DY 22: Pattern Formation

Time: Tuesday 9:30–12:15 Location: ZEU/0118

DY 22.1 Tue 9:30 ZEU/0118

Unexpected wave patterns observed within an extended parameter range of the Barkley model — Vladimir Zykov and •Eberhard Bodenschatz — Max Planck Institute for Dynamics and Self-Organization, D-37077 Goettingen, Germany,

The Barkley model is a widely accepted example of reaction diffusion systems demonstrating different self-organization processes including a creation of self-sustained spiral waves. Recently the study of the spiral wave dynamics performed within the extending parameter region of the Barkley model allowed us to reveal some unexplored features of these processes [1]. The latest computational results performed under a further expansion of the parameter range demonstrate the existence of spiral wave under completely unexpected conditions in monostable and bistable regions. These spirals exhibit absolutely unusual instability, which should be investigated. In parallel to spiral waves self-supported wave segments remaining critical fingers have been observed, which also demonstrated a similar unusual instability.

[1] V. S. Zykov and E. Bodenschatz, Unexplored aspects of the spiral wave dynamics in the Barkley model within an extended parameter range, Phys. Rev. E. 110, 064209 (2024).

DY 22.2 Tue 9:45 ZEU/0118

Dynamics of localized states in a weakly dissipative Korteweg-de Vries-Kuramoto-Sivashinsky Equation — •Justus Keussen[1], Daniel Greve[1], Julien Javaloyes[2], and Svetlana V. Gurevich[1,2,3] — [1]Institute for Theoretical Physics, University of Münster, Münster, Germany — [2]Universitat de les Illes Balears, Palma, Spain — [3]Center for Data Science, University of Münster, Münster, Germany

We are interested in the dynamics of localized solutions in a weakly dissipative Korteweg de Vries Kuramoto Sivashinsky equation, using a combination of analytical, numerical, and path-continuation methods. We show that a traveling solitary soliton exists and is stable over a certain parameter range, even though the homogeneous state is linearly unstable. Furthermore, we employ a variational ansatz to analytically determine the selected velocity of the localized state. Finally, path continuation in the domain size reveals that the corresponding bifurcation points on both the homogeneous and solitary branches follow a power-law scaling with the system length, implying that each domain size admits a finite interval of parameter values in which a stable solitary wave exists.

DY 22.3 Tue 10:00 ZEU/0118

Pattern formation and route to chaos in a two-species reaction-diffusion model with one conservation law — •Simon Navia Rafide[1] and Uwe Thiele[2] — [1]University of Münster, Münster Germany — [2]University of Münster, Münster Germany

In many intracellular reactions, the total amount of a substance remains constant. For example, in reactions involving proteins that can adopt different conformations, it is possible to observe spatio-temporal concentration patterns that differ in their behaviour from those in systems without such constraints. We explore a relatively simple two-species reaction-diffusion model with a single mass conservation law governing cell polarisation [1, 2]. Here, we investigate the bifurcation behaviour of the model in detail and, using numerical continuation and time simulations, show that time-periodic patterns follow a period-doubling route to chaos, which appear in two different flavours. Moreover, we propose an approximate model based on the first two instability modes that allows us to understand the underlying mechanisms behind the first steps of pattern formation.

[1] Kuwamura, M., Izuhara, H., & Ei, S. I., Oscillations and bifurcation structure of reaction-diffusion model for cell polarity formation. J. Math. Biol., 84, 2022. [2] S. Ishihara, M. Otsuji, A. Mochizuki, Transient and steady state of massconserved reaction-diffusion systems, Phys. Rev. E 75, 015203, 2007.

DY 22.4 Tue 10:15 ZEU/0118

The 3-Components Problem — •Davide Toffenetti[1], Beatrice Nettuno[1], Henrik Weyer[2], and Erwin Frey[1] — [1]Ludwig Maximilian University of Munich (LMU), Munich, Germany — [2]KITP, UC Santa Barbara, USA

Our work develops a general framework that connects reaction-diffusion systems with active-matter theories. Earlier studies showed that two-component mass-conserving reaction-diffusion (2cMcRD) systems can be mapped onto Model-B-type dynamics [1], which leads to the coarsening of patterns. We extend this idea by introducing a minimal three-component mass-conserving reaction-diffusion (3cMcRD) model. Using adiabatic elimination, we derive an effective active description for the total-mass dynamics, reminiscent of the well-known AMB+ theory. We validate the mapping through extensive numerical simulations.

