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Mini-symposium "Pattern Formation"
organised by Uwe Thiele
Institut für Theoretische Physik and Center of Nonlinear Science (CeNoS), Westfälische Wilhelms Universität Münster, Germany
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Six sessions with 26 talks in total, thematic boundaries between sessions will be diffuse

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SUB-SESSION: Pattern formation in active media (3)
Tuesday 10:30-12:00
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Classification of active systems: hydrodynamic equations, instabilities, and pattern formation
Fernando Peruani
Université Nice Sophia Antipolis, member of Université Côte d’Azur

From the remarkably large number of microscopic active models that have been studied, only a limited number of distinct, large-scale, self-organized patterns have been identified. Here, we will classify active systems according to their hydrodynamic equations and instabilities and identify three main large-scale structures that emerge: polar structures, nematic structures, and aggregates where local (orientational) order is absent. At the microscopic level, we will identify two main distinct classes of active systems: those where interactions depend on the relative velocity of the active particles, and those where interactions depend primarily on the relative position.

Nonlinear dynamics of moving cells
Falko Ziebert
Institute for Theoretical Physics, University of Heidelberg, Germany

Self-propulsion, i.e. self-organized motion in the absence of external forces, is an active research topic in non-equilibrium and nonlinear physics. The living realm presents plenty of examples, like crawling eukaryotic cells and swimming bacteria, having to move to survive or to fulfill their function.
I will give an introduction on substrate-based crawling motility and survey our recent advances in its modeling by nonlinear active-soft-matter-type continuum approaches. Our approach allows to describe, e.g., the subcritical onset of motion, cell movement on structured substrates (with modulated adhesion or stiffness), as well as

collective cell migration and motion in 3D confinement.
As a specific example, I will apply our framework to the spontaneous rotational states prior to the cell's motility onset and polarization, recently found experimentally by several groups (S. Lou et al. J. Cell Biol. 2015; F. Raynaud et al. Nature Phys. 2016). Our framework suggests that physical mechanisms suffice to explain such states. We interpret them as nonlinear shape deformation waves, derive a reduced description and also study the competition of waves vs. onset of motion.

Resting and Traveling Localized States in an Active Phase-Field-Crystal Model
Lukas Ophaus
Institut für Theoretische Physik, Universität Münster, Germany

The conserved Swift-Hohenberg equation (or Phase-Field-Crystal [PFC] model) provides a simple microscopic description of the thermodynamic transition between fluid and crystalline states. Combining it with elements of the Toner-Tu theory for self-propelled particles Menzel and Löwen [Phys. Rev. Lett. 110, 055702 (2013)] obtained a model for crystallization (swarm formation) in active systems. Here, we study the occurrence of resting and traveling localized states, i.e., crystalline clusters, within the resulting active PFC model. Based on linear stability analyses and numerical continuation of the fully nonlinear states, we present a detailed analysis of the bifurcation structure of periodic and localized, resting and traveling states in a one-dimensional active PFC model. This allows us, for instance, to explore how the slanted homoclinic snaking of steady localized states found for the passive PFC model is amended by activity. A particular focus lies on the onset of motion, where we show that it occurs either through a drift-pitchfork or a drift-transcritical bifurcation. A corresponding general analytical criterion is derived.

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SUB-SESSION: Dynamics of patterning fronts (5)
Tuesday 12:00-12:30, 15:30-18:00
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Front instabilities can reverse desertification
Cristián Fernández Oto
Universidad de los Andes, Chile

Degradation processes in living systems often take place gradually by front propagation. An important context of such processes is loss of biological productivity in drylands or desertification. Using a dryland-vegetation model, we analyze the stability and dynamics of desertification fronts, and show that linear and nonlinear front instabilities can result in self-recovery. The results are based on

the derivation and analysis of a universal amplitude equation, and should therefore be applicable to other living-systems contexts showing front-propagation phenomena.

