Subject	Description
Introduction to astrophysics	The topics covered by the course: Astronomical observations: contemporary astronomical instruments, observations at different wavelengths of radiation, physical processes related with emissions of radiation and particles Sun and other stars: fundamentals of stellar spectroscopy, basic knowledge of stellar structure and evolution, stellar life-cycles, synthesis and distribution of chemical elements, details of the structure of the Sun The Solar system and extrasolar planetary systems: contemporary knowledge of the Solar system, methods of searching and investigating extrasolar planets, orbital architectures, planet formation theories and astrophysical processes in circumstellar discs and environment, Earth-like planets Galaxies and the Universe: structure of the Universe at large scales, from galaxies through clusters and superclusters up to microwave background radiation and big-bang, theories of the evolution of the Universe Our place in the Universe: Earth and celestial sphere, importance of astronomy for science and philosophy, life in the Universe
Astrohydrodynamics	The lecture will include the following topics: Part I. Astrophysical applications of fluid dynamics. - Euler's equations of fluid dynamics, - selfgravitating fluids - Poisson's equation - sound waves, shock waves, supernova explosions, - fluid instabilities: convective, Raileigh-Taylor, Kelvin-Helmholtz, gravitational and thermal instabilities, - Bernouli's equation, spherical accretion and winds, - viscous flows, Navier-Stokes equation, Reynolds number, - vorticity equation, Kelvin's theorem of vorticity conservation, - turbulence and its astrophysical significance, - hydrodynamics of accretion disks, - hydrodynamical processes in star formation activity. Part II. Numerical methods for fluid dynamics. - elements of the theory of partial differential equations, method of characteristics, Riemann problem, Rankine-Hugoniot relations, linear hyperbolic systems - conservative form of hydrodynamics equations, shock waves, rarefaction waves and the solution of Riemann problem in fluid dynamics. - basic numerical methods for partial differential equations, von Neuman stability analysis of numerical schemes, - Riemann solvers and Godunov methods for fluid dynamics.
Electrodynamics and field theory	1. Quantities describing electromagnetic field and its sources. 1.1. Vector description. 1.2. Tensor description. 1.3. Differential forms. 2. Maxwell field equations. 2.1. Full form of the equations. 2.2. Material equations. 2.3. Differential form of field equations. 2.4. Field discontinuities. 3. Maxwell's methods of solving equations. 3.1. Behavioural laws.

	3.2. The problem of unambiguity. 3.3. Potential Theory. 4. Relativistic formulation of electrodynamics. 4.1. Einstein's principle of relativity. 4.2. Minkowski's spacetime. 4.3. Maxwell's equations in covariant form. 4.4. Lorentz transformation for electromagnetic field. 4.5. Variational principle. 5. Theory of radiation. 5.1. Electromagnetic field in media. 5.2. Radiation. The Lienard-Wührtt field. 5.3. Stationary and static fields. 5.4. Hamiltonian form of Maxwell's equations.
Physics Laboratory	Physics Laboratory is a laboratory where students make 3 advanced experiments selected from various fields of Physics. Each experiment has a separate list of literaturę references, provided by a supervisor. Each experiment requires from student to: prepare theoretical background description, prepare experimental setup and make an experiment, analyze results and prepare a report in a form similar to scientific publication as well as an oral presentation. Laser anemometry (Doppler effect), Zeeman effect in atoms, Determination of the ratio e/kB and the energy gap in semiconductors, Electron paramagnetic resonance (EPR), Compton effect, Franck-Hertz experiment.
Theoretical astrophysics laboratory 1	The student carries out the following topics in the form of tasks consisting of numerical calculations and report development. The following general topics are: - Solving ordinary differential equation systems using self-developed programs and software available in the public domain. - Solving partial differential equation systems using self-developed programs and software available in the public domain.
Theoretical astrophysics laboratory 2	The student carries out numerical calculations and writes reports. The proposed itopics are listed below, although alternatives are not excluded: - write from scratch a code that computes a model of a star using the polytropic equation of state - discuss late stages of stellar evolution using a publicly available stellar evolution code - analyze circumstellar material using a publicly available photoionization code
Theoretical astrophysics laboratory 3	The computational projects will be realized with the aid of the magnetohydrodynamical code PIERNIK. Students perform and analyze a series of numerical experiments including: supernova explosions, accretion disks, astrophysical jets and selected hydrodynamical instabilities (gravitational instability, thermal instability, Kelvin-Helmholtz instability) of astrophysical relevance.
Quantum optics 1	Lecture (30 hrs) 1. **General information about the subject – a review** (basic phenomena and processes, photons). • Orders of magnitude and units of physical quantities characterizing atoms, optical fields and interaction between them. Estimating the number of photons in a laser beam of given power and frequency. • Examples of quantum behaviour: photon detection after its passing through a Mach-Zehnder interferometer, nondemolition measurement.

