This is the detailed course outline for the compulsory courses of the Joint Astronomy Programme (JAP). In the following, optional topics are given in *italics*.

1 Fundamentals of Astrophysics: PH 217 3:0 (45 hours)

Introduction, Distance, Measurement system and devices:

- Celestial phenomena, their connection with established and new physics; typical physical scales/conditions in astrophysics; order of magnitude estimation
- Astronomical observations: electromagnetic waves, *cosmic rays, gravitational radiation*; earth vs. space based observations
- Measurement systems: celestial sphere, RA/DEC coordinates, Galactic coordinates, luminosity/flux magnitude scale, apparent/absolute magnitude, electromagnetic wavebands, spectroscopy
- Distance measurements: AU, parsec, standard candles, distance measurement by geometric means (parallax, distances to open clusters)
- Stellar mass measurement: visual, eclipsing, spectroscopic binaries
- Telescopes: radio, infrared, optical X-ray, gamma ray; collecting area, diffraction limit, atmospheric seeing, *adaptive optics, speckle imaging, aperture synthesis, spectroscopy (prisms and gratings), polarimetry, imaging, photometry*

[6 hours - `[21]: chapters 1, 2; [26]: chapter 1; [5]: chapter 27.1; [8]: chapter 1`]

Fundamentals of radiation and Sun as a star:

- Radiation: geometric optics, specific intensity, luminosity/flux, radiative transfer equation, extinction and emission of light, opacity, opticallly thick/thin media, black body radiation, *local thermal equilibrium between matter and radiation and its connection with black body radiation*
- Sun as a star (qualitative): Solar spectrum, effective temperature, luminosity, photospheric absorption lines, limb darkening; energy source: Kelvin time scale, nuclear fusion; energy transport in the sun, Thomson scattering, mean free path, photon diffusion inside the Sun; photosphere, chromosphere, transition region, corona; *X-ray emission, magnetic fields, Sunspots*

[5 hours - `[26]: chapters 2, 5; [21]: chapters 1, 2; [5]: section 27.1; [8]: chapter 1`]

Stellar structure:

- Stellar models: hydrostatic equilibrium, gas/radiation pressure; theoretical main sequence; opacity: Thomson, Kramer's, scattering, role of H^- opacity, energy balance, constitutive relations and detailed stellar structure, convective instability. Convection zones in stars
- Nuclear energy production: binding energy per nucleon, efficiency of fusion, calculation of nuclear reaction rates, tunneling in Coulomb barrier, Gamow peak. important nuclear reactions in stars: pp chain, neutrino production in the Sun and consequences; *neutrino oscillations*, CNO cycle, triple alpha reaction, *rate limiting reactions*, nuclear resonances
- Observed stellar properties: main sequence, luminosity dependence on mass, stellar classification based on spectra, connection with Saha ionization formula; HR diagram; star clusters and distance measurements

[9 hours - [21]: `chapter 2; [26]: chapters 6, 9; [5]: chapter 8, sections 10.3, 10.5; [8]: chapters 3, 4`]

Stellar evolution:

- Pre-main sequence evolution: Jeans instability, star formation, Hayashi track
- Post-main sequence evolution: Core He burning, shell burning, red giant phase, stellar winds, *Parker's model for solar wind*, planetary nebulae, white dwarf physics, electron degeneracy pressure, Chandrasekhar mass limit. Type II supernova, neutronization; formation of elements heavier than iron; Neutron stars(NS); NS observed as pulsars, pulsar magnetosphere, $\dot{P}$ from oscillating magnetic dipole formula, black hole formation for $M > N_S$; qualitative discussions of horizon, *Hawking radiation*, phenomenology of GRBs and connection with supernovae
- Binary system evolution: effective potential in rotating frame, Lagrange points, Roche lobe, mass overflow, Type Ia supernovae
- Accretion physics: energy efficiency; X-ray binaries vs supermassive BHs (AGN); thin disk model for optically thick accretion flows, *need for turbulent viscosity, magnetorotational instability*, derivation of multicolour blackbody spectrum, *opacity sources; observations*

[10 hours - [21]: `chapter 2, 4; [26]: chapters 6, 7, 10; [8]: chapters 4, 5`]

