Introduction to focus issue: In memory of Vadim S. Anishchenko: Statistical physics and nonlinear dynamics of complex systems

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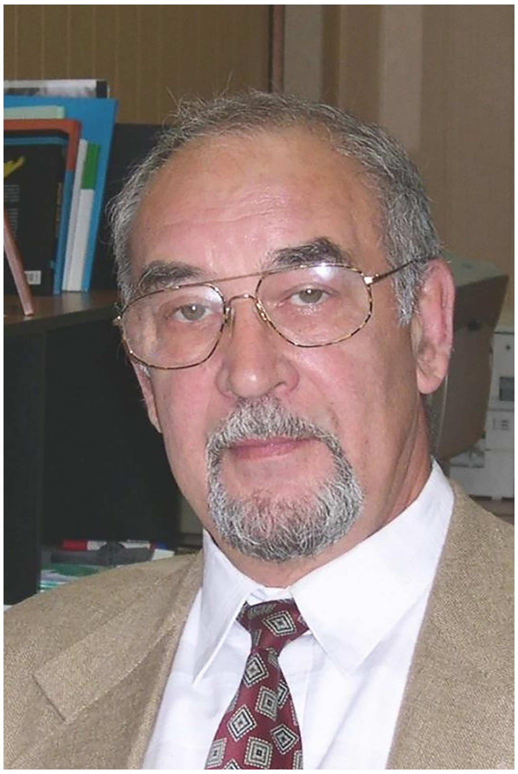
Anna Zakharova,[1,a] Galina Strelkova,[2] Eckehard Schöll,[1,3,4] and Jürgen Kurths[4,5,6]

AFFILIATIONS

[1]Institut für Theoretische Physik, Technische Universität Berlin, Hardenbergstr. 36, 10623 Berlin, Germany
[2]Institute of Physics, Saratov State University, 83 Astrakhanskaya Street, Saratov 410012, Russia
[3]Bernstein Center for Computational Neuroscience Berlin, Humboldt-Universität, 10115 Berlin, Germany
[4]Potsdam Institute for Climate Impact Research, Telegraphenberg A 31, 14473 Potsdam, Germany
[5]Institute of Physics, Humboldt University Berlin, 12489 Berlin, Germany
[6]Biology Department, Saratov State University, 83 Astrakhanskaya Street, Saratov 410012, Russia

[a]**Author to whom correspondence should be addressed:** anna.zakharova@tu-berlin.de



INTRODUCTION

Vadim Semenovich Anishchenko (born on October 21, 1943) studied Physics and Radiophysics at the Physics Department of Saratov State University (SSU, Saratov, Russian Federation) in 1961–1966. After graduating from the University, he was enrolled as an engineer at the Scientific and Research Institute of Mechanics and Physics of SSU. Vadim Anishchenko was seriously involved into scientific research and acquired deep knowledge in the field of oscillation theory and circuit theory and the theory of random processes and statistical radiophysics. He defended his Ph.D. thesis in 1970 devoted to noise properties of electron flows of microwave amplifiers, and since then, he started working as an Assistant at the Radiophysics Chair of Saratov State University.

A turning point in his work came from his acquaintance with Professor Yury L'vovich Klimontovich from Moscow State University (MSU) at the Workshop on stochastic self-sustained oscillations in 1980, where Vadim Anishchenko gave his first report on dynamical chaos, which aroused the interest of specialists. As a result of communication with Yu. L. Klimontovich, he participated in the MSU scientific seminars on synergetics, which brought together the leading specialists in physics of nonlinear phenomena of those years, his decision matured to devote his work to research in the field of deterministic chaos.