- Photon statistics: counting photons, statistics of the number of photons in a coherent beam, Poisson distribution and "Poissonian, super-Poissonian and sub-Poissonian light".

2. **Quantum theory of radiation**
   - Maxwell's equations (ME) for electric and magnetic fields, electromagnetic potentials, gauge
   - ME in Fourier space (r,t) -> (k_n, t), longitudinal and transverse components of electric and magnetic fields ("electrostatics" and "radiation")
   - Polarization and radiation modes
   - Dynamics of transverse fields, expression through normal variables
   - Vector and scalar electromagnetic potentials in Fourier space, longitudinal and transverse components of the vector potential, gauge, evolution equations
   - Coulomb gauge
   - Energy of radiation field, expression through longitudinal and transverse components of the electric field and vector potential in the Fourier space, analogy to a set of uncoupled harmonic oscillators
   - Quantization rules, creation and ahhinilation operators, Hamiltonian and momentum operator, number operator, eigenstates and eigenvalues of the Hamiltonian and momentum operator, radiation modes, photons.
3. **Quantum states of radiation**
   - Vacuum state and its basic properties.
   - Single-mode states, Fock (number) and coherent (quasiclassical, Glauber) states, their basic properties and interpretation. Multimode states.
   - Single- and multimode single-photon states.
   - Beam splitter and its classical and quantum model. Input and output states. Single-photon experiments, Hong – Ou – Mandel (HOM) effect.
   - Quadrature operators for radiation fields (definition, commutation rules, Heisenberg relations).
   - Squeezed states of radiation (definitnion, properties, generation scheme in a parametric process).
4. **Interaction of electromagnetic fields with atomic systems**
   - Time-dependent perturbation theory, transition amplitude and probability, transitions among discrete states and from discrete to continuous spectrum.
   - Interaction of atomic systems with classical electromagnetic fields (interaction Hamiltonian, electric – dipole and magnetic – dipole interaction, absorption and stimulated emission).
   - "Exactly solvable" models:Rabi model, Weisskopf-Wigner model..
   - Remarks on more complicated cases: more levels, more fields.

Exercises (30 hrs)

5. **Harmonic oscillator.** A review of the subject (a, a^+ and $n = a^+a$ operators, their basic properties and algebra, eigenstates and eigenvalues of harmonic oscillator Hamiltonian). Coherent states of harmonic oscillator and their properties: definition, decomposition in the Fock basis, Poissonian statistics of excitation numbers, graphical representation, temporal evolution, Heisenberg relations, quasiorthogonality and completeness, displacement operator for generation operator of coherent states from vacuum state.
6. **A few operator relations.** Functions of operators, commutation relations involving functions of operators, derivative of an operator, Glauber and Baker-Hausdorff formulas, displacement and squeezing operators.
7. **Spin ½ dynamics in a magnetic field as a prototype two-level system.** Magnetic resonance, classical and quantum description, Bloch, Schroedinger and von Neumann equations, evolution of expectation value of magnetization.
8. **Optical Bloch equations.**