Dewetting Fronts - Patterning in Free Surface Liquid Films

Walter Tewes
Institut für Theoretische Physik, Universität Münster, Germany

We investigate the dynamics and patterns of propagating instability fronts in free surface liquid films for different geometries by means of numerical time simulations, analytical approaches and numerical continuation.
For the case of linearly unstable flat films on non-inclined resting substrates, we show that steadily propagating dewetting fronts with simple periodic droplet pinch-off events are found for very small film heights. However, more intricate periodic structures can be formed due to secondary oscillations above a certain threshold film height of the initial flat film.
The propagating instability of Plateau-Rayleigh type is then studied for liquid ridges on solid substrate, where we calculate the speed of propagation through a marginal stability analysis.
Finally, we study dewetting in the meniscus region in a dip-coating geometry. While the transfer of flat films ("Landau-Levich films") from a bath of liquid onto a plate is well studied, here we present novel solution type corresponding to time-periodic droplet formation close to the meniscus. These solutions are investigated by time simulations in one and two dimensions as well as by numerical path continuation of time-periodic states. In parameter space, the onset of pattern formation in this geometry can be calculated by a marginal stability analysis of dewetting fronts into flat Landau-Levich films.

Marcel Clerc

From propagation from unstable state: theory and experiments

Departamento de Fisica, Santiago de Chile, Chile

Coexistence of states is an indispensable feature in the observation of domain walls, interfaces, shock waves or fronts in macroscopic systems. The propagation of these nonlinear waves depends on the relative stability of the connected equilibria. In particular, one expects a stable equilibrium to invade an unstable one, such as occur in combustion, in the spread of permanent contagious diseases, or in the freezing of supercooled water. Here, we show that an unstable state generically can invade a stable one in the context of the pattern forming systems. Based on a one-dimensional

model we reveal the necessary features to observe this phenomenon. This scenario is fullled in the case of a subcritical spatial instability. A photo-isomerization experiment of a dye-dopant nematic liquid crystal, allow us to observe the front propagation from an unstable state.

Patterning fronts in quasi-incompressible multicomponent liquids

Gyula Toth
Department of Mathematical Sciences, Loughborough University, UK

The main barrier to the successful quantitative numerical modelling of pattern formation phenomena in multicomponent liquids of varying density is the presence of sound waves. Since liquids are nearly incompressible, the fundamental time scale in the system is determined by the speed of sound, and therefore the time scales of pattern formation are practically inaccessible in computer simulations. To overcome the problem, the concept of quasi-incompressible liquids was introduced by J. Lowengrub and L. Truskinovsky in 1997. According to their original concept, mixing in a non-reactive multicomponent liquid can be approximated as a volume preserving process, i.e., the molecular volume (the volume occupied by a molecule) of a constituent doesn't change upon mixing. This assumption fixes the local density of the mixture as the function of the local composition, which results in the elimination of sound waves. The numerical solution of the quasi-incompressible hydrodynamic equations relies on the adaptation of Chorin's projection method to the generalized Poisson equation (G.I. Toth, Phys. Rev. E 94, 033114). To solve the discretized equations, a strictly mass and momentum conserving, energy stable time stepping scheme has been developed by using operator-splitting based, quasi-spectral semi-implicit methods. It has been shown that density contrast between components has a major effect on the behaviour of forming patterns in interface driven processes.

Haifaa Alrihieli, University of Leeds, UK
Title: Localized traveling waves in thermosolutal convection

Thermosolutal convection occurs in fluids subject to gradients both in temperature and concentration. With low solute diffusivity and temperature increase, steady convection can occur via a pitchfork bifurcation. When the solute diffuses faster than temperature, the primary bifurcation changes to a Hopf bifurcation leading to oscillatory convection. The critical point where the transition from steady to oscillatory convection called Takens-Bogdanov bifurcation (TB) point. At TB point, the existence of a global bifurcations (homoclinic and heteroclinic) can be established.

