STUDY PROGRAM

1. Study plan

Year of study: I
1st Semester

Course	O/F[1]	Course form[2]				No. of class hours	Assessment method[3]	ECTS credits
		W	K	L	S			
Astrophysics I	O	30	15			45	E/Z	5
Computational Methods I	O	30		30		60	Z	6
Data Analysis in Physics and Astronomy	O	15		30		45	Z	3
Modern Trends in Astrophysics I[4] or Selected Topics in Astrophysics I[4]	O/F[4]	10				10	Z	1
Astronomy-oriented study track[5]								
Introduction to Solar Physics	O/F[6]	15				15	Z	2
Laboratory of Theoretical Astrophysics or Laboratory of Magnetic Activity of the Sun and Stars	O/F[6]			30		30	Z	3
Physics-oriented study track[5]								
Advanced Statistical Physics	O/F[6]	30	30			60	E/Z	6
Elective Courses I[7]	F	course dependent						3[8]
Laboratory of CCD Photometry	F			45		45	Z	4
Advanced Topics of Stellar Structure and Evolution	F	30	30			60	E/Z	5
Quantum Electrodynamics	F	30	30			60	E/Z	6
Monografic Lecture[9]	F	30				30	E	3
Specialized Lecture[9]	F	30	30			60	E/Z	6
Ethics in Research	O		24			24	Z	3
English (B2+ level)	O		60			60	E	4
Initial training on OHS and fire protection	O	e-learning				4	Z	–
Polish for Foreigners (A1 level)[10]	O[10]		30			30	–	–

[1] of the course: O – mandatory, F – elective.

[2] Course form: W – lecture, K – class/project, L – laboratory/practice, S – seminar.

[3] Assessment method: E – exam, Z – passing with grade.

[4] Modern Trends in Astrophysics I/II/III/IV and Selected Topics in Astrophysics I/II/III/IV consist of short lectures of a monographic type, mainly delivered by visiting Professors. Students can attend and pass them in every semester. During the studies, it is required to complete a total of four such courses.

[5] Students choose between two alternative study tracks: astronomy- or physics-oriented. Courses within the chosen track become mandatory for them.

[6] Courses mandatory within one study track become optional for students of the alternative study track.

[7] Elective courses offered in the 1st semester can be taken in the 3rd semester and vice versa, subject to course prerequisites.

[8] Student completes one or more optional courses for at least 3 ECTS credits in total. Excess ECTS credits gathered in this semester count towards the number of ECTS points required to be gained within elective courses in the next semester.

[9] WThe list of Monographic/Specialized Lectures will be updated every year to reflect the current fields of research going on at the Faculty. Monographic/Specialized Lectures might be offered with fewer class hours than indicated and correspondingly fewer assigned ECTS credits. Classes associated with Specialized Lecture may take a different form, adequate to the course topic.

[10] Polish course is obligatory for foreigners only, subject to separate University regulations. 5 ECTS credits gained for this course do not count towards the total of 120 ECTS credits required to complete the curriculum and get the degree. Total number of class hours in the semester does not include the Polish course.

Total number of ECTS credits in the 1st semester: 30 within the astronomy-oriented study track, 31 within the physics-oriented study track

Total number of class hours in the 1st semester: 325 within the astronomy-oriented study track, 340 within the physics-oriented study track

Year of study: I
2nd Semester

Course	O/F[1]	Course form[2]				No. of class hours	Assessment method[3]	ECTS credits
		W	K	L	S			
Astrophysics II	O	30	15			45	E/Z	5
Computational Methods II	O	30		30		60	Z	6
Highlights of Modern Physics and Astrophysi*cs*	O				30	30	Z	3
Modern Trends in Astrophysics II[4] or Selected Topics in Astrophysics II[4]	O/F[4]	10				10	Z	1
Practical Astrophysics at Observatory[5]	O			15		15	Z	2
Astronomy-oriented study track[6]								
Variable Stars	O/F[7]	30				30	E	3
Advanced Solar Physics and Space Weather	O/F[7]	30	15			45	E/Z	4
Physics-oriented study track[6]								
General Relativity and Gravitation	O/F[7]	30	30			60	E/Z	6
Elective Courses II[8]	F	course dependent						7[9]
Laboratory of Stellar Spectroscopy	F			45		45	Z	4
Galactic Astronomy	F	30	30			60	E/Z	5
Theoretical and Observational Cosmology	F	30	30			60	E/Z	6
Non-Equilibrium Statistical Physics	F	30				30	E	3
Machine Learning	F	30		30		60	Z	6
Monografic Lecture[10]	F	30				30	E	3
Specialized Lecture[10]	F	30	30			60	E/Z	6
Polish for Foreigners (A1 level)[11]	O[11]		30			30	E	5

[1] Character of the course: O – mandatory, F – elective.

[2] Course form: W – lecture, K – class/project, L – laboratory/practice, S – seminar.

[3] Assessment method: E – exam, Z – passing with grade.

[4] Modern Trends in Astrophysics I/II/III/IV and Selected Topics in Astrophysics I/II/III/IV consist of short lectures of a monographic type, mainly delivered by visiting Professors. Students can attend and pass them in every semester. During the studies, it is required to complete a total of four such courses.

[5] Practical Astrophysics at Observatory consists of a one-week practice held in the Astronomical Observatory in Białków. Exact schedule during the semester will depend on weather conditions.

[6] Students choose between two alternative study tracks: astronomy- or physics-oriented. Courses within the chosen track become mandatory for them.

[7] Courses mandatory within one study track become optional for students of the alternative study track.

[8] Elective courses offered in the 2nd semester can be taken in the 4th semester and vice versa, subject to course prerequisites.

[9] Student completes optional courses for at least 7 ECTS credits in total, taking into account excess ECTS credits from the past semester. Excess ECTS credits gathered in this semester count towards the number of ECTS points required to be gained within elective courses in the next semester.

[10] The list of Monographic/Specialized Lectures will be updated every year to reflect the current fields of research going on at the Faculty. Monographic/Specialized Lectures might be offered with fewer class hours than indicated and correspondingly fewer assigned ECTS credits. Classes associated with Specialized Lecture may take a different form, adequate to the course topic.

