Introduction to astrophysics

Two-years course

Part 1. Astronomy.

1. Introduction. The observed ranges. Ground-based and space observatories. Unresolved issues (the nature of dark matter, gamma-ray bursts, etc.).
2. Radio astronomy. Optical astronomy. CCD, speckle interferometry, adaptive optics.
3. X-ray and gamma-ray astronomy. Neutrino astronomy. Gravitational wave detectors. The quantum limit of measurements.
4. Solar System – 1. Planets and satellites. The orbital elements (synodic, sidereal, draconic, tropical, and anomalistic periods). Saros.
5. Solar system – 2. Planetary magnetosphere. The rings of Saturn, and asteroids.
6. The Sun. The atmosphere and the photosphere. Spectral lines, the nature of the broadening. The transport equation, the limb darkening. Solar corona, and the active regions. The solar wind.
7. Stars - 1. Stellar magnitudes, spectral classification.
8. Stars - 2. GR-diagram. The chemical composition and evolution.
9. Binary stars. Visual and spectroscopic binary systems. The orbital elements and the mass function. Galactic black hole candidates.
10. The internal structure of stars. Main-sequence stars. Giants. White dwarfs. Chandrasekhar limit. Neutron stars. Defining the parameters of neutron stars from observations.
11. X-ray pulsars. The structure of the magnetosphere. Accretion disks. The standard model. Eddington limit. Quasi-periodic oscillations.
12. Transient processes. Cepheid stars and the oscillatory instability. Novae and supernovae, and their classification.
13. Diffuse matter. The interstellar dust. The gas component of the HI and HII, maser sources, molecular clouds. Cosmic rays, the problem of acceleration.
14. Galaxies and their classification. Evolution, structure, and stellar dynamics.
15. Active galactic nuclei. Quasars, radio galaxies, BL Lac. Unification model. Black holes as a source of activity. Electromagnetic model of the central engine. Microquasars.
16. Cosmology. Jeans instability. Clusters and superclusters. The inflationary model. Recent observational confirmation of the existence of "dark matter" and "dark energy".

Part 2. Astrophysics

1. The revolutionary character of the development of astrophysics in the second half of the twentieth century. Key discovering (CMB, quasars, pulsars, X-ray pulsars, gamma-ray bursts).
2. Radio pulsars – 1. Basic observational properties. The pulsar in the Crab nebula. Their occasional discovery in spite of theoretical prediction. Evolution of neutron stars due to magnetodipole radiation. The magnetosphere of radio pulsars.
3. Radio pulsars – 2. Model of a unipolar inductor. Current loss of neutron stars. The characteristic life time. Qualitative derivation of the magnetodipole losses.
4. Pulsar 1913 +16 is in a binary system. The first radio pulsar in a binary system. Doppler effect and its use in astronomy (superluminal sources, the definition of orbital elements, mass function.
5. Post-Newtonian corrections. Light deflection, Khvol'son-Einstein radius. Gravitational redshift, motion of the perihelion (periastron). Determination of the marginally stable orbit in the Paczynski-Wiita potential. Shapiro delay. Gravitational lenses and microlenses.
6. The emission of gravitational waves. The absence of dipole gravitational radiation. The energy density of gravitational field. Qualitative derivation of the gravitational losses.
7. Search for black holes. Black holes of solar mass. Supermassive black holes in the galactic nuclei. Methods of registration.
8. Gamma-ray bursts, their isotropi and inhomogeneous spatial distribution. Afterglow as a confirmation of cosmological nature of gamma-ray bursts. LogN-LogS creterium.
9. Introduction to General Relativity. Limitations of the classical theory of gravity. Group properties for rotations. The invariance of the electrodynamic equations under Lorentz transformations.
10. Tensors in physics. The metric tensor in different coordinates. Energy-momentum tensor.
11. Curvature. The triangles and circles. The Gaussian curvature. Curvature of a sphere in different coordinates.
12. Einstein's equation. Heuristic arguments. Gravity is the curvature. Definition of the curvature through the acceleration of free fall. Limiting transition to nonrelativistic case.
13. Cosmology. Friedmann model. Friedmann solution for a flat metric.
14. The Einstein equations in a weak gravitational field. The analogy with the equations Maxwell. Geodetic and Lense-Thirring precession as an analogy of the Larmor precession.
15. Black Holes. Schwarzschild metric. The gravitational radius. Equation of motion of the light. The radius of the marginally stable orbit. Kerr metric, ergosphere.