Galaxy and Extragalactic astronomy

- Types of galaxies: spirals, ellipticals and irregulars, Hubble pitchfork classification
- Milky Way components: gas, stars, magnetic field and cosmic rays, satellites, 21cm line, rotation cure, dark matter; HII regions, phases and components of interstellar medium, cosmic rays
- Galactic dynamics: orbits in axisymmetric potentials, epicyclic limit; Oort's A & B constants, local differential rotation, *Collisionless Boltzmann equation, Jean's equations, DFs, f(E),* isothermal models of gas in galaxies
- Active galaxies: observations of active galaxies, quasars, unified model, radio lobes and jets; relativistic apparent superluminnal motion, Doppler boosting, blazars; $M-\sigma$ relation for central black holes; Sgr A*, the Galactic centre black hole
- Extragalactic distance scale, structure on the largest scales

[8 hours - [21]: `chapters 5, 6; [5]: chapters 25, 27, 28`]

General relativity and cosmology

- Olber's paradox; difficulty with Newtonian cosmology, brief introduction to general theory of relativity, especially the line element, Schwarszschild metric
- FRW metric as a consequence of cosmological principle; Hubble's law; redshift; angular diameter and luminosity distances; Friedmann equation; accelerating universe
- Friedman equation, accelerating universe; evolution of scale factor, density parameter, LCDM cosmology, flatness and horizon problems, basics of inflation theory
- Thermal history of the universe, big bang nucleosynthesis , microwave background
- Brief introduction to structure formation

[7 hours - [13]: `chapters 17, 18,19; [8]: chapters 10,11,14`]

2 Radiative Processes in Astrophysics: PH 362, 2:0 credits (30 hours)

Radiation transfer: Definitions of specific intensity, mean intensity, flux and energy density; Equation of radiation transfer; solutions in some specific cases, optical depth; Thermal emission; Blackbody spectrum and its characteristics; Kirchoff's law; Einstein coefficients

[5 hours - `[25]: chapter 1`]

Radiation fields: Review of Maxwell's equation, Poynting theorem; Electromagnetic potentials; Green function in Lorentz gauge; Retarded potentials; Fields in near zone and at far distances; Radiation from non-relativistic particles (Larmor's formula); Dipole approximation; Spectrum of dipole radiation; Scattering of EM waves, Thomson scattering, scattering by a bound charge; Polarisation; Stokes parameters

[5 hours - `[25]: chapter 2`]

Relativistic effects on radiation: Review of Lorentz transformation of E and B fields; Radiation from relativistic particles; Angular distribution of emitted power; Invariant phase volumes and specific intensity

[3 hours - `[25]: chapters 3, 4`]

Bremsstrahlung: Thermal Bremsstrahlung; free-free absorption; examples from astrophysics

[2 hours - `[25]: chapter 5`]

Synchrotron radiation: Motion of charged particle in uniform B field; spectrum of synchrotron radiation; difference between cyclotron and synchrotron radiation; angular distribution and polarization; radiation from non-thermal electrons; synchrotron loss time; *minimum energy estimates*; synchrotron self-absorption

[5 hours - `Rybicki : chapter 6`]

Compton scattering: Energy transfer from electrons at rest; Inverse Compton scattering; Scattered power and spectrum; Inverse Compton loss time scale; Comptonization; *Basics of Sunyaev-Zeldovich effect*; maximum brightness temperature

[5 hours - `[25] : chapter 7`]

Plasma effects: Cerenkov radiation; EM wave propagation in magnetised plasma: Dispersion relation, Faraday rotation

[2 hours - `[25] : chapter 8`]

Atomic structure: Selection rules, *Milne relation for recombination coefficients*; Line broadening, Doppler broadening, natural broadening, collisional broadening and Voigt profile; *curve of growth*

[3 hours - `[25] : chapters 9, 10`]

3 Introduction to Fluid Mechanics and Plasma Physics, PH 363, 2:0 credits (30 hours)

Introduction to fluids (3 hours):
Fluids as continuous medium with length and times scales > mean free path and collision times. Local thermal equilibrium, pressure $p = p(\rho; s)$; e.g. perfect gas equation of state. Flow and velocity field, convective derivative. Equations of fluid dynamics (mass, momentum and entropy) for ideal fluids. Condition on equation of state for hydrostatic equilibrium.
Worked examples: Hydrostatic equilibrium of plane-parallel atmosphere; isothermal atmosphere and scale length. Convective instability and Schwarzschild's criterion.

Elementary properties of flows (5 hours)
Equations of fluid dynamics in conservation form, conserved flux densities in steady flow. Streamlines and Bernoulli's equation with applications (e.g. lift on a 2-dimensional aerofoil; small-Mach no. condition for flow to be nearly incompressible). Vorticity, Kelvin's circulation theorem, vorticity conservation in 2-dim flows, vortex stretching in 3-dim flows. Rotating fluids: Coriolis force, geostrophic flows.
Worked/Home examples: Solar Wind and Bondi accretion/Accretion disc, von Ziepel's theorem, Taylor-Proudman theorem.