[11] Polish course is obligatory for foreigners only, subject to separate University regulations. 5 ECTS credits gained for this course do not count for the total of 120 ECTS credits required to complete the curriculum and get the degree. The total number of class hours in the semester does not include the Polish for Foreigners course.

Total number of ECTS credits in the 2nd semester: 31 within the astronomy-oriented study track, 30 within the physics-oriented study track

Total number of class hours in the 2nd semester: 308 within the astronomy-oriented study track, 293 within the physics-oriented study track

Year of study: II
3rd Semester

Course	O/F[1]	Course form[2]				No. of class hours	Assessment method[3]	ECTS credits
		W	K	L	S			
Modern Trends in Astrophysics III[4] or Selected Topics in Astrophysics III[4]	O/F[4]	10				10	Z	1
Astronomy-oriented study track[5]								
Stellar Pulsations	O/F[6]	30	30			60	E/Z	5
Physics-oriented study track[5]								
Astroparticle Physics	O/F[6]	30	30			60	E/Z	5
Elective Courses III[7]	F	course dependent						13[8]
Laboratory of Stellar Pusations	F			15		15	Z	2
Planetary Systems and Astrobiology	F	30				30	E	3
Advanced Topics of Stellar Atmospheres	F	30	30			60	E/Z	5
Compact Stars	F	15	15			30	Z	3
Relativistic Astrophysics	F	30	30			60	E/Z	6
Advanced General Relativity	F	30	30			60	E/Z	6
Gravitational Waves	F	15		15		30	Z	3
Monografic Lecture[9]	F	30				30	E	3
Specialized Lecture[9]	F	30	30			60	E/Z	6
Master's Seminar I	O				30	30	Z	2
Master's Degree Project I[10]	O/F[10]					ND[10]	Z	8

[1] Character of the course: O – mandatory, F – elective.

[2] Course form: W – lecture, K – class/project, L – laboratory/practice, S – seminar.

[3] Assessment method: E – exam, Z – passing with grade.

[4] Modern Trends in Astrophysics I/II/III/IV and Selected Topics in Astrophysics I/II/III/IV consist of short lectures of a monographic type, mainly delivered by visiting Professors. Students can attend and pass them in every semester. During the studies, it is required to complete a total of four such courses.

[5] Students choose between two alternative study tracks: astronomy- or physics-oriented. Courses within the chosen track become mandatory for them.

[6] Courses mandatory within one study track become optional for students of the alternative study track.

[7] Elective courses offered in the 3rd semester can be taken in the 1st semester and vice versa, subject to course prerequisites.

[8] Student completes optional courses for at least 13 ECTS credits in total, taking into account excess ECTS credits from the past semester. Excess ECTS credits gathered in this semester count towards the number of ECTS points required to be gained within elective courses in the next semester.

[9] The list of Monographic/Specialized Lectures will be updated every year to reflect the current fields of research going on at the Faculty. Monographic/Specialized Lectures might be offered with fewer class hours than indicated and correspondingly fewer assigned ECTS credits. Classes associated with Specialized Lecture may take a different form, adequate to the course topic.

[10] Upon choosing the topic of his/her Master thesis, the student carries out the Master's Degree Project I/II in one of the research groups at the Faculty. The total workload expected for this is 200 hours per semester, corresponding to 8 ECTS credits. The number of class hours is project-specific, and hence, remains udefined.

Total number of ECTS credits in the 3rd semester: 29
Total number of class hours in the 3rd semester: 232

Year of study: II
4th Semester

Course	O/F[1]	Course form[2]				No. of class hours	Assessment method[3]	ECTS credits
		W	K	L	S			
Modern Trends in Astrophysics IV[4] or Selected Topics in Astrophysics IV[4]	O/F[4]	10				10	Z	1
Elective Courses IV[5]	F	course dependent						13[6]
Extragalactic Astronomy	F	30	30			60	E/Z	5
Astero- and Helioseismology	F	15				15	Z	2
High-energy Astrophysics	F	30	30			60	E/Z	5
Computational Gravity	F	15		15		30	Z	3
Neutrino Physics	F	30				30	E	3
Monografic Lecture[7]	F	30				30	E	3
Specialized Lecture[7]	F	30	30			60	E/Z	6
Entrepreneurship and Intellectual Property Protection	O	15				15	Z	2
Master's Seminar II	O				30	30	Z	2
Master's Degree Project II[8]	O/F[8]					ND[8]	Z	8
Master Thesis and Master's Degree Examination[9]	O[9]					–	E	4

[1] Character of the course: O – mandatory, F – elective.

[2] Course form: W – lecture, K – class/project, L – laboratory/practice, S – seminar.

[3] Assessment method: E – exam, Z – passing with grade.

[4] Modern Trends in Astrophysics I/II/III/IV and Selected Topics in Astrophysics I/II/III/IV consist of short lectures of a monographic type, mainly delivered by visiting Professors. Students can attend and pass them in every semester. During the studies, it is required to complete a total of four such courses.

[5] Elective courses offered in the 4th semester can be taken in the 2nd semester and vice versa, subject to course prerequisites.

[6] Student completes optional courses for at least 13 ECTS credits in total, taking into account excess ECTS credits from the past semester.

[7] The list of Monographic/Specialized Lectures will be updated every year to reflect the current fields of research going on at the Faculty. Monographic/Specialized Lectures might be offered with fewer class hours than indicated and correspondingly fewer assigned ECTS credits. Classes associated with Specialized Lecture may take a different form, adequate to the course topic.

[8] Upon choosing the topic of his/her Master thesis, the student carries out the Master's Degree Project I/II in one of the research groups at the Faculty. The total workload expected for this is 200 hours per semester, corresponding to 8 ECTS credits. The number of class hours is project-specific, and hence, remains udefined.

[9] Includes writing and submitting a Master thesis on the previously selected topic, as well as passing the Master's degree exam.