In 1986, Vadim Anishchenko defended his Doctor of Sciences thesis (Habilitation) on mechanisms of emergence and properties of chaotic oscillations in radiophysical systems with a finite number of degrees of freedom. It was the first work in the Soviet Union, which was fully devoted to the problems of dynamical chaos. He and his former student V. Astakhov developed already in 1983 the first radiophysical generator of chaotic oscillations, which is described by a three-dimensional autonomous differential system.[1] It is now known as the Anishchenko–Astakhov oscillator and serves as one of the basic models of spiral chaos in nonlinear dynamics. Using this model, the route to chaos via the Feigenbaum scenario was studied both experimentally and numerically. The effect of basic frequency locking of chaotic oscillations—chaos synchronization—was demonstrated experimentally for the first time for a harmonically driven Anishchenko—Astakhov oscillator. Based on his thesis, Vadim Anishchenko published a pioneering scientific monograph "Stochastic Oscillations in Radiophysical Systems" first in Russian (1986) and then in English (1987 and 1989) in the Teubner-Texte zur Physik Publishing House.[2,3]

Since 1988 and until his passing away on November 30, 2020, Vadim Anishchenko was Professor and Head of the Radiophysics and Nonlinear Dynamics Department of Saratov State University. Vadim S. Anishchenko was an internationally recognized expert in the theory of nonlinear oscillations, the theory of dynamical chaos, and synchronization of complex nonlinear systems, in the theory of fluctuations in nonlinear systems and statistical radiophysics. Among numerous achievements in Vadim's scientific work, the most bright contributions include effects of forced and mutual phase-frequency synchronization of spiral chaos observed numerically and experimentally;[4] the effect of stochastic resonance in a noise-free chaotic system with two symmetric chaotic attractors;[5,6] the phenomenon of stochastic synchronization when the mean switching frequency is locked by an external periodic signal;[6,7] the synchronization effect of two-frequency quasiperiodic oscillations;[8,9] mechanisms and properties of phase and amplitude chimeras in networks of nonlocally coupled chaotic oscillators,[10–12] new types of chimera states—coherence-resonance chimera[13,14] and solitary state chimera,[15] and synchronization of chimera states in multilayer networks of coupled nonlinear oscillators.[16–21]

Vadim's contribution to physics and nonlinear dynamics was acknowledged by his receipt of the prestigious Alexander von Humboldt Research Award in 1999. Vadim Anishchenko was an Honored Scientist of the Russian Federation (1995), a Honorary Educator of the Russian Federation (2019), and a Honorary Professor of Saratov State University. A complete list of V.S. Anishchenko's publications has about 530 titles. Among them, there are about 500 scientific articles, 23 monographs and textbooks, including seven monographs in English, two of which were published by Springer.[22,23]

Vadim Anishchenko was the founder of one of the leading scientific schools on radiophysics and nonlinear dynamics in the Russian Federation. Seven Doctor of Sciences (Habilitation) theses (Professors A. B. Neiman, V. V. Astakhov, T. E. Vadivasova, D. E. Postnov, A. V. Hohlov, A. N. Pavlov, and G. I. Strelkova) and 23 Ph.D. theses were defended under Vadim Anishchenko's supervision. He was scientific supervisor of more than 40 scientific grants, which were funded by the Russian Foundation for Basic Research, the U.S. Civilian Research and Development Foundation, the Grant Program of the President of the Russian Federation, the Ministry of Science and Higher Education of the Russian Federation, the Russian Science Foundation, and the German Research Foundation (DFG). He gave over 60 talks and plenary lectures at numerous international scientific conferences and schools. He also organized six international scientific conferences and workshops on nonlinear dynamics in Saratov. Taking into account Vadim's experience and scientific achievements in October 2013, he was appointed as Advisor to the Rector for Science. During the last 6 years, Vadim was Principal Investigator of the Collaborative Research Center (CRC) SFB 910: Control of Self-Organizing Nonlinear Systems, where he led the first Russian Project in a German CRC.

Vadim Anishchenko and his group had a long-term and highly successful collaboration with Professor Werner Ebeling (Berlin) on statistical physics, Professor Lutz Schimansky-Geier (Berlin) on noise-induced transitions, stochastic resonance, and stochastic synchronization, Professor Jürgen Kurths (Berlin/Potsdam) on nonlinear dynamics and synchronization in various dynamical systems, Professor Eckehard Schöll (Berlin) on partial synchronization patterns in complex networks of coupled oscillators including chimera states. He also published a number of research papers in coauthorship with Professor Leon Chua, Professor Frank Moss, Professor P. V. E. McClintock, Dr. Astero Provata, Professor Tomasz Kapitaniak, and many other internationally leading scientists.