In the past, two dimensional nonlinear thermosolutal convection with

Boussinesq approximation has been considered analytically by many researchers, who use the truncation method to reduce the full partial differential equations to low order sets of ordinary differential equations. Such an approach makes it difficult to explore the full behavior of the system near the TB point in an extended domain. This work develops a partial differential equation model which replicates the linear behaviour of thermosolutal convection and whose amplitude equations can be reduced to the Takens-Bogdanov normal form. This model for thermosolutal convection is useful in two ways. Firstly, we can easily investigate the behaviour of small amplitude solutions near onset, both analytically and numerically. Secondly, we can explore the global behaviour of the system in extended domains and identify parameter ranges where spatially localized solutions are possible.

Spatially localised states are normally found in regions of bistability between two different solutions. Using amplitude equations to identify bistable regions in our model system, we numerically obtain different types of spatially localized states. This talk will focus on two examples for localised travelling waves: localised travelling wave in a background of trivial/flat state and localised travelling waves in a background of steady state.

Dynamics of Confined Membranes
Olivier Pierre-Louis
UMR5306 CNRS, Université Claude Bernard Lyon 1, France

Bilayer lipid membranes are abundant in biological systems. They are found in cell membranes, skin, pupils, articulations and pulmonary organs. Here we wish to investigate the consequences of confinement on the dynamics of membranes. We study the dynamics of a fluid membrane with bending rigidity and area conservation confined between two attractive walls. This geometry is firstly inspired by adhesion of biological cells. We find that these dynamics define a novel universality class for phase separation in two dimensions with unique features due to the membrane bending rigidity and area conservation. Indeed, standard models for 2D phase separation developed to study spinodal decomposition in alloys, magnetic systems, or reaction-diffusion systems, are generically described by the time-dependent Ginzburg-Landau equation (or its conserved version the Cahn-Hilliard equation), and give rise to power-law coarsening, i.e. perpetual increase of the domain size. Here, we show that the dynamical equations governing confined membranes share similarities with the Swift-Hohenberg equation, however with a time-dependent tension that enforces membrane area conservation. Within this model, membrane adhesion domains exhibit a transition to coarsening controlled by the total excess area of the membrane. For small excess area, we find frozen flat adhesion domains. However, for intermediate excess area, coarsening is observed, with a coexistence between flat domains and wrinkle domains. Finally, for large excess area, a the membrane forms a frozen labyrinthine pattern of wrinkles.

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SUB-SESSION: Patterns in heterogeneous media (6)
Wednesday 10:30-12:30 AND 15:00-16:00
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Size Matters in Pattern formation
Walter Zimmermann
Theoretische Physik, Universität Bayreuth, Germany

Pattern formation and selection are fundamental, omnipresent principles in nature - from small cells up to geological scales. In real systems, boundaries are always present and their effects are important for understanding {\color{red}patterns in nature and their function}. For example, in finite systems patterns are stable in larger wavenumber range and one finds multistability with respect to different wave number and pattern orientations. Another example, are nonlinear traveling waves, which inevitably change into standing waves in sufficiently small, confined systems. This transition is a robust universal property of nonlinear waves which appear in many nonequilibrium systems. We demonstrate this generic finding for complex Swift-Hohenberg model and test these generic findings for two concrete systems: a model for the cellbiological Min reaction and an extended Brusselator model. Our generic results highlight the importance of universal principles from pattern formation theory for self-organization in nature.

Temporal Localized Structures in an Inhomogeneous Parameter Landscape
P. Camelin (1), M. Marconi (1), J. Javaloyes (2), M. Giudici* (1)
(1) Université Côte d'Azur, Institut de Physique de Nice, France
(2) Departament de Fisica, Universitat de les Illes Balears,Palma de Mallorca, Spain

Position and speed of temporal localized structures in mode-locked semiconductor laser can be controlled by introducing a parameter landscape along the resonator. This is obtained by modulating the pumping current quasi synchronously with the cavity roundtrip. We show that localized structures dynamics is affected by the lack of parity symmetry of the system.