Total number of ECTS credits in the 4th semester: 30
Total number of class hours in the 4th semester: 192

2. Course content

No.	Course	Content
1.	Data Analysis in Physics and Astronomy	Statistical frameworks and data analysis. Classical statistical inference. Bayesian statistical inference. Data mining and searching for structure in point data. Data dimensionality and its reduction. Regression and model fitting. Data classification. Time series analysis.
2.	Astero- and Helioseismology	Basic issues and concepts: oscillation mode, identification of modes, seismic model of a star, evolutionary period changes. Helioseismology: short history, properties of solar oscillations, asymptotic relations, principles of helioseismic inversion, inversion for solar rotation and solar structure. Heat driven pulsators: δ Scuti stars, β Cephei stars, Slowly Pulsating B-type (SPB) stars, γ Doradus stars, constraints on: rotational profile, element mixing processes, efficiency of convection, opacity data. Compact pulsators: white dwarfs (WD: DAV, DBV, DOV), hot subdwarfs (sdB, sdO), WD and sdB pulsators as a boundary condition for stellar evolution theory, WD pulsators as Galactic chronometers, WD pulsators as cosmic laboratories for fundamental physics. Solar-like pulsators: asteroseismic diagnostic signatures, asteroseismic diagram, scaling relations, main sequence stars, subgiants, red giants.
3.	Practical Astrophysics at Observatory	Heliophysical part: Getting acquainted with the heliophysical instrumentation located at the Astronomical Observatory in Bialkow – Large Coronagraph (LC), Horizontal Telescope (HT), Multi-channel Subtractive Double-Pass spectrograph (MSDP spectrograph). Presentation of the principle of operation of the MSDP imaging spectrograph. Spectroscopic heliophysical observations in the hydrogen H-alpha spectral line, by the use both solar telescopes (LC, HT) and the MSDP imaging spectrograph. Theoretical introduction to the physics of solar active phenomena observed at the Bialkow Observatory (solar flares, prominences, filaments, eruptions). MSDP data processing and analysis of active phenomena recorded during observations at the Bialkow Observatory. Spectral analysis of the hydrogen H-alpha line during various active phenomena observed on the Sun. Astrophysical part: Acquaint to the observation site and observational instruments. Construction of the telescope located at the Astronomical Observatory in Bialkow: optics, mount, CCD detector, filter wheel, autoguider, telescope control, and operation of the observational dome. An introduction to astrophysical observations: observation conditions, small and large ground-based telescopes, space telescopes, photometry, spectroscopy. General discussion of the observation technique used at the astrophysical observatory of the University of Wrocław: multicolor photometry, differential photometry, and photometric time series. Summary of the research subjects studied at the astrophysical observatory of the University of Wrocław: multicolor photometry of star clusters (open and globular clusters), color-magnitude diagrams, photometric variability of stars (pulsating stars, eclipsing stars, irregular variables). Discussion and (partial) execution of a typical course of astrophysical observations: calibration frames (images before and after calibration), observations of selected objects, ways of performing of photometric measurements, and a light curve.

4.	Astrophysics I	Introduction, basic definitions, stellar parameters: Astronomy as an observational science, astrophysics. Celestial sphere, coordinate systems used in astronomy. Stellar parallax, cosmic distance scale, distance ladder. Blackbody radiation. Stellar spectra, flux, effective temperature. Spectral classification. Magnitude scale, bolometric magnitude, luminosity, colour index. Stellar parameters. Determination of stellar masses and radii. Hertzsprung-Russell diagram. Tools of astrophysics: Electromagnetic spectrum, observing windows. Ground-based and space observatories. Telescopes. Detectors. Infrared, ultraviolet, X-ray and gamma astronomy. Observing techniques: imaging. Observing techniques: photometry. Observing techniques: spectroscopy. Observing techniques: optical and radio interferometry. Observing techniques: astrometry. Observing techniques: polarimetry. Stellar atmospheres: Description of radiation field. Interaction of light and matter, stellar opacity. Radiative and convective transfer. Transfer equation and its formal solution. Equations of hydrostatic and radiation equilibrium. Gray atmosphere, diffusion approximation, LTE approximation. Models of stellar atmospheres. Spectral lines and their profiles, formation of spectral lines. Atmospheric abundances of stars. Ages of stars. Stellar structure and evolution: Interstellar matter (IM), dust and gas, absorption by IM. Formation of stars, virial theorem, the Jeans mass. Pre-main sequence evolution. Stellar interiors, hydrostatic equilibrium. Basic equations. Sources of stellar energy, opacity, equation of state, transport of energy. Models of stellar interiors. Degeneracy of matter. Main-sequence evolution. Post-main-sequence evolution. Testing the theory of stellar evolution (stellar clusters, stellar pulsations). Stellar variability and its origin. The Sun: Solar interior. Solar atmosphere. Activity of the Sun, solar cycle. Solar pulsations. Solar neutrino problem.
5.	Astrophysics II	Final stages of stellar evolution: Core-collapse supernovae. Neutrino astronomy. White dwarfs. Physics of degenerated matter. Chandrasekhar limit. Neutron stars, pulsars. Stellar black holes. Gamma-ray bursts. Cosmic rays, Cerenkov telescopes. Close binary stars: Evolution of binary stars. Accretion disks. Tidal phenomena. Type Ia supernovae. Stellar mergers. Gravitational waves and their detection. Solar System, extrasolar planets: Solar System, planets. Elements of celestial mechanics (orbits, Kepler laws). Small bodies in the Solar System. Formation of planets. Extrasolar planets, detecting techniques. Evolution of planetary systems. Galaxies: The Milky Way Galaxy (components, kinematics, the central supermas-sive black hole). Types of galaxies and their parameters. Formation and evolution of galaxies. Active galactic nuclei and quasars. The large-scale structure of the Universe. Gravitational lensing. Cosmology: Friedmann equations. Cosmological models, their parameters and testing. Expansion of the Universe and its acceleration. Early Universe. Inflation. Primordial nucleosynthesis. Microwave background radiation. Dark matter and dark energy. Theories of modified gravity.
6.	Relativistic Astrophysics	Introduction: planets, stars, galaxies – scales and units. Reviewing statistical mechanics and introducing the concept of an equation of state – equilibrium physics. Describing structure and evolution of stellar objects using the concept of hydrostatic equilibrium; Newtonian and general relativistic approaches. Understanding the decoupling of radiation from matter to describe stellar atmospheres – opacity and mean-free path.