Many people who communicated with Vadim Anishchenko noted his broad outlook, fundamental knowledge, and judgments and were amazed by his incredible foresight and boundless dedication to the cause of life. He was a very kind, sympathetic, cheerful, and caring person. He was very much loved by friends, colleagues, employees, and students. We all miss him.

IN THIS ISSUE

This Focus Issue is dedicated to the memory of Vadim S. Anishchenko, an outstanding scientist in the field of nonlinear dynamics of deterministic and stochastic systems. We are happy to present such an impressive collection of articles, contributed by his colleagues, collaborators, and friends, related to Vadim Anishchenko's work on the theory of nonlinear oscillations, bifurcations, dynamical chaos, synchronization, stochastic processes and noise in nonlinear systems, stochastic bifurcations, strange nonchaotic attractors, partial synchronization patterns in complex networks of coupled oscillators and coupled maps including chimera states, and applications of methods of nonlinear dynamics in biology and medicine.

Dynamical chaos and bifurcations

Deterministic chaos and bifurcations were the very first research topics that had been studied by Vadim Anishchenko and his group and served as a very successful start of his bright scientific carrier. These fundamental research directions still attract a lot of attention of experts in nonlinear dynamics, physics, and mathematics. Gonchenko *et al.*[24] discuss the role of the curve-doubling bifurcations in the formation of chaotic dynamics and consider two types of the curve-doubling bifurcations: length doubling and component doubling. The authors study scenarios of the emergence of discrete Lorenz and Shilnikov attractors in three-dimensional Henon maps. In the paper by Chigarev *et al.*,[25] the concepts of relative dimensions and mutual singularities are applied to characterize the fractal properties of overlapping attractor and repeller in modified Anosov and Chirikov maps. It is shown that the relative Rényi and Kullback–Leibler dimensions as well as the mutual singularity spectra for the attractor and repeller can be well approximated under the orthogonality assumption of two fractals. Janson and Marsden[26] conceive and prove a principle behind optimization, which uses bifurcations caused by time delay in nonlinear dynamical systems and could potentially be implemented in analog circuits. The authors hypothesize and verify that, in a special class of delay equations involving the gradient of the cost function, an increase of delay induces a chain of global bifurcations, which effectively remove the barriers between the minima and enable the system to "explore" the vicinities of all minima. de Wolff and Schneider[27] study the failure of Pyragas control of periodic orbits and equilibria. They derive a fundamental observation on the invariance of the geometric multiplicity of the trivial Floquet multiplier and show that this observation leads to a clear and unifying understanding of the odd-number limitation, both in the autonomous and the non-autonomous setting. Korneev *et al.*[28] demonstrate a hard self-oscillation excitation in systems with infinitely many equilibrium points forming a line of equilibria in the phase space. The authors use as an example a nonlinear memristor-based self-oscillator model and show that the bifurcation phenomena are similar to the excitation scenario via the subcritical Andronov–Hopf bifurcation observed in classical self-oscillators with isolated equilibrium points. Stankevich and Volkov[29] investigate the emergence of hyperchaos in a system of three identical ring synthetic genetic oscillators (repressilators) located in different cells and indirectly globally coupled by quorum sensing. They hypothesize that hyperchaos is the result of merging the saddle-focus periodic orbit corresponding to the rotating wave regime with chaos and present considerations in favor of this conclusion. Almazova *et al.*[30] analyze the time series of chaotic dynamical systems with the use of autoencoders, i.e., configurations of neural networks that map identical output to input. They estimate the dimension of the latent space numerically and show that the constructed chaotic autoencoders produce maximal Lyapunov exponents as the original chaotic systems and thus encompass their essential dynamical information. In the paper by Astakhov *et al.*,[31] a model of an autonomous three-mode ring generator based on the van der Pol oscillator is presented where periodic, two-frequency quasiperiodic, three-frequency quasiperiodic, and chaotic self-oscillations are observed. The authors demonstrate that the transitions to chaos occur as a result of a sequence of torus doubling bifurcations. Kruglov with coauthors[32] study numerically and experimentally a transition to chaos via the destruction of a two-dimensional torus. They use the Hénon map and the Toda oscillator under quasiperiodic forcing in numerical simulation and a quasi-periodically excited RL-diode circuit as an experimental setup. They establish that the chaotic attractor in these systems has an additional zero Lyapunov exponent, which strictly follows from the structure of mathematical models. Newman *et al.