Pattern formation by heterogeneous parametric excitation: localization, Rabi oscillations, and PT symmetry
Mónica Garcia-Nustes, Fernando Mellado-Humire and Yogesh Joglekar
Instituto de Física, Pontificia Universidad Católica de Valparaíso

Parametric oscillators are a paradigmatic model of an out-of-

equilibrium system where structures as solitons and patterns appear. The continuous losses on the system are compensated by a parametric forcing that can be either uniformly distributed in space or localized. Localization can be produced by a finite substrate or by heterogeneities in the medium. In fact, heterogeneous forcing is a common physical condition. In this work, we show recent results on pattern formation in a parametric system subject to a heterogeneous forcing. We explore interesting phenomena as the formation of a localized pattern, pattern interaction, Rabi-like oscilla- tions and PT symmetry in a dissipative (out-of-equilibrium) system. We also present some experimental realizations conducted in a shallow water trough subjected to a parametric force with a tunable localization. New perspectives and future works will be discussed.

Formation and Spatial Localization of Phase Field Quasicrystals

Priya Subramanian
University of Leeds, UK

The dynamics of many physical systems often evolve to asymptotic states that exhibit spatial and temporal variations in their properties such as density, temperature, etc. Regular patterns such as graph paper and honeycombs look the same when moved by a basic unit and/or rotated by certain special angles. They possess both translational and rotational symmetries giving rise to discrete spatial Fourier transforms. In contrast, an aperiodic crystal displays long range order but no periodicity. Such quasicrystals lack the lattice symmetries of regular crystals, yet have discrete Fourier spectra. We look to understand the minimal mechanism which promotes the formation of such quasicrystalline structures arising in diverse soft matter systems such as dendritic-, star-, and block co-polymers using a phase field crystal model. Direct numerical simulations combined with weakly nonlinear analysis highlight the parameter values where the quasicrystals are the global minimum energy state and help determine the phase diagram. By locating parameter values where multiple patterned states possess the same free energy (Maxwell points), we obtain states where a patch of one type of pattern (for example, a quasicrystal) is present in the background of another (for example, the homogeneous liquid state) in the form of spatially localized dodecagonal (in 2D) and icosahedral (in 3D) quasicrystals. In two dimensions, we compute several families of spatially localized quasicrystals with dodecagonal structure and investigate their properties as a function of the system parameters. The presence of such metastable localized quasicrystals is significant as they affect the dynamics of the soft matter crystallization process.

Three-dimensional doubly diffusive convectons: instability and transition to complex dynamics

Cedric Beaume
Department of Applied Mathematics, University of Leeds, UK

Doubly diffusive convection in a closed vertically extended 3D container driven by competing horizontal temperature and concentration gradients is studied. No-slip boundary conditions are imposed. The buoyancy number N=-1 to ensure the presence of a conduction state. The primary instability is subcritical and generates two families of spatially localised steady states known as convectons. The convectons bifurcate directly from the conduction state and are organized in a pair of primary branches that snake within a well-defined range of Rayleigh numbers as the convectons grow in length. Secondary instabilities generating twist result in secondary snaking branches of twisted convectons. These destabilize the primary convectons and are responsible for the absence of stable steady states, localized or otherwise, in the subcritical regime. As a result, once the Rayleigh number for the primary instability of the conduction state is exceeded, the system exhibits an abrupt transition to large amplitude spatio-temporal chaos. These numerical results are confirmed by determining the stability properties of all convecton states as well as spatially extended convection.

Multiscale Modelling of Graphene from Nano to Micron Scales

Tapio Ala-Nissila
Aalto University, Finland, and Loughborough University, UK

Over the last few years novel two-dimensional materials and nanoscopically thin heteroepitaxial overlayers have attracted intense attention due to their unusual properties and important technological applications. Many physical properties of these systems such as thermal conductivity and electrical transport are intimately coupled to the large scale mechanical and structural properties of the materials. However, modeling such properties is a formidable challenge due to a wide span of length and time scales involved. In this talk, I will review recent significant progress in structural multi-scale modeling of two dimensional materials and thin heteroepitaxial overlayers [1], and graphene in particular [2], based to a large extent on the Phase Field Crystal (PFC) model combined with standard microscopic modeling methods (classical Molecular Dynamics and Quantum Density Functional Theory). The PFC framework allows one to reach diffusive time scales for structural relaxation of the materials at the atomic scale, which facilitates quantitative characterisation of domain walls, dislocations, grain boundaries, and strain-driven self-organisation up to almost micron length scales. This allows one to study e.g. thermal conduction and electrical transport in realistic multi-grain systems [3].