7.	High-energy Astrophysics	Physical quantities and units used in high-energy Astrophysics. Observation techniques (detectors, Voltaire optics, aperture modulated telescopes). X-ray and gamma astronomy (development of techniques for recording and analysing satellite data). Electromagnetic processes in matter (Coulomb scattering, ionisation losses, braking radiation, thermal bremsstrahlung). Interaction of radiation with matter and magnetic field (Cherenkov radiation, Compton scattering, inverse Compton effect, synchrotron radiation, synchrotron absorption, synchrotron-self-compton radiation, formation of electron-positron pairs, positron and electron annihilation). Accretion disks (accretion efficiency for white dwarfs and neutron stars, accretion efficiency for black holes for Schwarzschild and Kerr metrics, accretion types, Eddington luminosity limit, black holes in X-ray binaries and AGN, thin accretion disks, thick accretion disks, powering the accretion disk, influence of the magnetic field on the accretion disk). Cosmic rays (composition of cosmic rays, energy spectrum, modulation of cosmic rays, chemical content of elements in cosmic rays, the highest energies of cosmic rays, Great Atmospheric Air Showers (electromagnetic and muon cascades), recording methods, observation projects, distribution of cosmic rays, energy density, Greisen-Zatsepin-Kuzmin cutoff). Neutrino astronomy (description of neutrino properties, astrophysical sources of neutrinos, detection of neutrinos, observations of solar neutrinos and the problem of their quantity, neutrino oscillations, other neutrino sources, cosmic rays and the Earth's atmosphere, supernova explosions (neutrino formation mechanism and observations), AGN – mechanisms of neutrino formation). Gamma-ray bursts (observation properties, determination of distances, burst formation sites, proposed models, observation of kilonova phenomena - detection of gravitational waves, distances, masses, detection of gamma rays).

8.	Galactic Astronomy	General structure of the Galaxy. Interchange of matter between stars and ISM. Forms of ISM: gas and dust, extinction, reddening. Stellar clusters: globular and open, moving cluster. Milky Way in near and far infrared. Velocity of the Sun with respect to neighbouring stars: apex, centroid. LSR and peculiar velocities. Determination of Solar LSR velocity in respect to the Galaxy centre. Determination of the peculiar velocity of the Sun. Simple model of the Galaxy rotation: velocity vector of a star in respect to the Sun. Oort's approach to the Galaxy rotation. Oort's constants. Differential rotation of the Galaxy: geometric interpretation. Galactic rotation curve from radio observations of HI clouds. Determination of the Sun – galactic center distance. Estimation of the Galaxy mass from Oort's constants. Models of mass distribution in the Galaxy. Surface brightness of galaxies. Visual versus dynamical mass of the Galaxy. Dark matter. Distribution of stellar velocities: fast and slow stars, orbits. Distribution of components of peculiar velocities for slow stars: ellipsoid and dispersion. Relationship between velocity dispersion, spectral type and metallicity. Asymetric distribution of the rotational component of the peculiar velicities. Scattering of the stellar orbits leading to the increase of the peculiar velocity dispersion. Disc and halo kinematics. Star counts methodology. Relation between star-counts and their space distribution. Kapteyn's universe. LF, ILF and SFR functions. LF for galactic disc and for stars in GC. Height scale and its dependence on spectral type. Discovery of spiral arms in the Galaxy. Stability of spiral arms and density waves. Mechanism of star formation in spiral arms. Discovery of galactic bar. Stellar populations of the Galaxy. Thin and thick discs. Gas and dust distribution in the Galaxy. ELS model of the Galaxy orogin: free infall and energy dissipation. SZ model of the Galaxy formation: acrection. Chemical evolution of the Galaxy. Age and spatial distribution of globular clusters. Origin of the thick disc. Centre of the Galaxy with a black hole.
9.	Extragalactic Astronomy	Components of the Milky Way Galaxy: stars vs interstellar matter, central object, rotation curve, populations, chemical composition and kinematics. Classification of normal galaxies, Hubble sequence, different galaxy classification systems. Global parameters of galaxies: masses, sizes, luminosities, composition, stellar populations. Observational evidence for the existence of dark matter. Spectra of galaxies versus their composition. Methods for determining distances to galaxies. Formation of galaxies, galaxy evolution scenarios, the importance of collisions and mergers of galaxies in their evolution. The Local Group, components and characteristics. The nearest galaxies: Sagittarius dwarf galaxy, Magellanic Clouds, M31 and M33. Dwarf galaxies: types and properties. Virgo and Coma clusters of galaxies, the large-scale structure of the Universe. The unified model of the AGN, Seyfert galaxies, blazars, radio galaxies. Active galaxies, sources of non-thermal radiation in active galaxies. Quasars and their spectra, interpretation of quasar spectra. Supermassive black holes, relations between supermassive black hole masses and other galaxy parameters. Gravitational lensing: conditions and examples of the formation of Einstein rings, double and multiple images. Weak lensing and microlensing.
10.	Highlights of Modern Physics and Astrophysic*s*	Presentation and discussion of selected topics of modern physics and astrophysics, with emphasis placed on major achievements, groundbreaking discoveries and leading trends of current research, as well as the impact of astrophysical research on science and civilization. Review of literature and other sources on a given topic, preparing an abstract of oral presentation, delivering a talk, scientific discussion, writing an essay.