Only 3cMcRD systems and their associated effective active theory produce finite-wavelength patterns such as dots, stripes, and foam-like structures, in contrast to the coarsening dynamics of 2cMcRD models. Employing a local quasi-steady-state approximation, we further determine the thresholds separating distinct pattern-forming regimes. In particular, we analyze how fingering instability emerges from an initially flat interface, marking the transition to foam-like patterns.

Our approach naturally generalizes to systems with more than three components and and to more general active-matter theories.

[1] Weyer, Brauns & Frey (2023). Phys. Rev. E 108, 064202.

DY 22.5 Tue 10:30 ZEU/0118

Coarsening dynamics and interface instabilities in coupled conserved pattern-forming systems — Benjamin Winkler[1], Sergio Alonso[2], and •Markus Bär[3] — [1]RKI and FU Berlin, Germany — [2]UPC Barcelona, Spain — [3]PTB and TU Berlin, Germany

We investigate the coarsening dynamics of non-variationally coupled, mass-conserved pattern-forming systems. Our main example is a model describing multiscale pattern formation via the interaction of membrane binding proteins with a multicomponent lipid membrane. We find that the coupling of a reaction-diffusion system for a protein species to an equation describing the phase composition of a lipid membrane exhibiting active phase separation leads to arrested coarsening for strong enough coupling. In addition, inverse coarsening is found if simulations start from large domains. We show that these phenomena are closely connected with interface instabilities and an exceptional point in the linear properties of the spatially homogeneous state both of which emerge for strong-enough non-variational coupling. Similar phenomena are also found in a version of the non-reciprocally coupled Cahn-Hilliard equations, which have similar linear behavior and instabilities, and in a qualitative model for a compressible active polar fluid. The nonlinear evolution of the interface instability and the emerging complex patterns depend, however, on the specific form of the chosen model. This is demonstrated with a survey of possible dynamical evolutions in different models.

DY 22.6 Tue 10:45 ZEU/0118

Leading mechanisms of defibrillation: A computational approach to study the differences between monophasic and biphasic waveforms — •Daniel Frühwald[1] and Thomas Lilienkamp[1,2] — [1]Nuremberg Institute of Technology Georg Simon Ohm, Computational Physics for Life Science, Nuernberg, Germany — [2]Max Planck Institute for Dynamics and Self-Organization, Biomedical Physics Group, Goettingen, Germany

Sudden cardiac death caused by, for example, malignant ventricular arrhythmia, results in an estimated 600,000 deaths per year in the European Community alone. In addition, atrial fibrillation is the most common cardiac arrhythmia worldwide, affecting worldwide more and more people with around 33.5 million in 2010 and 59 million people in 2019. In both diseases, the heart can be reset to sinus rhythm by cardioversion: The application of a high-energy defibrillation shock delivered either from an external device, or from implantable cardioverter defibrillators (ICDs). In both cases, patients suffer from significant side effects due to this treatment, including additional tissue damage and post-traumatic stress. The introduction of biphasic waveforms, instead of monophasic ones enabled a significant reduction in energy leading to mitigated side-effects. While many hypotheses for the increased efficiency of biphasic waveforms exist, the underlying mechanisms are not entirely understood. In a statistically driven multi-scale study, we use numericalsimulations to investigate the influence of different cardiovascular structures on the success rate of defibrillation.

15 min. break

DY 22.7 Tue 11:15 ZEU/0118

Travelling waves of invasion in ecological communities with phenotypic variation — •Pierre A. Haas — Max Planck Institute for the Physics of Complex Systems — Max Planck Institute of Molecular Cell Biology and Genetics — Center for Systems Biology Dresden

Bacterial populations can switch to slowly growing "persister" subpopulations that are resilient to competition. Here, I will present a minimal model for the effect of this phenotypic variation on the spatial competition of two species. One of these species switches, both randomly and in response to the other, competitor species, to such a persister phenotype. One would expect this phenotypic switching to slow down the travelling wave by which the competitors invade the first species.
Combining exact results and numerical calculations, I will show that, surprisingly, this expectation does not hold true: phenotypic switching does not affect the speed of this wave. Somewhat conversely, I will demonstrate that phenotypic switching can speed up the reverse wave by which this species invades the competitors. This suggests that, counterintuitively, persisters can be an offensive, rather than defensive ecological strategy.

