantifiable via entropy measures. Our joint view on heart and brain dynamics may foster new perspectives on the function and pathology of both organs.