1. K. R. Elder et al,. Phys. Rev. Lett. vol. 108, 226102 (2012); Phys. Rev. B vol. 88, 075423 (2013); J. Chem. Phys. 144, 174703 (2016).
2. P. Hirvonen et al., Phys. Rev. B 94, 035414 (2016).

3. Z. Fan et al., Phys. Rev. B vol. 95, 144309 (2017); Nano Lett. 7b172 (2017); K. Azizi et al., Carbon 125, 384 (2017).

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SUB-SESSION: Pattern formation in technological processes (4 talks)
Thursday 10:30-12:30
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The Spontaneous Formation of Nanopatterns in Velocity-Dependent Dip-Coated Organic Films: From Dragonflies to Stripes

Patrick Huber
Institute of Materials Physics and Technology, Hamburg University of Technology (TUHH), Germany

We present an experimental study of the micro- and mesoscopic structure of thin, medium length, n-alkane films on the native oxide layer of a silicon surface, prepared by dip-coating in a n-$C_{32}H_{66}$/n-heptane solution. Electron micrographs reveal two distinct adsorption morphologies depending on the substrate withdrawal speed v. For small v, dragonfly-shaped molecular islands are observed. For a large v, stripes parallel to the withdrawal direction are observed. These have a few hundred micrometer lengths and a few-micrometer lateral separation. For a constant v, the stripes' quality and separation increase with the solution concentration. Grazing incidence X-ray diffraction and atomic force microscopy show that both patterns are 4.2 nm thick monolayers of fully extended, surface-normal-aligned alkane molecules. With increasing v, the surface coverage first decreases, then increases for $v > v_{cr}$ 0.15 mm/s. The critical v_{cr} marks a transition between the evaporation regime, where the solvent's meniscus remains at the bulk's surface, and the entrainment (Landau-Levich-Deryaguin) regime, where the solution is partially dragged by the substrate, covering the withdrawn substrate by a homogeneous film. The dragonflies are single-crystals with habits determined by dendritic growth in prominent 2D crystalline directions of randomly seeded, quasi-hexagonal nuclei. The stripes' strong crystalline texture and the well defined separation are due to an anisotropic 2D crystallization in narrow liquid fingers.

Control and selection of spatio-temporal patterns in dynamic self-assembly systems

Svetlana Gurevich, Markus Wilczek, Walter Tewes, Timmy Ly, Uwe Thiele

Institute for Theoretical Physics, University of Münster, Germany
Center for Nonlinear Science (CeNoS), University of Münster, Germany

Self-organization or dynamic self-assembly is a mechanism responsible for the formation of complex structures through multiple interactions among the microscopic components of the system. We are interested in the formation of regular stripe patterns during the transfer of surfactant monolayers from water surfaces onto moving solid substrates by means of a generalized Cahn–Hilliard equation. A combination of numerical simulations and continuation methods is employed to investigate stationary and time–periodic solutions of the model. Further, the influence of the spatio–temporal forcing on the patterning process is discussed. We show that the occurring locking effects enable a control mechanism via properties of the forcing and facilitate the production of patterns with a broader range of features. In two dimensions, the production of a variety of complex patterns can be achieved through the competition of intrinsic properties of the pattern forming system and the external forcing.

Complex wave dynamics in falling liquid films

Dmitri Tseluiko
Department of Mathematical Sciences, Loughborough University, UK

We consider a liquid film flowing down an inclined wall that may be subjected to an additional external effects, such as an electric field. We analyse the Stokes–flow regime, using both a non–local long–wave model and the full system of governing equations. For an obtuse inclination angle and strong surface tension, the evolution of the interface is chaotic in space and time. However, a sufficiently strong electric field has a regularising effect, and the time–dependent solution evolves into an array of continuously interacting pulses, each of which resembles a single–hump solitary pulse. For an acute inclination angle and a sufficiently small supercritical value of the electric field, solitary–pulse solutions do not exist, and the time–dependent solution is instead a modulated array of short–wavelength waves. When the electric field is increased, the evolution of the interface first becomes chaotic, but then is regularised so that an array of pulses is generated. A coherent–structure theory for such pulses is developed and corroborated by numerical simulations.