Linear Waves and Instability (3 hours):
Sound waves: wave equation, dispersion relation and general solution of initial value problem. Gravity waves: consider one fluid on top of another with both fluids moving with different horizontal speeds in the same direction; derive the dispersion relation; discuss internal and surface gravity waves, Rayleigh-Taylor & Kelvin-Helmholtz instabilities (see section 1.4 of [11])
Home work: Inertial waves in a steadily rotating flow.

Navier-Stokes equation (3 hours):
Non ideal fluids: discuss at elementary kinetic theory level the origins of dissipation and transport, viscosity as energy dissipation and momentum transport. Motivate derivation of Navier-Stokes equation. Derive equation for viscous energy conservation and entropy production. Order-of-magnitude discussion of boundary layers. Scaling in the NS equations: Reynolds number, order-of-magnitude discussion of Stokes flow past a sphere at low Re, transition to turbulence, phenomenological treatment of Kolmogorov cascade.
Home work: Stokes flow past a sphere at low Re.

Supersonic flow (4 hours):
De-Laval nozzle, shock formation, shock thickness and viscosity, Rankine-Hugoniot jump conditions. Brief discussion of cooling and cooling length, isothermal shocks. Order-of-magnitude discussion of Sedov-Taylor blast wave. Application to supernova shocks, discussion of adiabatic and momentum conserving phases of evolution.
Home work: Riemann invariants in 1-dim flows. Full solution of Sedov-Taylor.

Convection (2 hours):
Thermal diffusivity and its effect on the entropy equation. Conductive and convective transport of heat equation. Mixing length theory and transport of heat, application to plane-parallel atmospheres and stars.
Home work: Rayleigh-Benard convection.

Introduction to Plasmas (3 hours):
Particle orbit theory and adiabatic invariants. 2-component plasmas. Debye shielding and length in a plasma in thermal equilibrium. Cold plasma oscillations.

Magnetohydrodynamics (5 hours):
Derivation of induction equation, magnetic diffusion, flux freezing. Lorentz force and momentum

equation. Alfvén, fast and slow waves. Elements of dynamo theory.
Worked examples: Parker spiral, Pulsar magnetospheres, Magnetorotational instability.

Collisionless plasmas (2 hours):
Coulomb collision times. 6-dim phase space, distribution functions. Vlasov equation. Landau damping.
Worked example: Connections with stellar systems.

Recommended references: [7], [18], [1], [6], [17], [2].

4 Galaxies and the Interstellar Medium: PH 365, 3:0 credits (45 hours)

Milky Way Galaxy (5 hours):

- Concept of MW as a galaxy: star counts, Kapteyn universe, Shapley's determination of the centre of the MW; Shapley-Curtis debate [`[3]: chapter 1.2`]
- The Milky Way as seen at various wavelengths; structure of the MW, typical scales of length, mass and stellar/gas; major constituents– dark matter, different stellar populations, interstellar medium– different components, brief introduction to the cycle of ISM-stars-ISM
- Kinematics: radial and tangential velocity measurements, stellar kinematics, rotation curve of the MW using the terminal velocity at tangent-point, evidence for dark matter [`[3]: chapter 10.6`]
- Disc scale length and height; disc sub-populations (thin/thick disc stars); spiral arms, winding dilemma, spiral density waves, pattern speed (estimation from locations of open clusters) [`[4]: chapter 6.2; [3]: chapter 10.4`]
- Galactic spheroid: globular clusters, bulge, stellar motions [`[3]: chapter 10.2`]
- Central black hole, its mass and observations of orbits of nearby stars

Physics of stellar systems (4 hours) :

- Open clusters, globular clusters and the galaxy itself are examples of 'stellar systems'; crossing time; mean potential and total potential energy in a constant density sphere; equation of motion of N-body stellar system; total momentum, angular momentum and energy as constants of motion
- Virial theorem for stellar systems, mass estimate [`[4]: chapter 4.8`]
- Collisions in stellar systems, relaxation time scale, estimates for open cluster, globular cluster, galaxy; *Ambartsumian's model of collisional evolution of open clusters* [`[4]: chapter 1.2`]

Morphology of galaxies (4 hours):

- The Hubble sequence, the galaxy luminosity function, the Local Group.
- Photometry of elliptical galaxies, shapes of elliptical galaxies, correlations among global parameters of elliptical galaxies
- Photometry of disk galaxies, bulge-disk decomposition, colour and metallicity gradients, spiral structure, barred galaxies

[`[3]: chapter 4; [4]: chapter 1.1`]