Quantum optics 2	Lecture: 1) Introduction: Single photon physics. 2) Quantum information encoding in a single photon polarization state. 3) Quantum communication protocols exploiting polarization states. Practical implementation: quantum key distribution. 4) Single photon spatial mode and the methods of quantum states encoding. 5) Multilevel quantum states -- generation and detection. Majorana representation. 6) Practical implementations of quantum information processing based on spatial mode encoding. 7) Parametric down conversion process -- quantum description and experimental methods. 8) Single photon detection 9) Phase space and Wigner function Tutorials – calculations on selected problems, such as: 1) simple examples on "quantum world" sizes, 2) Bell states, Pauli matrices, transformations on Bloch sphere, 3) coding information in single-photons' polarization states, 4) quantum key distribution schemes, practical implementations, 5) Helmholtz equation, gaussian beam, propagation in fibers, 6) Jones matrices, optical networks, 7) single photon spatial mode encoding, 8) higher-dimensional entangled states generation methods, 9) nonlinear processes, parametric down conversion, phase matching conditions, 10) "cat" states and Wigner function.
Classical and celestial mechanics	The topics covered by the course include: 1) The fundamental concepts of Newtonian mechanics and the gravitational potential theory, gravitational potential outside uniform spheroid and due to uniform disk (ring), motion in rotating reference frames, elements of the rigid body dynamics, basic concepts in the Lagrangian mechanics. 2) The N-body problem in the classical framework, the first integrals of the equations of motion, the virial theorem, the dark matter concept, planetary N-body problemn and the equations of motion in relative coordinates, Jacobi and Poincare variables. 3) The Taylor integration scheme for the ordinary differential equations (ODE) as the canonical method of solving the equations of motion in classical and celestial mechanics, perturbed two body problem (e.g., due to relativistic and non-point mass interactions). 4) The theory of motion in central force fields, qualitative analysis of systems with one-degree of freedom, the two body problem, elements of conic curves theory, Keplerian laws, classification and parametrisation of Keplerian orbits (geometric and dynamical elements), simple models of motion in galactic gravitational environments (such as the Henon-Heiles model, the logarithmic, and the Yukawa potentials). 5) Orbits of the planets in the Solar System, the figure of the Earth, tidal interactions among the Earth, Moon, and Sun, the secular evolution and the long-term stability of the Solar system. 6) The two-body orbits kinematic fitting (the Neutsch method) and the merit function for observations made with various techniques (astrometry, eclipse timing, radial velocities), determining the mass function and orbits of binary stars and extrasolar planetary systems. 7) The circular and elliptic restricted three body problems as the fundamental models for astrodynamics (motion of man-made objects in space) and a non-trivial generalisation of the Kepler problem, libration points, elements of the stability and deterministic chaos theory.
Biophysics	1. What is biophysics? 2. How big are molecules, what are special features of biological matter? 3. Energy in living systems. Thermodynamics and metabolism. Enzymes. 4. Flow of genetic information. DNA. Central Dogma of Molecular Biology. 5. Proteins, membranes and their structures. 6. Free energy in biology. Chemical equillibrium.