*[33] propose a new mathematical approach to treat finite-time dynamical systems in terms of a slow–fast formalism in which the slow time only exists in a bounded interval and consider stability in the singular limit. They apply this to one-dimensional phase dynamics and provide stability definitions being analogous to the classical infinite-time definitions. Scully *et al.*[34] focus their study on the qualitative and quantitative characterization of chaotic systems by using a symbolic description. They consider the Lorenz and Rössler models and demonstrate that with an adequately chosen symbolic partition, three measures of complexity work remarkably well for characterizing the degree of chaoticity and precisely detecting stability windows in the parameter space. Khovanov[35] proposes a stochastic approach for generating training time series and characterizing their predictability and applies it for analyzing the Lorenz system and the Anishchenko–Astakhov generator. Besides, this approach is extended to critically assess a reservoir computing model used for chaotic time series prediction. Flynn *et al.*[36] prove analytically that certain symmetries in the training data forbid the square readout matrix to exist. They explore these results numerically by training the reservoir computer to specifically reconstruct the coexistence of the Lorenz attractor and its mirror-attractor. Dmitriev and his coauthors[37] consider the application of dynamical chaos for the illumination of the surrounding space by artificial incoherent sources of microwave radiation. It is shown that with the help of directional antennas connected to specially designed sensitive elements, it is possible to create receivers with spatial resolution for visualizing a part of the surrounding space in artificial radio light. In the paper by Akther *et al.*,[38] a new deterministic model of the memristive devices is introduced which is justified from the Fokker–Planck description to capture the noise-driven dynamics that noise has been known to produce in the diffusive memristor. They find that the deterministic model is capable of replicating the two main forms of spiking observed in the stochastic version, providing with a better understanding of how to control the seemingly random spiking of stochastic diffusive artificial neurons. Shabunin[39] investigates a spatiotemporal chaos regime in a ring of logistic maps with symmetric diffusive couplings when the coupling strength is varied. The authors hypothesizes that the system of diffusive couplings in a network can be considered as a spatial filter with selective properties defined by its wave characteristics and check this suggestion numerically. Feudel and Feudel[40] study numerically the bifurcations of thermal convection in a rotating spherical shell heated from the inner sphere and driven by the buoyancy of a central gravity field. The authors investigate the influence of an additionally imposed differential rotation of the inner sphere with respect to the outer one on the heat transfer and, more generally, on the whole bifurcation structure. In the paper by Zhou *et al.*[41], the analytical periodic solution of the swing in the flexible shaft rotating-lifting system is derived using perturbation analysis. The authors propose a bi-directional impulse control method for suppressing chaos and validate its efficiency and robustness to parameter uncertainties by simulations.

Stochastic processes and noise

Besides pioneering works on dynamical chaos, Vadim made invaluable contributions to the theory of stochastic processes and noise in nonlinear systems. In particular, he was fascinated by the constructive role of noise and noise-induced effects, studying such phenomena as stochastic resonance, coherence resonance, stochastic bifurcations. Moreover, Vadim investigated noisy chaos and drew important and intriguing parallels between the dynamics of deterministic chaotic and noisy periodic nonlinear systems.[22] Vadim's most cited article with over 500 citations is devoted to the phenomenon of stochastic resonance.[6] This direction of studies remains up-to-date and is attracting attention of many researchers.

del Rio and collaborators[42] investigate a period-doubling cascade to chaos in the presence of intrinsic electronic noise. They show that the intrinsic noise strength can significantly alter the cascade besides producing an expected truncated cascade. Ryashko and Bashkirtseva[43] study stochastic transitions, chaotic transients, and riddled basins in coupled periodic logistic maps. In particular, they uncover how random noise deforms deterministic dynamical regimes, causes "order-chaos" transformations, and destroys regimes of in-phase and anti-phase synchronization.