Connecting monotonic and oscillatory motions of the meniscus of a volatile polymer solution to polymer transport and deposit morphology

Mohammad Abo Jabal[1], Ala Eghbaria[1], Anna Zigelman[1], Uwe Thiele[2], and Ofer Manor[1]

[1] Wolfson Department of Chemical Engineering, Technion – Israel Institute of Technology, Haifa, Israel 32000
[2] Institut für Theoretische Physik and Center of Nonlinear Science (CeNoS), Westfälische Wilhelms Universität Münster, Germany

We study the interplay of the evaporative receding motion of the meniscus of a polymer solution and the resulting pattern deposition of the polymer by vaporizing a solution of poly-methyl-methacrylate (PMMA) in toluene inside a micro-chamber. We observe qualitatively different deposition patterns when
varying the molecular mass of the polymer, the initial polymer concentration, and the temperature and dimensions of the micro-chamber. The motion modus of the three-phase contact line between the solution, its vapor, and the substrate correlates directly with the modus of deposition. Both modi change with the P\'{e}clet number, characterizing the ratio between rate of polymer convection to result from solvent evaporation and the rate of polymer diffusion, which is connected to the molecular mass of the polymer. At low P\'{e}clet numbers the contact line moves monotonically and deposition is continuous, producing a homogeneous deposit layer. At larger P\'{e}clet numbers, we find an oscillatory motion of the contact line; the deposition is then periodic, producing a stripe pattern. The oscillatory motion differs from the well known stick-slip motion reported in the absence of confinement. The confinement reduces the evaporation rate of the solvent, which may support periodic sequences of advancing and receding contact line motions that overall de-wet the substrate. This oscillatory motion is attributed to the opposing influences of evaporation and Marangoni forces. The Marangoni contribution results from the dependence of the surface tension of the solution on polymer concentration.

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SUB-SESSION: Delayed-feedback control of Pattern Formation (4)
Thursday 15:30-17:30
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Mode-locked lasers with optical self feedback: Pattern formation in the time domain

Kathy Lüdge
Institut für Theoretische Physik, Technische Universität Berlin

Integrated semiconductor lasers with gain and absorber sections can be operated as pulsed light sources due to the mode-locking of longitudinal resonator modes. Those pulses repeat with the cavity round trip time, however, the pulse positions are subject to a relatively high timing jitter. Optical self feedback can reduce this jitter, but, nonresonant feedback also leads to complex bifurcations scenarios and the stabilization of higher order mode-locking as well as the creation of complex pulse trains. In this talk we discuss how different quasi-periodic pulsating solutions emerges with increasing mode number in mode-locked devices. The focus will be on identifying qualitative changes of the output pulse trains and the underlying bifurcation structure by means of path continuation in the limit of short delay times. Pseudo-space-time representations of the light output help to classify the dynamic regimes that can be interpreted as pattern formation in the time domain.

Neutral Delay Differential Equations for Mode-Locked lasers : Fundamental Satellites Instabilities

Christian Schelte (1,2), Soizic Terrien (3), Julien Javaloyes* (1), and Svetlana V. Gurevich (2,4)

(1) Non Linear Wave Group (ONL), Dept. of Physics, University of Balearic Islands, Spain
(2) Institute for Theoretical Physics, University of Münster, Germany
(3) Department of Mathematics, University of Auckland, Auckland
(4) Center for Nonlinear Science (CeNoS), University of Münster, Germany

Passively mode-locked semiconductor lasers can be modeled via Delay Differential Equations (DDEs) and this approach is particularly useful when the geometry of the laser is that of a ring laser. Such DDE models predicted the existence of a regime of temporal localization to be found in the long cavity limit. Here, by taking the long delay limit, the pulses become individually addressable localized structures. The existence of this regime was successfully disclosed experimentally using Vertical-Cavity Surface-Emitting Lasers [1]

In this work we show that while localization also exists in Standing-wave (Fabry-Perot) lasing cavities, a proper modeling requires instead using Neutral DDEs. In addition, we show that this geometry yields additional features in which the localized states develop infinitely many satellites. The latter may become unstable thus leading to a global bifurcation of the pulse train.