Part 3. Plasma physics

1. Mathematics at a minimum: a basis of vector analysis in three dimensions. Curl and divergence of vector fields, geometric meaning. The Laplace operator. Fourier transform.
2. Fundamentals of electrodynamics. Maxwell's equations. The solution of the Poisson equation using the Fourier transform, the formula of Coulomb and Biot-Savart-Laplace.
3. Averaging (statistical and within infinitesimal volume) of Maxwell equations in a medium, mean fields. Determination of conductivity and dielectric tensors in the plasma.
4. The concept of quasi-neutrality, Debye length. Ideal and nonideal plasma. The condition of thermodynamic equilibrium in astrophysical plasmas. Derivation of the Saha expression.
5. Quantum degenerate plasma. The condition of the plasma equilibrium in a potential field. Chandrasekhar limit.
6. Thompson cross section, radiation-reaction force (qualitatively). Eddington luminosity.
7. Exact solution to the Debye screening in dimension 1 and 3.
8. Langmuir waves in plasma. Derivation of the plasma frequency. Landau damping of plasma waves, qualitative derivation of the expression for the increment. The analogy with the Cerenkov effect. Beam instability. The main idea of the saturation of the instability (qualitatively).
9. Transverse waves in a plasma, the dispersion relation. Phase and group velocity. The reflection of short waves from the ionosphere of the Earth. Derivation of expressions for the dispersion measure.
10. Ion sound in a homogeneous plasma. Derivation of short- and long-wavelength limit. A complete picture of the dispersion curves for linear oscillations in a homogeneous plasma.
11. Collisions of particles. Derivation of the collision frequency. Radiation of the plasma.
12. The motion of charged particles in a magnetic field. Adiabatic invariants.
13. The motion of particles in the Earth's radiation belts, the numerical simulation. Magnetic mirrors, Fermi acceleration.
14. Plasma in a magnetic field. Derivation of the dielectric tensor of cold plasma.
15. Waves in a magnetized plasma. Derivation of the dispersion curves in the case of longitudinal and transverse propagation. Faraday effect, Faraday pulsation and their astrophysical applications.
16. Hydrodynamics of plasma in a magnetic field. The generalized Ohm's law.
17. Freezing of the magnetic field. Astrophysical examples: the collapse of a star, Io and Jupiter, the magnetosphere of pulsars.
18. The equilibrium of plasma in a magnetic field. Examples of equilibrium configurations: *z*- and theta-pinches.

Part 4. Quantum mechanics

1. Introduction. The revolutionary character of the development of quantum mechanics in the first quarter of the twentieth century. The discreteness of the energy (photoelectric effect, the spectrum). Planck constant. Determination of Planck length, time, and mass.
2. Wave as a particle. Thomson cross section, the classical electron radius. Compton effect. The corrections to the Coulomb law at the Compton scale, the vacuum polarization in strong fields.
3. Particle as a wave – 1. The uncertainty principle for the waves. The group velocity. Wave path of a moving ship, the definition of the angle.
4. Particle as a wave – 2. Relations for the energy and momentum. The uncertainty principle. Lower levels as a consequence of the uncertainty relation. Phase and group velocity for particles.
5. Dualism. Passage of the light through a polarizer. The interference of the electron. The levels of Bora as a consequence of the wave nature of electrons (constructive interference of de Broglie waves). Bohr radius. The size of Rydberg atoms with $n = 700$. Lifetime in cyclotron radiation.
6. Why are incompatible classical gravity and quantum theory. Matvei Bronstein breakthrough – with the derivation in a weak gravitational field. As supersymmetry solves this problem.
7. The quasi-classical limit for large n. Characteristic electric and magnetic fields. Neutron stars as sources of high magnetic fields.
8. Fundamentals of quantum mechanical formalism. Probability, ensemble, measurement, and collapse of the wave function. The concept of a Hilbert space.
9. Spin. Stern-Gerlach experiment. Rotations in three dimensions. The spin space as a two-dimensional Hilbert space.
10. The decay of a spinless particle into two particles with spin ½. Einstein-Podolsky-Rosen paradox.
11. Hidden variables. Their experimental violation. Bell's inequalities.
12. The many-worlds interpretation. The measuring device. The uncertainty relation between energy - time. Passage of the package. The broadening of the lines that have a finite lifetime.
13. The identity of the particles. Connection between spin and statistics. The quantum limit of detection of gravitational waves.
14. The density of states. Casimir effect. Chandrasekhar limit.
15. Quantum mechanics in solid state physics. Quasimomentum, band structure. Peierls transition.