The impact of noise is of particular importance for neural systems and networks. Bashkirtseva and her colleagues[44] study stochastic effects in multirhythmic nonlinear systems using a map-based neuron model proposed by Rulkov. They analyze noise-induced transitions and chaos-order transformations of dynamics caused by random forcing. Rajagopal *et al.*[45] study wave propagation and wave re-entry phenomena in a network of the modified FitzHugh–Nagumo neuron model and reveal noise-induced suppression of spiral waves. Goldobin[46] develops a circular cumulant representation for the recurrent network of quadratic integrate-and-fire neurons in the presence of noise. The two-cumulant neural mass models suggested by Goldobin allow to go beyond the Ott–Antonsen Ansatz and describe the effect of noise on hysteretic transitions between macroscopic regimes of a population with inhibitory coupling. Coupled excitable systems subject to noise are investigated in the papers.[47,48] Zaks and coauthors[47] study the phenomenon of transient bursting, caused by additive noise in a set of two coupled FitzHugh–Nagumo systems. Combining numerical simulations with measurements in an analog electronic circuit, they show that the lifetimes of transient bursting states obey an exponential distribution. The authors relate this distribution to the probability for a stochastic trajectory to temporarily escape from the local basin of attraction of the equilibrium. Klinshov and his collaborators[48] investigate the interplay of global attractive coupling and individual noise in a system of identical active rotators in the excitable regime. By analyzing the nonlocal nonlinear Fokker–Planck equation for the thermodynamic limit, they disclose a complex bifurcation scenario with regions of different dynamical regimes, including collective oscillations and coexistence of states with different levels of activity. Blyuss and his collaborators[49] derive and analyze a novel predator–prey model, providing a framework for studying realistic predator–prey systems with Holling type III functional response in the presence of stochasticity, where an important role is played by non-negligible predator maturation delay. Wang and coauthors[50] propose a new path integration algorithm for the non-autonomous vibro-impact system and investigate stochastic P-bifurcations. In the work of Smirnov,[51] a system of two stochastic Kuramoto oscillators is considered within the framework of dynamical causal effects. Paying special attention to the phenomenon of effective synchronization, Smirnov investigates phase-dynamic quantifiers of directional couplings between oscillatory systems.

Coupled oscillators and networks

A major focus of Vadim's research during the last 10 years were coupled oscillators and dynamical networks of time-continuous oscillators and time-discrete maps. Recent advances in this field are presented by various articles in this Focus Issue. Ashwin *et al.*[52] study dead zones and phase reduction of general coupled oscillators. A dead zone in the interaction between two dynamical systems is a region of their joint phase space where one system is insensitive to the changes in the other. The authors give applications to coupled multiscale oscillators where coupling on only one branch of a relaxation oscillation can lead to the appearance of dead zones. Hong and Martens[53] consider the phase coherence dynamics in a two-frequency and two-coupling model of coupled oscillators, where coupling strengths and natural oscillator frequencies for individual oscillators are bimodally distributed and may assume one of two values (positive or negative). The resulting dynamics splits into phase-locked or drifting subpopulations, and the induced patterns are different for correlated and uncorrelated disorder. Ross *et al.*[54] investigate the dynamics of two coupled Kuramoto phase oscillators with distributed delays, where the delay distribution is considered either inside or outside the coupling function. For both distribution types, various branches of phase-locked solutions are computed, and regions of their stability are identified for uniform, weak and strong gamma distributions. The paper by Hui *et al.*[55] deals with effects of propagation delay in coupled oscillators with both direct (diffusive) and indirect (via the environment) coupling, where delay appears in the indirect coupling path. The authors present theory and simulations for chaotic and FitzHugh–Nagumo oscillators, and an electronic experiment, and show that the presence of propagation delay prevents oscillation death and helps revival of oscillation. Bandyopadhyay and Banerjee[56] discuss the revival of oscillation and symmetry breaking in coupled quantum oscillators, using the formalism of open quantum systems and phase space representation of quantum mechanics. They demonstrate that in the deep quantum regime, in sharp contrast to the classical system, controlling a feedback parameter in the coupling path fails to revive oscillation from a state of suppressed oscillations, rather it results in a transition from quantum amplitude death to oscillation death. Chetverikov *et al.*[57] study the control of electron and electron–hole pair dynamics on nonlinear lattice layers and bilayers by strong solitons. Considering the quantum dynamics of electrons and holes moving in two-dimensional triangular lattices, they show that nonlinear lattice deformations, i.e., solitons, are capable of trapping excess electrons or electron–hole pairs thus forming novel bosonic quasiparticle compounds.