11.	Quantum Electrodynamics	Lagrangian formalism and Noether theorem. Quantization of scalar, Dirac and electromagnetic fields. Klein-Gordon and Dirac equations. Feynman rules. S matrix and cross sections. Ward-Takahasi identities, LSZ reduction formulas, optical theorem.
12.	Ethics in Research	The specifics of ethics, code ethics vs. situational ethics, the difference between ethical codes and laws, selected provisions of ethical codes; copyright law and the ethical dimension of plagiarism, the ethical foundations of copyright law, copyright law in the field of scientific research, borderline areas: self-plagiarism, cryptocitation, the problem of duplication of publications and "salami slicing", the credibility of research, the norms governing co-authorship of papers; ethical aspects of reviewing publications: Conflict of interest, challenges to the anonymity of reviews, the problem of bias, confidentiality of data, scope of expertise; ethical aspects of patent law; conflict of interest in scientific research; falsification of research results; social responsibility of the scientist; problems of the modern world; problems of research ethics related to work at the university: closed scientific environment, bullying (sexuality, carnality), verbal bullying, types of bullying specific to the university environment, use of institutional advantage: teacher-student relationship, promoter-doctoral student, scientist experienced more-less).
13.	Gravitational Waves	Einstein's equations, linear approximation, post-Newtonian approximation. Mathematics and physics of gravitational waves. Astrophysical and cosmological sources of gravitational radiation. Gravitational waveforms of binary systems. Detection of gravitational waves.
14.	Astroparticle Physics	Introduction (The standard model (SM) of elementary particles. Fermions and bosons in SM. Units in astrophysics and elementary particle physics. Natural units.) Lagrange formalism (Introduction. Classical fields. Lagrangian for scalar fields. Conserved quantities from the Lagrange function. Lorentz-Transformation. Invariance under global gauge transformations. Noether's theorem.) Quantized fields (Spinor fields and Dirac equation. Scalar field and Klein-Gordon equation. Quantization of the scalar field. Vector fields and quantum electrodynamics: the classical electromagnetic field, lagrangian of the electromagnetic field, quantization of the electromagnetic field. The evolution operator. Wick's Theorem. Feynman's diagrams. Mott and Rutherford cross-section. The phenomenology of weak interactions. Lifetime of the neutron and beta-decays. Neutral interactions. Neutrino-electron interaction. Higgs mechanism of electroweak symmetry breaking.) Thermal evolution of the Universe (Physics at lepton era: a recourse in thermodynamics, thermodynamics of ultra-relativistic and non-relativistic gases, particle-antiparticle annihilation and neutrino decoupling. Nucleosynthesis. Recombination: helium-recombination, hydrogen-recombination.) Cosmic rays (Primary cosmic rays. Secondary cosmic rays. X-rays and γ-rays. The abundances of cosmic rays. Ultra-high energy cosmic rays. Particle acceleration mechanisms. Interaction with CMB radiation.) Supernovae and neutron stars (Stellar evolution and supernova progenitors. Collapse phase. Neutrino emission. Nucleosynthesis in supernovae. Neutron stars as laboratories for particle physics. Structure of neutron stars: Equation of state and gravitational equilibrium. Neutrino cooling of neutron stars. Axion cooling of neutron stars. Physics of neutron star magnetosphere: composition, particle acceleration, synchrotron emission.) Neutrino physics (Neutrino interactions with matter, cross-section. Neutrino masses. Solar neutrinos. Supernova neutrinos. Neutrino oscillations and propagation through matter. Atmospheric neutrinos. Neutrino telescopes, Cherenkov effect in water and ice. Sources of high-energy neutrinos.)

15.	Neutrino Physics	A short history of neutrino physics: beta-decay, Pauli hypothesis, Fermi theory, discovery of neutrino in 1950s, discovery of muon neutrino. Neutrinos in the Standard Model, charge current and neutral current processes. Dirac and Majorana neutrino. Neutrino interactions with electrons, hadrons and nuclei. Detection of neutrinos. Neutrino mass, neutrino oscillations, neutrino oscillation experiments. Neutrino oscillation parameters. Solar neutrinos, solar neutrino flux, pp neutrinos, CNO cycle. Deficit of solar neutrinos. MSW effect for solar neutrinos. Supernovae neutrinos, diffuse neutrino spectrum, information from SN1987. Relic neutrinos as Big Bang remnants. Leptogenesis, measurement of CP violation in neutrino oscillations. Astrophysical sources of high-energy neutrinos. Neutrino telescopes, IceCub, km3net experiments.
16.	Computational Gravity	Computational gravity and the use of modern computer tools (Mathematica and some elements of Cadabra software). Various symbolic and numerical computations within the framework of General Relativity. Computer-assisted solving of Einstein equations (Friedmann–Lemaître–Robertson–Walker, deriving Reissner–Nordström solution, etc.). Gravitational models (modified theories, higher dimensions, cosmological constant, variation principle). Coupling gravity to scalar theory, electromagnetism. Black holes (orbits in Schwarzschild and Kerr spacetimes, black hole singularities and Kretschmann invariant). Selected cosmology and astrophysical phenomena.
17.	Variable Stars	Criteria used to classify variable stars. History of the discovery of variable stars, catalogues of variable stars. General classification of variable stars, stars exhibiting simultaneously different types of variability. Types of Cepheids, use of Cepheids as standard candles, Baade-Wesselink method, Hertzsprung progression. Pulsating stars in the classical instability strip. Pulsating stars of the main sequence, Beta Cephei and SPB-type variables. Compact pulsating stars (white dwarfs, hot sub-dwarfs). Pulsating types of red giants. The Sun as a pulsating star, solar-type oscillations, their nature and detection methods. Binary stars: classification criteria, proximity effects and tidal effects. Determination of the parameters of the components of binary systems (including masses, radii and ages). Cataclysmic and pre-cataclysmic stars, novae. Stars exhibiting rotational variability, pulsars. Eclipsing phenomena in star-other object (e.g. star-planet) systems. Microlensing, detection methods and use. Massive photometric sky surveys – motivations and examples. Variability detection methods, automatic classification of variable stars.
18.	Compact Stars	Observations of Compact Stars (CS). CS properties. Equation of state for the CS crust Dense nuclear matter and quark matter in the CS interior. General relativistic CS structure. Neutrino processes and CS cooling. CS at birth: Supernovae and protoneutron stars. Gravitational wave signals and black hole formation. Exploring CS matter in heavy-ion collision laboratories.
19.	English (B2+ level)	Vocabulary and grammar resources of the English language corresponding to proficiency at B2+ level of the Common European Framework of Reference for Languages. Topics within the field of sciences, in particular physics and astronomy. Specialized vocabulary and grammar structures used in academic environment, enabling the student to understand and analyse professional texts/lectures, as well as to describe and present astrophysical issues.
20.	Polish for Foreigners (A1 level)	Vocabulary and grammar rules necessary to achieve fluency at level A1 of the Common European Framework of Reference for Languages. Topics related to everyday life.