	7. Propagation of signals along neurons. Ion channels. 8. Hormones, homeostasis, regulation, biocatalysis and drugs. 9. Oxygen pathways in human body. 10. Spectroscopies in biophysical research: Lambert-Bear Law, Jablonski diagram, absorption vs fluorescent spectroscopy, IR and Raman, NMR and EPR. 11. AFM, optical tweezers and single molecule nanomechanics. 12. Computer modeling of biomolecules I (fundamentals) 13. Computer modeling of biomolecules II (free energy, advanced methods) Exercises: A. Thermodynamics – basic concepts. Classical problems solutions. B. Protein structure (pdb, vmd, visualization software) – practical tutorial. C. Practical MD simulations: case studies, computer data analysis. D. Demonstration of AFM biophysical measurements (in the Lab).
Stellar physics	The topics covered by the course: - fundamentals of stellar spectroscopy, observations and analysis - the physical laws and equations of stellar structure, problems related with numerical solutions, examples of computer codes, examples of results - formation of stars, main evolutionary stages, different stellar remnants - nucleosynthesis in stars, mass-loss from stars, explosions, chemical evolution of the Universe - stars exchanging mass in binary systems - variable stars, causes of variability, importance for astrophysics - details of the structure of our Sun - contemporary problems of stellar studies, main unsolved issues
Galaxies: formation and evolution	Program of the lecture: 1. Present-day galaxies: photometric components, galaxy classification, morphological structures, mass distribution, gravitational potential. 2. Star forming galaxies, early type galaxies. 3. Stars, dark matter, interstellar gas, magnetic fields and cosmic rays. 4. Stellar orbits. 5. Statistical description of stellar and dark matter particles – Jeans equations. 6. Dynamics of the interstellar medium, star formation. 7. Gravitational instability and spiral structure. 8. Formation and evolution of Dark Matter Halos 9. Theory of Galaxy formation 10. Galaxy evolution.
Astrochemistry and astrobiology	Astrochemistry (15h) 1) Historical roots of astrochemistry. 2) Production of chemical elements in stars. 3) The Big Bang nucleosynthesis - first atoms. 4) Molecular complexity - "bottom-up" and "top-down" approaches. Organic mole$ 5) Processes on dust grains. Astrobiology (15h) - formation and evolution of planetary systems

	- physicochemical conditions on the planets and moons of the Solar System - emergence and evolution of life - rocky exoplanets and exomoons in circumstellar habitable zones - the Drake equation, methods of searching for extraterrestrial intelligence
Optical astrophysics laboratory	- telescope types, telescope mount types, - CCD (Charge-Coupled Devices): operation, types, coating, analog-to-digital converters - characterization of CCD: quantum efficiency, readout noise, dark current, CCD pixel size, pixel binning, full well capacity and windowing, overscan and bias, CCD gain and dynamic range, - CCD imaging: image or plate scale, flat fielding, calculation if read noise and gain, Signal-to-Noise ratio, basic CCD data reduction, CCD imaging, - Photometry and Astrometry: stellar photometry from digital images, two-dimensional profile fitting, aperture photometry, absolute versus differential photometry, astrometry, pixel sampling. - fits format, AstroImageJ software - performing optical observations with the use of one of three optical telescopes at the Institute of Astronomy
Radioastronomy laboratory	- history of radio astronomy, - low noise radio receivers and their parameters, signal processing, - observations and data reduction of observations using the 32 m radio telescope, - proposing, scheduling and data reduction of selected interferometer data.
Statistical physics	Lectures 1. (4 h) Stochastic processes, Markov chains and Langevin equation. 2. (4 h) Entropy vs. information. Probability distribution of maximal entropy. 3. (4 h) Description of statistical systems. Evolution and equilibrium states. Liouville equation. Thermodynamic formalisms. 4. (4 h) Thermodynamics of gas systems: a) perfect gas b) nonideal gases (virial expansion, mean field theory) 5. (4 h) Thermodynamics of magnetic systems: a) paramagnetics and Curie law b) Ising model of nearest neighbours interaction c) phase transition in a Curie-Weis-Kac model 6. (2 h) Grand canonical ensemble and theory of phase transitions 7. (2 h) Quantum Statistical systems: a) formalism of statistical quantum mechanics, b) open systems and semigroup dynamics b) multilevel system: Bose-Einstein and Fermi-Dirac statistics 8. (6 h) Thermodynamics of quantum gases a) electron gas in metal, Fermi energy b) relativistic electron gas, stability of white dwarfs