Synchronization

Synchronization of nonlinear dynamical systems has been a central object of research of the Saratov School founded by Vadim Anishchenko for many decades. Moskalenko *et al.*[58] study multistability near the boundary of generalized synchronization in unidirectionally coupled chaotic systems. The efficiency of the method is checked with examples of unidirectionally coupled logistic maps and Rössler systems in the intermittent generalized synchronization regime. Berner *et al.*[59] investigate generalized splay states in networks of phase oscillators. These form a special class of phase-locked states, i.e., complex synchronization patterns. For a general class of phase oscillator networks, stability conditions are expressed in terms of just a few observables such as the order parameter and the trace of the Jacobian. These findings are generalized to phase oscillators with inertia and adaptively coupled phase oscillator models. In the paper by Kasatkin and Nekorkin[60], transient circulant clusters in a two-population network of Kuramoto phase oscillators with different rules of coupling adaptation are considered. As a result of these adaptation rules, splay states may be suppressed and transient circulant clusters may emerge, where each population contains a pair of anti-phase clusters whose size and composition slowly change over time. Solitary states may also appear in one of the populations. Shepelev *et al.*[61] demonstrate that repulsive inter-layer coupling in a two-layer network of 2D lattices of van der Pol oscillators induces anti-phase synchronization. While in single-layer 2D lattices of repulsively or attractively coupled van der Pol oscillators typically labyrinth-like patterns or regular spiral waves, respectively, are found, in the two-layer network anti-phase synchronization occurs for all combinations of intra-layer coupling. Frolov and Hramov[62] study extreme synchronization events in a Kuramoto model, in particular, the interplay between resource constraints and explosive transitions. Excessive synchronization in neural networks reflects undesired pathological activity, including various forms of epilepsy. Considering excitability resource constraints, the authors demonstrate that the interplay between increased excitability and explosive synchronization induced by the hierarchical organization of the network forces the system to generate short-living extreme synchronization events, which are well-known signs of epileptic brain activity. Afifurrahman *et al.*[63] are concerned with collective dynamics of balanced neuronal networks in the presence of finite-width pulses. They investigate two populations of identical excitatory and inhibitory neurons in a random network of phase oscillators coupled through exponential pulses with different widths and find robust collective irregular dynamics, which collapses onto a fully synchronous regime if the inhibitory pulses are sufficiently wider than the excitatory ones. The transition to synchrony is accompanied by hysteresis, i.e., the coexistence of collective irregular and synchronous dynamics. Plotnikov and Fradkov[64] study synchronization of nonlinearly diffusively coupled networks. The system is reduced to the form of mean-field dynamics and a synchronization-error system. The conditions for network synchronization are established based on the stability analysis of the synchronization-error system using the circle criterion, and the results are applied to a network of neural-mass populations with a connected undirected graph. Eser *et al.*[65] investigate the transition to synchronization in a two-layer network of FitzHugh–Nagumo oscillators with time-switching inter-layer links and focus on the role of the number of inter-layer links and the timescale of topological changes. They particularly find that, for a critical switching time, the transition from the network state of low inter-layer synchronization to high inter-layer synchronization occurs abruptly as the number of inter-layer links increases. In the paper by Shena *et al.*,[66] the phenomena of intermittent and complete synchronization between two out of three identical, magnetically coupled Superconducting Quantum Interference Devices (SQUIDs) are investigated numerically. Complete chaos synchronization as well as intermittent chaos synchronization between two SQUIDs of the trimer are identified and characterized using the complete Lyapunov spectrum of the system and appropriate measures.