21.	Theoretical and Observational Cosmology	History of cosmology. Newtonian cosmology, Friedmann equations and matter dominated universe. Relativistic generalization of Friedmann equations: radiation dominated universe, cosmological constant, general equations of state. Light propagation in expanding universe: red shift and angular distance. De Sitter universe and cosmological inflation. Inhomogeneous universe, evolution of instabilities in Newtonian theory (quantitative). Relativistic theory of gravitational instabilities. Fluctuations in inflationary scenario and primordial fluctuations. Cosmic Microwave Background and cosmological parameters. Dark matter and structure formation.
22.	Computational Methods I	Basic operations. Ordinary differential equations. Boundary value problems. Special functions, Fourier transformation and Gauss quadrature.
23.	Computational Methods II	Random numbers and Monte Carlo techniques. Partial differential equations. Particle code problems and smoothed particle hydrodynamics.
24.	Non-Equilibrium Statistical Physics	Basics of kinetic theory (Distribution function, detailed balance, Boltzmann kinetic equation. The H-theorem, transition to hydrodynamics. Weakly inhomogeneous gases. Transport coefficients: thermal conduction, shear, and bulk viscosity Onsager's relations. Dynamical derivation of the BKE from Bogolyubov hierarchy. Radiative transport in stellar atmospheres as a kinetic process. Thermal conductivity and shear viscosity of stellar matter in the non-degenerate regime.) Diffusion processes (Fokker-Planck equation. Diffusion of heavy particles in a gas, ionization, and recombination. Stellar opacities in multi-component plasma.) Degenerate systems (Quantum liquids, quasiparticles, and their kinetics. Applications: sound attenuation in Fermi gases, transport in metals and liquid helium. Applications to white dwarfs: electrical conduction of electron gas in the degenerate regime. Applications to neutron stars: shear viscosity and thermal conductivity of neutron matter in the degenerate regime from Fermi-liquid theory.) Advanced methods (Green's functions methods in kinetics, real-time contour formulation of the theory. Projection operator methods, Kubo formula for transport coefficients Electron self-energy and Landau damping in white dwarf stars. Computation of transport coefficient of quark matter in neutron stars from Kubo formulas.)
25.	General Relativity and Gravitation	Special Theory of Relativity: Minkowski spacetime, Lorentz transformations, accelerated observers. Einstein's Equivalence Principle. Tensor calculus. Manifolds and tensor fields. Affine and metric geometry: conncection, parallel transport, metric, geodesics, curvature. Energy-momentum tensor. Einstein's equations. Newtonian limit. Tests of General Relativity. Schwarzschild's geometry, black holes, hydrostatic equilibrium of stars. Cosmology: Friedmann's equations. accelerated expansion, dark energy, dark matter. Gravitational waves.
26.	Master Thesis and Master's Degree Examination	Writing and submitting the Master thesis, prepared in accordance with the requirements set by the Faculty of Physics and Astronomy of the University of Wrocław for dissertations at the level of second-cycle studies. Upon a positive assessment of the thesis – passing the master's exam on the terms set out in the conditions for graduating in the field of Astrophysics.

27.	Laboratory of Magnetic Activity of the Sun and Stars	Calibration methods for spectroscopic observations of solar flares and prominences obtained in the optical range. Ultraviolet spectroscopy and photometry of active solar phenomena. Temporal evolution of stellar and solar flare emissions. Strategies and methods used in the modelling of solar and stellar flares. One-dimensional models of the active atmosphere of the Sun and stars. Distributions of non-thermal electrons in the flaring loop (Fokker-Planck). Diagnostics of star spots based on the photometric modulations. Analysis of solar and stellar activity cycles. Detection of stellar flares in global surveys of the sky.
28.	Laboratory of Theoretical Astrophysics	Introduction to MESA stellar evolution code. Description of the possibilities and limitations of the program. Calibration of numerical parameters in order to obtain results that make physical sense. Learning how to model different astrophysical objects: molecular clouds contracting on the main sequence, main sequence stars, red giants, AGB stars, horizontal branch stars, white dwarfs, black holes. Analysis of physical processes in different phases of stellar evolution (nuclear reactions, convection, diffusion of chemical elements, energy transport, mass loss, mixing of matter, angular momentum transport). Modeling the evolution of binary systems with mass exchange between the components.
29.	Laboratory of CCD Photometry	The student learns about the use of the CCD camera for photometric observations, gets acquainted with the properties of various types of images obtained by the camera, performs reduction and calibration of photometric observations, constructs and interprets color-brightness and color-color diagnostic diagrams, analyzes the results of photometric observations and derives physical properties of stars, compares the obtained results with scientific literature, draws conclusions from the performed analysis.
30.	Laboratory of Stellar Pusations	Learning how to use computer programs for computing the pulsations of stars of various types. Getting to know the methods of identifying modes and getting to know the codes that enable such identification. Learning the methods of constructing seismic models and constraining the free parameters of the models of stellar structure and evolution. Getting to know the numerical methods used in the computer programs and understanding their limitations.
31.	Laboratory of Stellar Spectroscopy	The student learns about the use of the CCD camera for spectroscopic observations, gets acquainted with the properties of various types of images obtained by the camera, performs reduction and calibration of spectroscopic observations, determines the radial velocities of single and double stars, constructs models of stellar atmospheres, calculates the synthetic spectrum, determines atmospheric parameters stars, determines the projected stellar rotation velocities, compares the obtained results with the scientific literature, draws conclusions from the performed analysis.
32.	Master's Degree Project I/II	Student carries out the Master's Degree Project I/II in one of the research groups at the Faculty, in accordance with the chosen topic of his/her Master thesis. This includes the review of literature and other sources related to the subject of Master thesis, mastering the necessary research tools and techniques, carrying out scientific research constituting the basis for Master thesis, as well as analyzing, elaborating, evaluating and interpreting the obtained results.