DY 22.8 Tue 11:30 ZEU/0118

How spatial patterns can lead to less resilient ecosystems — •David Pinto-Ramos and Ricardo Martinez-Garcia — Center for Advanced Systems Understanding (CASUS), Helmholtz-Zentrum Dresden-Rossendorf, Görlitz D-02826, Germany

Several theoretical models predict that spatial patterning increases ecosystem resilience. However, these predictions rely on simplifying assumptions, such as assuming isotropic and infinitely large ecosystems, and empirical evidence directly linking spatial patterning to enhanced resilience remains scarce. We introduce a unifying framework, encompassing existing models for vegetation pattern formation in water-stressed ecosystems, that relaxes these assumptions. This framework incorporates finite vegetated areas surrounded by desert and anisotropic environmental conditions that lead to non-reciprocal plant interactions. Under these more realistic conditions, we identify a novel desertification mechanism, known as nonlinear convective instability in physics but largely overlooked in ecology. These instabilities form when non-reciprocal interactions destabilize the vegetation-desert interface and can trigger desertification fronts even under stress levels where isotropic models predict stability. Importantly, ecosystems exhibiting periodic vegetation patterns are more susceptible to nonlinear convective instabilities than those with homogeneous vegetation, suggesting that spatial patterning may reduce, rather than enhance, resilience. These findings challenge the prevailing view that self-organized patterning enhances ecosystem resilience.

DY 22.9 Tue 11:45 ZEU/0118

Time-crystals in actively mode-locked lasers — Elias Koch[1], Ruiling Weng[2], Jesús Yelo-Sarrión[2], Josep Batle[2], Julien Javaloyes[2], and •Svetlana V. Gurevich[1,3] — [1]Institute for Theoretical Physics, University of Münster, Wilhelm-Klemm-Str.9 48149 Münster, Germany — [2]Departament de Física and IAC3, Universitat de les Illes Balears, Campus UIB 07122 Mallorca, Spain — [3]Center for Data Science and Complexity (CDSC), University of Münster, Corrensstrasse 2, Münster, 48149, Germany

We propose a time-delayed model for the study of active mode-locking that is devoid of restriction regarding the values of the round-trip gain and losses. There, we report the occurence of discrete time-crystal phases and crystallites. By tuning either the bias current or the modulation frequency, the system undergoes a spontaneous symmetry-breaking transition from the harmonically mode-locked state towards robust, highly coherent time-crystal states that persist indefinitely. Two equivalent time-crystal configurations, shifted by one driving period, can coexist as domains separated by sharp, long-lived boundaries analogous to domain walls. Additionally, we present recent experimental results that are in good quantitative agreement with the theoretical predictions. Our findings demonstrate that mode-locked semiconductor lasers offer a readily accessible platform to explore and control non-equilibrium phases of light, enabling practical implementations of time-crystal physics in photonic systems.

DY 22.10 Tue 12:00 ZEU/0118

Unified Simulation Framework for Multi-Soliton Dynamics in Femtosecond Lasers — •Julia A. Lang[1], Julien Javaloyes[2], Svetlana V. Gurevich[3], and Georg Herink[1] — [1]University of Bayreuth, Germany — [2]University of the Balearic Islands, Spain — [3]University of Münster, Germany

Ultrafast lasers exhibit a rich variety of multi-pulse dynamics, strongly influenced by the underlying laser architecture and system-specific nonlinear effects.

In this contribution, we present a novel simulation approach that flexibly integrates diverse effects into a single, unified framework. A key feature of our model is the inclusion of full gain dynamics. This enables us to reproduce a wide range of experimentally observed soliton interactions, including harmonic mode-locking in erbium fiber lasers [1], the formation of soliton molecules via delayed feedback [2] or Raman-induced soliton molecules in Ti:sapphire lasers [2].

We introduce a classification of characteristic inter-soliton trajectories by attributing hierarchies of critical weights to nonlinear effects. The resultant classification provides deeper insights into the origins of multi-pulse interactions and enables novel approaches for harnessing multi-soliton applications.

[1] Lang JA et al. Sci Adv. 2024;10(2):eadk2290.
[2] Nimmesgern L et al. Optica. 2021;8(10):1334.
[3] Völkel A et al. Nat Commun. 2022;13(1):2066.