Rajagopal *et al.*[67] consider the effect of magnetic induction on the synchronizability of neuronal networks. Using the master stability approach, they analyze various neuron models with electromagnetic flux induction for various values of the flux coupling coefficient and find that flux coupling increases the synchronization for all neuron models considered. Rakshit *et al.*[68] study synchronization in ensembles of Hindmarsh–Rose neurons interacting based upon temporal long-range connections through electrical couplings. The authors adopt the connections associated with the direct one-path network to form a small-world network and follow-up with the corresponding long-range network. They also show that the analytically derived stability condition for the complete synchrony state agrees well with the numerical results. Rathore *et al.*[69] show that inhibitory couplings in one layer in multiplex networks of Kuramoto models can lead to explosive synchronization transitions in the rest of the layers feed-forwarded through intermediate layer(s). The authors also demonstrate that the characteristics of the transition emergent in the other layers can be entirely controlled by the multiplexing and intra-layer coupling strengths of the multiplex networks.

Partial synchronization and chimeras

During recent years, the Saratov School of Vadim Anishchenko, in close international collaboration with the group of Eckehard Schöll in Berlin, has established a major hub of research on chimera states, i.e., spatially coexisting domains of synchronized and desynchronized dynamics, and other partial synchronization patterns. This has stimulated a broad range of research activity world-wide. Bera *et al.*[70] focus on spiral wave chimera-like transient dynamics in a three-dimensional grid of diffusive ecological systems composed of prey–predator patches, where the patches are connected in a three-dimensional medium through local diffusion. They explore the transition scenarios and investigate the long time behavior of these states, where synchronized or desynchronized patterns appear through the deformation of the incoherent spiral core. Rajagopal *et al.*[71] study bistable vibrational energy harvesters under periodic and quasiperiodic excitations. The bistable energy harvesters are described by a double potential, and they form a two-dimensional lattice with non-local coupling, where chimera states may emerge. The desired state, however, is complete synchronization for both periodic and quasiperiodic excitations. Jaros *et al.*[72] demonstrate chimera states for networks of phase oscillators with unidirectional coupling. For a small network consisting of only three identical oscillators, tiny chimera islands arise in the parameter space, surrounded by chaotic switching behavior caused by a collision of counterpropagating rotating waves. For larger networks, the islands merge into a single chimera continent. Andrzejak[73] draws an intriguing connection between chimeras and self-similar fractals and shows for two pairs of two complex-valued identical quadratic maps that chimeras are confined by fractal boundaries in the complex plane. The Mandelbrot set is defined by the set of parameter values for which the map remains bounded when initiated at the origin of the complex plane. The boundaries between bounded and divergent solutions are fractals showing a rich variety of esthetic patterns, and the set of bounded solutions is divided into countless subsets throughout all length scales in the complex plane. Shepelev *et al.*[74] explore spatiotemporal patterns in a 2D lattice of van der Pol oscillators with linear repulsive and nonlinear attractive coupling, modeling an electronic circuit. This interaction leads to the emergence of standing waves with periodic dynamics in time and the absence of any propagating wave processes. A lot of different spatiotemporal patterns occur when the coupling parameters are varied, including regular and complex cluster structures, such as chimera states. Tsigkri-DeSmedt *et al.*[75] study synchronization patterns in a network of leaky integrate-and-fire oscillators with nonlocal connectivity under probabilistic small-world rewiring. They demonstrate that the random links lead to the emergence of chimera-like states where the coherent regions are interrupted by short-lived solitary states. Counterintuitively, random links enhance the appearance of chimera-like states for parameter values that otherwise support synchronization. The paper of Sawicki *et al.*[76] deals with synchronization scenarios in three-layer networks of FitzHugh–Nagumo oscillators where the middle (relay) layer is a single node, i.e., a hub. Various relay synchronization scenarios are found in dependence on the inter-layer coupling strength and inter-layer time delay, including double chimeras, i.e., chimera states in the remote layers whose coherent cores are synchronized with each other and salt-and-pepper states. At very low intra-layer coupling strength, chimeras may be induced by the hub. Barabash *et al.*[77] investigate partial synchronization in the second-order Kuramoto model of heterogeneous phase oscillators with inertia. They analyze the stability of partial synchronization patterns and derive explicit bounds that relate the maximum natural frequency mismatch, inertia, and the network size that can support stable partial synchronization. In particular, they predict threshold-like stability loss of partial synchronization caused by increasing inertia.