[1] M. Marconi et al. , Phys. Rev. Lett. , 112:223901, Jun 2014

Delay models in nonlinear laser dynamics

Andrei Vladimirov
Weierstrass Institute, Berlin, Germany

An approach to the modelling of nonlinear dynamics in multimode lasers using delay differential equations (DDEs) is discussed. We consider DDE models of different multimode laser devices: passively mode-locked semiconductor lasers generating short optical pulses with high repetition rates, frequency swept lasers used in optical coherence tomography, and broad area external cavity lasers capable of generating the so-called light bullets. We present the results of numerical simulations of different dynamical states in these lasers and discuss asymptotic approaches to the stability analysis of stationary and periodic operation regimes in the large delay time limit. In particular, distributed and nonlocal delay models for modelling the effects of dispersion and transverse diffraction on

the laser dynamics are discussed.

Delayed-feedback control in reaction-diffusion systems
Eckehard Schöll
Technische Universität Berlin, Institut für Theoretische Physik, Germany

Time-delayed feedback control and nonlocal spatial coupling can be used as means of
controlling spatio-temporal patterns in reaction-diffusion systems. We review deterministic and noise-induced
spatio-temporal dynamics in the framework of simple paradigmatic models of reaction-diffusion systems
describing neural excitation waves or nonlinear semiconductors or electrochemical systems.

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SUB-SESSION: Environmental spatial patterns (5)
Friday 10:30-13:00
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Vegetation pattern formation and ecosystem function in the Anthropocene
Ehud Meron
Blaustein Institutes for Desert Research & Physics Department Ben-Gurion University of the Negev

Dryland landscapes show a variety of vegetation pattern-formation phenomena, two striking examples of which are banded vegetation on hill slopes and nearly hexagonal patterns of bare-soil gaps in grasslands (“fairy circles”). Vegetation pattern formation is a population-level mechanism to cope with water stress, that is coupled to other response mechanisms operating at lower and higher organization levels, such as phenotypic changes at the organism level and biodiversity changes at the community level. Uncovering the roles that vegetation pattern formation plays in the functioning of dryland ecosystems is a challenging problem of particular significance in the current era of climate change and massive human intervention in natural ecosystems. In this talk I will present a platform of mathematical models for dryland ecosystems and use it to study (i) mechanisms of vegetation pattern formation, (ii) the variety of extended and localized patterns that can appear along the rainfall gradient, (iii) the impact of pattern formation on ecosystem response to droughts, and (iv) forms of high-integrity human intervention that do not impair ecosystem function. Universal aspects that might be applicable to other living systems will be emphasized.

Vegetation patterns under the sea

Emilio Hernández-García
IFISC (CSIC-UIB), Campus Universitat de les Illes Balears 07122
Palma de Mallorca, Spain

Pattern formation in distributions of terrestrial plants, driven by factors such as competition for water or nutrients or interactions with herbivores, has been a subject of intense research in the last years. Here we report on the observation from air images and from sonar data of analogous pattern forming phenomena in meadows of seagrasses, mainly Posidonia oceanica and Cymodocea nodosa, in the Mediterranean Sea. We derive a macroscopic model from the growth rules of these clonal plants that is able to provide an explanation to the observed submarine patterns of isolated 'fairy circles', and landscapes of spots and stripes, and link the prevalence of one over the others to the conditions of the meadow. Beyond a qualitative description of the observed patterns, the model fits well measurements of the population density of Posidonia which show great variability close to the coast, where patterns typically appear.