	c) Bose-Einstein condensation, nonlinear Gross-Pitayevski equation d) photonic gas and thermal radiation e) phonons and crystals Exercises: 1. (2 h) Random variables and their properties. 2. (2 h) Stochastic matrices and Markov evolution. 3. (2 h) Combinatorics of quantum statistics. 4. (2 h) Evolution of a system of N harmonic oscillators. 5. (2 h) Gibbs distribution. Velocity distribution. Doppler broadening of line shapes. 6. (2 h) Virial expansions for thermodynamic parameters. 7. (2 h) Joule-Thompson process 8. (2 h) Correlation function in Ising model. 9. (2 h) Classical and quantum entropy and their properties. Klein inequality. 10. (4 h) Entanglement and quantum correlations. 11. (4 h) Thermal radiation. Planck distribution. Wien law. Stefan-Boltzmann law.
From complex chemistry to new physics	1) Introduction: Operators, atomic units, molecular Hamiltonian, and Born-Oppenheimer approximation. 2) General introduction to the many-electron theory • The Hartree-Fock (HF) method (self-consistent field approach, canonical orbitals, Slater-Condon rules, and Koopman's theorem) • Density Functional Theory (DFT) (the Hohenberg–Kohn theorems, v- and N-representability, and Kohn–Sham Density Functional Theory (non-interacting kinetic energy and the Kohn–Sham equations) • Gaussian basis sets (Gaussian and Slater-type orbitals, spherical and cartesian Gaussians, extrapolation techniques), molecular orbitals, electron density-their interpretation and visualization • A brief introduction to the post-Hartree-Fock methods: Moller-Plesset perturbation theory, Configuration Interaction, and Coupled-Cluster Ansatz • Time-dependent HF and DFT methods • Atomic and molecular properties (dipole moments, electronic spectra, transition dipole moments, and dipole polarizabilities) • Technical aspects of electronic structure calculations: convergence difficulties, point group symmetries, convergence acceleration (damping, level shifting, and the direct inverse iterative subspace (DIIS) technique), scans of potential energy surfaces and analysis of dissociation energy limits • Example calculations: singlet-triplet excitations, local, charge-transfer, and Rydberg excited states 3) Nuclear motion • Potential energy curves of diatomic molecules • Bound state energies: discrete variable representation (DVR) and Numerov methods • Rotational spectroscopy • Vibrational transitions in diatomic molecules • Polyatomic molecules: vibrational SCF • Cold collisions and near-threshold bound states 4) Case studies • Chemical reaction energies, reactivity, and formation of simple amino acids • Spectroscopy of simple molecules: NH and SrF • Hyperfine structure, isotopic effects in spectroscopy, and standard model violation effects

Advanced mathematical methods	I. Tensor calculus 1) tensor algebra, 2) tensor analysis: covariant derivative, parallel transport, 3) Lie derivative, Killing vectors, differential forms II. Complex analysis 1) Cauchy-Riemann conditions, 2) Cauchy theorem, 3) residua and its applications, 4) contour integration, 5) Green functions. III. Elements of group theory 1) introduction to discrete and continuous group, 2) basics of representation theory, Schur lemmae, 3) elements of Lie group and Lie algebra theory.
Large-scale Universe	Large-scale astrophysical individual and statistically defined objects: galaxies, clusters of galaxies, voids, cosmic web, baryon acoustic oscillations, cosmic microwave background fluctuations; Physical cosmology: hot big bang model (FLRW model, Hubble-Lemaitre expansion, cosmic microwave background, primordial nucleosynthesis), Friedmann equations, Einstein static solution, Einstein-de Sitter model, scale-factor--time--redshift relations, comoving arc length, angular diameter distance, luminosity distance, cosmological paradoxes, LambdaCDM model, general-relativistic models and their observational foundations, galaxy formation
General relativity	List of topics: 1. Recollection of tensor analysis 2. Symmetric spaces 3. Conservation principles 4. Relativity principles 5. Einstein's general relativity equations 6. Schwarzschild's solution of Einstein's equations for spherically symmetric case in vacuum 7. Observable effects of general relativity theory 8. Friedmann's solutions – cosmological models 9. Gravitational waves
Quantum information	1. Basic theory of convex sets 2. Basic theory of classical channels and measurements 3. Quatnum mechanics as a on-commutative generalisation of probility calculus. 4. Postulates of quantum mechanics in comparison to classical theory 4. Basics of theory of spin 5. Qubit states and dynamics in Bloch ball 6. Uncertainty principle in Bloch ball 7. Quantum channels and POVMs 8. Composite system and dilation theorems 9. Distinguishability of quantum states 10. Processing states of photon polarisation 11. No-cloning theorem and BB84 protocol 10. CHSH inequality, non-kolmogorovness of quantum theory and no-signaling condition