33.	Entrepreneurship and Intellectual Property Protection	Introduction to a global high technology market. Assessment of individual business skills. Selection of a new business idea from a high technology area. Market evaluation of a new idea/technology. Study of market competitiveness. Possible methods of IP assessment and protection. Raising capital for innovative activity/business. Successive stages of the introduction of a technology to the market. Registration and introduction of a new entity into the market.
34.	Stellar Pulsations	Basic concepts and mathematical issues: oscillation mode, radial and non-radial pulsations, spherical harmonics, basic coordinate systems and transformations between them, the Eulerian and Lagrangian description, perturbation of the surface element and its normal. Types of pulsating variables: stellar pulsations across the Hertzsprung-Russell diagram, instability domains, basic properties of different types. Oscillation properties: the Lamb and Brunt-Vaisala frequency, acoustic and gravitational modes, propagation diagrams, conditions for trapping of modes, pulsation constant, period-luminosity relation. Mathematical description of pulsations: general equations of hydrodynamics, linear non-radial non-adiabatic pulsations, boundary conditions, adiabatic and quasi-adiabatic approximation, Sturm-Liouville type problem, variational principle, asymptotic dispersion relations. Excitation mechanism: Eddington valve mechanism, self-excitation (opacity) mechanism, work integral, stochastic excitation by turbulent convection. Detection of pulsating stars: Fourier methods, statistical methods, wavelet analysis. Observed characteristics and identification of pulsation modes: light variations of a pulsating star, changes of radial velocity, modelling of line profile variations, methods of the mode identification from photometry and spectroscopy. Basic effects of rotation: advection, rotational splitting of modes, Coriolis force, Ledoux constant, effects of moderate rotation, centrifugal force. Helio- and Asteroseismology: seismic model of a star, the most important achievements of helioseismology, examples of asteroseismic modelling.
35.	Master's Seminar I/II	Presentation and discussion of recent achievements, major problems and main research trends in different areas of modern astrophysics, the scope of scientific research conducted at the Faculty of Physics and Astronomy of the University of Wrocław in the field of astrophysics, and the subjects of Master theses prepared by the students. Presentation and discussion of the initial or expected results of the students' scientific work. The issues of proper use of sources, critical analysis of their content, presentation rules and techniques, the ability to transfer a message, correct reasoning, and conducting scientific discussion based on factual argumentation.
36.	Initial training on OHS and fire protection	Basic concepts of occupational safety and health (OSH). Harmful and oppressive factors that can occur during classes. Legislation on health and safety at the universities. What to do in the case of an accident. Basic rules of first aid. OHS and fire protection hazards in the place of learning. Organization of fire protection. Causes and spreading of fires. Basic duties and tasks resulting from fire prevention regulations. What to do in the event of fire. Rules of using the fire-fighting equipment and devices.

37.	Machine Learning	Machine learning language environments (PyTorch, TensorFlow, Keras, SciKit-Learn, NumPy). Linear and nonlinear regression, polynomial curve fitting, and classification. Bias-variance trade-off. Radial basis functions. Neural networks. Activation functions, optimization algorithms. Cross-validation, regularization, bootstrap. Convolutional neural networks and visual data analysis. Batch-normalization, Dropout. Pre-trained models. Transfer learning. Detection of the objects by U-Net type networks. Recurrent neural networks in series analyses. Generative adversarial neural networks.
38.	Planetary Systems and Astrobiology	Definitions of life (biological, reductionist, cybernetic and others). Organic matter in the Universe (synthesis of organic particles on Earth, extraterrestrial organic matter on Earth, formation of biological systems, formation of living organisms). Conditions conducive to the emergence and evolution of living organisms (friendly planets and moons of planets, habitable zone of a planetary system, galactic habitable zone). Life in the solar system: planets (energy, organic matter, water). Life in the solar system: Jupiter's moons, Saturn's moons. Living in extreme conditions (extremophiles). Extrasolar planets: methods of detection. Characteristics of extrasolar systems (presentation and discussion of the latest results). Atmospheres of exoplanets. Methods of searching for life on extrasolar planets (biosignatures).
39.	Modern Trends in Astrophysics I/II/III/IV	Presentation and discussion of recent achievements and main research trends in the field of modern astrophysics, including the impact of astrophysics discoveries on our understanding of the world and the progress of science, as well as their civilizational significance.
40.	Introduction to Solar Physics	Solar interior, distribution of physical parameters and chemical composition of solar plasma, the neutrino problem. Interaction of magnetic field with plasma, basics of magnetohydrodynamics of the solar phenomena, solar dynamo. Activity of the Sun; short and long term solar variability. Solar atmosphere. Quiescent and active structures in the solar chromosphere and corona. Solar eruptions and ejections. Sun-Earth connections. Space Weather. Solar wind. Modern space and ground-based solar telescopes and observing techniques. Multi-wavelength imaging and spectroscopic methods.
41.	Selected Topics in Astrophysics I/II/III/IV	Selected issues in the field of astrophysics, including recent discoveries and key research problems. Presentation of the directions of astrophysical research in other scientific centres, discussion of research methods and techniques used there, as well as their most important achievements.
42.	Monografic Lecture	Specific advanced issues related to the field of study, taking into account the proposed topics of master theses. Their original and regularly updated content closely reflects the current research areas at the Faculty of Physics and Astronomy, being also adjusted to the particular fields of scientific interest of the students.
43.	Specialized Lecture	Specific advanced issues related to the field of study, taking into account the proposed topics of master theses. Their original and regularly updated content closely reflects the current research areas at the Faculty of Physics and Astronomy, being also adjusted to the particular fields of scientific interest of the students. Lectures are accompanied by classes of a form adequate to the course topic.