Work done in collaboration with D. Ruiz, D. Gomila, T. Sintes, N. Marbà and C. Duarte

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Spirals and arcs vegetation patterns in arid ecosystems: a self-organized response to water scarcity

Mustapha Tlidi
Université Libre de Bruxelles (U.L.B), Bruxelles, Belgium.

Vegetation patterns belong to the class of dissipative structures found out of equilibrium. We report for the first time on the formation of spirals like vegetation patterns in isotropic and uniform environmental conditions. The vegetation spirals presented in this contribution are not waves and they do not rotate. In the context of ecology and plant ecology, spiral pattern are not yet documented. They have never observed in nature nor predicted by mathematical modeling. We use the generic interaction-redistribution model based on the relationship between the structure of individual plants and the nonlocal interactions existing within plant community. This single variable model allows us to test a set of predictions for resources-limited ecosystems. We show that for moderate aridity conditions, a single or more localized patches can exhibit a curvature instability. During time evolution, the biomass in the central portion of the localized patch decays followed by transition to the formation of a doughnut-like shape. This structure breaks down to arcs of vegetation and transform into spirals like patterns.

Isolated or interacting spirals and arcs observed in South America

(Bolivia) and North Africa (Morocco) are interpreted as a result of curvature instability that affect the circular shape of localized patches. Quantitative interpretation of observations and of the predictions provided by the theory is illustrated by recent measurements of a peculiar plant morphologies (the Alfa plant, or Stipa Tenacissima L.) originated from the northwestern Africa and the southern part of the Iberian Peninsula.

Convection in salt playa

Lucas Goehring
Nottingham Trent University, UK

The polygonal patterns of ridges in salt flats, playa, and pans are shockingly regular features of arid landscapes. They are most well-known from places like Death Valley, or Salar de Ununi. They also form in the salt crusts covering large pans like the Sua or Etosha pans, which are some of the primary sources of airborne dust in sub-saharan Africa. Such crusts typically display a pattern of polygonal cells, a few meters across, bounded by ridges a few centimetres in size. No conclusive explanation for these features has ever been given, but their resemblance to polygonal terrain, or columnar joints, has led to speculation that they are formed by fracture patterns of the salt crust. Here, we instead argue that the pattern cannot be properly understood unless it is considered in light of subsurface convection of salt-rich ground-water. In particular, we propose that surface evaporation creates a salt-rich surface layer of water that is unstable to Rayleigh-Bénard convection within the pore space of the playa soil. This convection creates variations in salt concentration, which allow for the selective deposition of salt around the perimeters of the convection cells, hence appearing as a regular surface pattern. We support this argument with a linear stability analysis of the geophysical situation, numerical simulations of the stratified fluids, analogue experiments, and field observations.

The Role of Self-Organized Spatial Patterns in the Design of Agroforestry Systems (short talk?)

Omer Tzuk1* Hannes Uecker2, Pedro Berliner3, Ehud Meron1
1 Department of Physics, Ben-Gurion University of the Negev, Beer Sheva, Israel
2 Department of Mathematics, Universit\"at Oldenburg, Oldenburg, Germany
3 Jacob Blaustein Institute for Desert Research, Sede-Boqer Campus, Israel

The development of sustainable agricultural systems in drylands is currently an important issue in the context of mitigating the outcomes of population growth under the conditions of climatic

changes. The need to meet the growing demand for food, fodder, and fuel under the threat of climate change, requires cross-disciplinary studies of ways to increase the livelihood while minimizing the impact on the environment. Practices of agroforestry systems, in which herbaceous species are intercropped between rows of woody species plantations, have shown to increase land productivity. As vegetation in drylands tends to self-organize in spatial patterns, it is important to explore the relationship between the patterns that agroforestry systems tend to form, and the productivity of these system in terms of biomass, their resilience to droughts, and water use efficiency.

A spatially-explicit vegetation model for two species that compete for water and light and may exploit soil layers of different depths will be introduced. Spatially-uniform and periodic solutions, and their stability properties, will be presented for different scenarios of species and environmental conditions. The implications for optimal intercropping in terms of biomass productivity, water use efficiency, and resilience to environmental changes, will be discussed.