Description of stellar systems (7 hours):

- Galaxies as collisionless stellar systems, distribution function (DF) in 6-dim, collisionless Boltzmann equation (CBE) [`[4]: chapter 4.1`]
- Potential theory: spherical density distribution, potential-density pairs (Henon isochrone, Plummer models, etc) [`[4]: chapters 2,3 `]

- Jeans theorem and collisionless equilibria, isotropic DF (f(E))– isothermal, king model (and other useful models such as Hernquist, Jaffe, isochrone), non-spherical mass distribution (Kuzmin disc) [[4]: chapter 4.8]
- Axisymmetric systems, DFs of the form f(E, L_z), Schwarzschild DF as a model of the solar neighbourhood, comparison with observations [[4]: chapter 4.4]
- Orbital structure in a spherically symmetric potential– rosette orbits, radial and angular periods, axisymmetric potentials in the limit of near-circular orbits, radial and angular frequencies, Oort constants A and B, and their determination from stellar kinematics [[4]: chapters 3.2, 3.3; [3]: chapter 10.3]
- Mergers and dynamical friction [[4]: chapters 8.1. 8.5; [3]: chapter 4.6.1]
- Globular clusters [[3]: chapter 4.5; [4]: chapter 7.1]

Active galaxies (5 hours): Observational properties and types of AGNs, The black hole paradigm, Radio emission– 'radio galaxies', Optical and high energy emission, Unification scheme [[16]: chapters 1,4,8,9,10,12]

Clusters of galaxies (2 hours): Dynamics and mass estimate; morphology-density relation; intra-cluster gas, cooling flow, Sunyaev-Zeldovich effect [[20]: chapters 4.1-4.3]

Intergalactic medium (1 hour): Absorption systems, the Gunn-Peterson effect [[20]: chapter 19; [22]: chapter 2.8]

Formation and evolution of galaxies (2 hours): Observational constraints; Lyman break galaxies; red/blue sequence, importance of cooling, origin of angular momentum [[20]: chapter 20; [22]: chapters 2.6, 8]

Interstellar medium (15 hours)

- How ISM is detected: absorption of starlight, optical emission [[3]: chapter 8.1]
- microscopic processes: collisional processes, typical cross-sections and rates; equilibria, line excitation [[10]:chapter 2]
- HII regions; forbidden lines, thermal and ionization equilibrium, early dynamics of HII regions, Photo-dissociation regions [[10]: chapter 27]
- HI 21 cm radiative processes [[10]:chapter 8]
- shocks– late time dynamics of HII regions, evolution of supernova remnants, stellar winds [[10]: chapters 36-39]
- physics of dust grains ([10]: chapters 21-26]
- two phase model of ISM, introduction to three phase model [[10]: chapter 30]

5 General Relativity and Cosmology: PH 371 3:0 (21+24=45 hours)

Review of Special Relativity (SR): Invariance of interval, Lorentz transformations; four vectors; *relativistic action and* equations of motion; energy and momentum in SR; stress-energy tensor in SR [3 hours, `[28]: chapter 2, § 1-8, 10`]

General Theory of relativity: Equivalence principle; freely falling observers as inertial observers; need for arbitrary coordinate transformations for description of physics in an arbitrary gravitational field; introduction to metric; general covariance and the notion of contravariant and covariant vectors; equations of motion *using the action principle*; geodesic equation for massive particles, Christoffel symbols [7 hours, `[28]: chapter 3, § 1-4, § 1-9`, `Classical Theory of Fields, Landau and Lifshitz (LL): chapter 10`]

Applications of Schwarzchild metric: gravitational redshift; *event horizon*; effective potential, particle orbits; precession of orbits, case of mercury; geodesic equation for massless particles: bending of light [5 hours, `[28]: chapter 3, § 5, chapter 8, § 1-7; [13]: chapter 14`]

Curvature of space-time; energy-momentum tensor and Einstein equations; weak field limit of gravity; gravitational waves; Hulse-Taylor pulsar as a test of GR. `Double pulsar system as a test of GR` [3 hours, `[28]: chapter 6, § 1-5, chapter 7: § 1-2, chapter 10: § 1-3; [19]: chapter 13, [13]: chapter 21`]

Black holes in astrophysics: black hole at the centre of Milky Way; Accretion discs around black holes, energy extraction, efficiency; observational evidence (3 hours, `[13]: chapters 13, 15; [12]`)

Background Cosmology: Hubble's law; homogeneous and isotropic universe; Newtonian cosmology; generalization to the FRW metric [3 hours, `[28]: chapter 14, § 1-6`]