44.	Advanced Solar Physics and Space Weather	Solar atmosphere: Introduction to the solar atmosphere and solar spectrum. Radiative transfer equation. Radiative transfer in the solar atmosphere. Absorption cross section for bound-bound processes. Spectral line profiles. Local Thermodynamic Equilibrium (LTE). Excitation and ionization equilibria. Saha equation. Spectral lines in local thermodynamic equilibrium. The Eddington-Barbier Relation. The Planck Function. The Gray Atmosphere. Gray Limb Darkening in the Eddington Approximation. Solar spectroscopy: Spectral lines and continua. Line broadening. Zeeman and Stark effects. UV and X-ray spectrum of the Sun. Mechanisms of solar radio emission. Dynamical processes in the solar atmosphere: Solar photosphere. Solar granulation and supergranulation as an example of convective motion. Schwarzschild criterion for convective instability. Observations of solar oscillations. Hydrodynamic equations. Waves. Basic assumptions used in the construction of the photosphere models. Solar interior and magnetism: Solar interior. Solar dynamo. Solar rotation. Observations of solar magnetic field. Overview of main solar magnetic activity phenomena: sunspots, flares, coronal mass ejections. Hydrostatic equilibrium. The basic equations of magnetohydrodynamics (MHD). Dynamics of coronal magnetic loops and Holes. Elements of helioseismology. Outer layers of the solar atmosphere: Chromosphere and spicules. Transition region. UV and X-ray emission of the solar atmosphere. The Sun in millimeter wavelengths (ALMA). Quiet-Sun corona – observations and models. Coronal holes and jets. Modelling of the solar photosphere, chromosphere and corona. Non-Local Thermodynamic Equilibrium (NLTE) methods. Construction of semiempirical models. Temperature minimum. Heating of the upper solar atmosphere. Solar activity: Observations of solar activity. Active regions. Structure of sunspots. Quiescent and active prominences. Solar flares and Coronal Mass Ejections (CME). Eruptions of solar prominences. Flare loops. Nanoflares and other small scale energetic phenomena in the solar atmosphere. Solar activity cycles. Activity behavior over the solar cycle. The Sunspot Number and other indices of activity. Long-term evolution of solar activity. Sun-Earth connections and space weather: Introduction to Sun-Earth connections. Solar wind. Earth magnetosphere and ionosphere. Effects of solar activity on Earth atmosphere and magnetosphere. Space weather. Structure of the heliosphere. Geomagnetic activity and magnetic storms. Geomagnetic indices. Radio emission of the Sun.

45.	Advanced Statistical Physics	Statistical physics of interacting gases (Gibbs' formulation of equilibrium state thermodynamics of interacting gases. Partition function. Mayer’s cluster expansion. Virial expansion. Beth-Uhlenbeck approach to quantum gases. Equation of state of multicomponent plasma with applications to stars. Chemical equilibrium and Saha equation. Gravitational equilibrium of stars for different equations of state.) Statistical physics of quantized fields. (The method of quantized fields. Low-temperature behavior of Bose gas, Bose-Einstein condensation. Low-lying excitations in Fermi systems. Fermi-liquid theory. Equation of state of degenerate matter, white dwarfs, and neutron stars. Weak equilibrium and change neutrality conditions. Gravitational equilibrium of white dwarfs and neutron stars.) Phase transitions (Phase transitions in Van-der-Waals gas. Lattice models. Spontaneous magnetization of a ferromagnet. Lattice gas and binary alloys. Ising model in the Bethe approximation. Critical exponents. Thermodynamic inequalities. Landau’s theory of second-order phase transitions. Crystallization of white dwarf matter. Phase transitions from hadronic to quark matter in neutron stars.) Renormalization group approach (Basic scalings. Simple examples of renormalization. General formation of renormalization group equations. Fluctuation-dissipation theorem. Linear response theory. Photon and neutrino interactions in the stellar matter within the linear response theory.) Fluctuations (Thermodynamic fluctuations. Spatial correlations. Fluctuation analysis on the example of Brownian motion. Statistical physics of nuclear reaction in stars, pycnonuclear reactions in neutron stars.)
46.	Advanced Topics of Stellar Atmospheres	Introductory information: objectives of stellar atmosphere research, spectral classification. Modelling of stellar atmospheres: assumptions and equations. Energy transfer mechanisms (radiation, convection, diffusion). Interaction of radiation and matter. Atomic data required to build a model of the atmosphere. Basic models of atmospheres, assumptions: 1D geometry, assumption of local thermodynamic equilibrium, mixing length theory, blanketing. Realistic atmosphere models: 3D geometry, no local thermodynamic equilibrium, stellar wind and more. Models of the Sun's atmosphere. Methods of analysis of stellar spectra. Determination of atmospheric parameters (e.g. effective temperature, surface gravity, chemical composition).
47.	Advanced Topics of Stellar Structure and Evolution	Deepening the knowledge of evolutionary states of various types of stars through expanding the knowledge of physical laws necessary for modeling them. Discussion of issues related to thermodynamics, equation of state, energy transport, angular momentum transport and the effects of mixing elements in conditions of stellar interiors, cosmic and stellar nucleosynthesis. Familiarization with the equations of structure and evolution of stars, equations of state for fermions and bosons (in conditions of none, total and partial degeneracy). Getting to know the numerical methods for constructing evolutionary models of various types of stars. Getting to know the types of nuclear reactions, cross sections, reaction rates, radiation induced reactions, photodisintegration, reactions involving charged particles and reactions involving neutrons. Discussion of changes of the chemical element abundances resulting from nuclear processes. Discussion of nuclear reaction cycles (pp, CNO, CNO hot cycle, 3alpha, explosive burning helium and other advanced nuclear reaction cycles involving the burning of carbon, neon, oxygen, silicon).

48.	Advanced General Relativity	From Newton to Einstein: conceptual foundations of general relativity. Motion of particles and geodesic equation. Geodesic deviation and curvature. Energy momentum tensor and Einstein equations. Gravitational waves, theory and observations. Black holes, theory and observations. Gravitational lensing, theory and observations. Some modern developments in general relativity.