	11. Quantum teleportation 12. Measures and criteria of entanglement 13. Quantum Shor algorithm 14. NMR realisation of quantum computer 15. Quantum tomography, estimation theory, MUBs and POVMs 16. Dynamics of open quantum systems, decoherence, quantum error-correcting codes
High-energy astrophysics	1) Radiative transfer - including definitions of: emission and absorption coefficients, specific intensity, optical depth, flux density etc. We will discuss also different solutions of the radiation transfer equation. 2) Thermal radiation and the physical laws that describe this process. 3) Radiation of moving charges – Larmor's formula and characteristic of this emission. 4) Transformation of the radiation (frequency, energy, angles etc.) from the particle comovig frame to the observer's frame. 5) Different types of the bremsstrahlung process (thermal, relativistic). 6) From the cyclotron to the synchrotron emission – an useful approximations. 7) Synchrotron emission of a single particle. 8) Synchrotron emission produced by different types of particle energy distributions. 9) Synchrotron self-absorption process. 8) Thompson scattering. 9) Compton scattering. 10) Inverse Compton scattering. 11) Synchrotron self-Compton emission scenario. 12) External inverse-Compton emission scenario. 13) Particle acceleration – first and second order Fermi processes. 14) Evolution of particle energy spectrum.
Atomic and molecular physics	1. Atomistic concept of matter construction - historical outline 2. The Schrodinger equation for atoms and molecules 3. Separation of the motion of nuclei and electrons in molecules 4. The Schroedinger equation with the electron Hamiltonian for atomic and molecular systems 5. Methods of approximate solution of the Schroedinger equation: variational method and perturbation expansion 6. Independent-electron approximation - construction of a many-electron wave function in the form of a Slater determinant - application of the variation method in the independent-electron model - Hartree-Fock equation 7. Effects of electron correlation - going beyond the Hartree-Fock approximation - formalism of the second quantization, many-body and diagrammatic techniques - many-body perturbation theory (Moller-Plesset perturbation theory) - configuration interaction method - coupled-cluster method - advantages and disadvantages of different approximate methods for electron correlation description (variationality and size extensivity) 8. Nondynamic electronon correlation - introduction to approximate multi-reference methods of solving the Schroedinger equation for atomic and molecular systems
Condensed matter physics	1. Basic phenomena and physical properties of semiconductor materials. Solid state band model. Doped semiconductors. 2. Description of the semiconductor in the state of thermodynamic equilibrium, concentration of electric charge carriers, Boltzmann relationship, balance of carrier concentration, electric neutrality equation. 3. Transport of carriers in a semiconductor. Charge carriers in the electric field. Conductivity.

	4. Hall effect. 5. Non-equilibrium phenomena in a semiconductor. Generation, recombination and trapping processes. 6. Diffusion. 7. Principle of current flow. Equations of transport. 8. p-n connector. 9. Diodes. Photodiodes. Solar cells. Resistor. Transistor. Thermistor. 10. Metal-semiconductor contacts. Surface conditions. MIS and MOS structures. 11. Experimental methods of semiconductor characterization.
Optoelectronics laboratory	Optoelectronics laboratory is focused on properties, applications and characterization of various optical instruments/devices that source, detect and control light. The course participants learn physical processes responsible for generation and detection of light by semiconducting devices, especially modern light sources (LEDs, lasers) and photon detectors. Their properties are characterized experimentally by spectrally - and time-resolved techniques. A lot of emphasis is put on techniques of modulation and transmission of light by nonlinear crystals and glass fibers. Each topic is widely discussed and experimentally illustrated by personally arranged setup. The list of task: Photometry – spectroscopic measurements Photometry – colorimetry Optoelectronic detectors Modulation of light Semiconductor laser Second-harmonic generation Matrix methods in optics. Gaussian beams. Optical fibers