Applications: Biology, medicine, epidemiology, and ecology

Along with the fundamental studies of dynamical systems and networks, Vadim and his colleagues also focused their research on applications of methods of nonlinear dynamics and statistical physics in various scientific fields, in particular, in biology and medicine. Nowadays, this research direction is very thriving and important in science. Sysoev and Bezruchko[78] propose a new approach to the reconstruction of a nonlinear second-order oscillator model from its experimental series. They show that this new technique can work for sufficiently high noise levels for different types of autonomous van der Pol-like systems and for ensembles of such systems, providing a new approach to the realization of the Granger-causality idea. Ponomarenko *et al.*[79] explores the correlation degree between the respiration processes and autonomic control of the heart rate for people of different age and reveals that the correlation monotonically decreases with increasing age. Pavlov and his collaborators[80] show that the multiresolution wavelet analysis (MWA) combined with the detrended fluctuation analysis (DFA) can be applied to characterize different physiological conditions by analyzing the electrical brain activity in mice. Machine learning techniques are successfully used by Fernanders and his co-workers[81] to reconstruct the wavelength dependence of the absorption coefficient of human normal and pathological colorectal mucosa tissues. Lainscsek with her coauthors[82] apply the dynamical ergodicity measure together with cross-dynamical delay differential analysis to intracranial electroencephalographic data from patients with epilepsy and find distinct dynamical states that were highly predictive of epileptic seizures. Runnova with her collaborators[83] propose a modification of joint recurrence quantification analysis for identifying individual characteristics applied to human electroencephalography (EEG) using short time series. The effective use of the wavelet–skeleton approach is presented in the paper by Sergeev *et al.*[84] to find characteristic patterns in the electroencephalograms of healthy adult patients and patients with cognitive dysfunctions. Semenova and Tuchin[85] propose an improved 3D model of the epidermal layer of the skin and study the proliferation of cancer cells under an osmotic pressure. Bahramian with his coauthors[86] explore the collective behavior in a two-layer neuronal network with time-varying chemical connections, where one layer is composed of a Petri net and the second one is a ring of coupled Hindmarsh–Rose neurons. The impact of mixed coupling on synchronization in multiplex models of neuron–glial systems is investigated in the paper by Makovkin *et al.*[87] Pattanayak with co-workers[88] revisit a tri-trophic resource–consumer–predator food chain model and show bistability and transition to monostability via a border collision that leads to a state of predator extinction. Kundu *et al.*[89] scrutinizes the robustness of a multilayer ecological network sustaining gradually over harvested patches and reports how asymmetries in the interlayer and intralayer dispersal strengths as well as the network topologies influence the global persistence of species in the network. Galler and coauthors[90] develop a deterministic compartmental model for the spreading dynamics of bovine viral diarrhea within a herd and derive the basic reproduction number. They systematically investigate the interplay between noise and the intrinsic time scales of an extended susceptible–infected–recovered (SIR) model by considering a stochastic transmission coefficient. An efficient method is proposed by Li and co-workers[91] to identify the decentralized influential spreaders on networks by edge percolation under the Susceptible–Infected–Recovered (SIR) model. In the paper by Abdelouahab *et al.*,[92] a novel epidemiological model describing the evolution of tuberculosis in a human population is proposed, and stability and bifurcation of the solutions of this model are investigated. Bertacchini with her collaborators[93] focus their study on the probability of distribution of the SARS-CoV-2 infection rate and using a combination of methods typical of complex systems, find manifestations of the virus behavior such as cluster formation and bifurcations, and detect the virus phase transitions, typical of adaptive biological systems.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts of interest to disclose.

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