Einstein's equations for FRW universe; the average density of universe; notion of critical density deciding the geometry of the universe; contents of the universe; need for dark matter; cosmological redshift; look back time; age of the universe; distance measures in an expanding background; observational evidence (observations of SN Ia); accelerating universe; dark energy [3 hours, `[28]: chapter 15, § 1-3`, research papers]

Schematic thermal history of the universe; phase space distribution function; thermodynamics in early universe; origin of dark matter; neutrinos as dark matter [3 hours, `[15]: chapters 3,5`]

Nucleosynthesis in the early universe; cosmic background radiation and the epoch of recombination; inflationary universe [2+1+1 hours, `[15]: chapters 4, 8; Weinberg; [23]`]

Structure formation in the universe; Newtonian perturbation theory, Zel'dovich approximation, spherical top-hat collapse [4 hours, `[24], chapter 2`; `[23]`]

Density perturbations as a Gaussian stochastic process; evolution of the two-point correlation function and power-spectrum [2 hours, `[24], chapter 3`]

Comparison with observations: galaxy power spectrum—evolution and Baryon Acoustic Oscillations First light in the universe; reionization of the universe; Gunn-Peterson test; *quasars as probes of the epoch of reionization* [1+1+1 hours, `[9]: chapter 10, PC, chapter 24`]

CMB anisotropies: Theory and observational evidences [2 hours, `[9]: chapters 3-9` and research papers]

6 Astronomical Techniques: PH 377 0:2 (9 hours + project)

Introductory Talks (9 hours):

- **Optical/UV/IR:** Brief historical account; Introduction to the idea of multiwavelength astronomy; Importance of visible/UV/IR observations from astrophysics point of view; Basics of telescope - collecting area, field of view, diffraction limit/resolution, seeing; Basics of detectors; Fundamental Techniques: Photometry, Spectroscopy, Timing and Polarimetry; Current research activities and upcoming instruments in visible/UV/IR. (3 hours)

- **Radio Astronomy:** History of Astronomical observations in radio; Importance of radio observations from astrophysics point of view; Fundamental Techniques used in radio: Imaging, Spectroscopy, Timing and Polarimetry; Single dish and Array Telescopes; Aperture synthesis; Current research activities and upcoming instruments. (3 hours)

- **High Energy Astronomy:** History of Astronomical observations in X-ray and gamma-ray; Importance of high energy observations from astrophysics point of view; Fundamental Techniques used X-rays and gamma rays: Imaging, Spectroscopy, Timing and Polarimetry; Current developments and upcoming facilities. (3 hours)

[`useful references: https://science.nrao.edu/opportunities/courses/era, http://gmrt.ncra.tifr.res.in/gmrt_hpage/Users/doc/WEBLF/LFRA/index.html, [27], [14]`]

Hands on experience:

- **Visit to facilities:** One and half day trip to the Vainu Bappu Observatory; One and half day trip to the Gauribidanur Observatory; Day trip to the ISRO Satellite Centre.

- **Project:** One semester project to be designed to offer exposure to the details of some of the techniques in one of the above three based on data analysis or instrumentation.

References

[1] Acheson: Elementary Fluid Dynamics

[2] R. Blandford & K. Thorne: Application of Classical Physics; `http://www.pma.caltech.edu/Courses/ph136/yr2011/`

[3] J. Binney & M. Merrifield: Galactic Astronomy

[4] J. Binney & S. Tremaine: Galactic Dynamics

[5] Carroll B. W. & Ostle, D. A.: An introduction to Modern Astrophysics, Pearson Education-Addison Wesley, 2007.

[6] F. F. Chen: Introduction to Plasma Physics and Controlled Fusion

[7] A. Rai Choudhuri: The Physics of Fluids and Plasmas

[8] A. Rai Choudhuri: Astrophysics for Physicists

[9] S. Dodelsen: Modern cosmology

[10] B. Draine: Physics of the Interstellar and Intergalactic Medium

[11] P. G. Drain & W. H. Reid: Hydrodynamic stability

[12] Frank, King, Raine: Accretion power in astrophysics

[13] James B. Hartle. San Francisco, CA, USA: Addison Wesley

[14] C. R. Kitchin: Astrophysical Techniques

[15] E. Kolb & M. S. Turner: The early universe

[16] J. Krolik: Active Galactic Nuclei - From the Central Black Hole to the Galactic Environment (Princeton Series in Astrophysics)

[17] R. Kulsrud: Plasma Physics for Astrophysics

[18] Landau & Lifshitz: Fluid Mechanics

[19] Landau & Lifshitz: The classical theory of fields

[20] M. S. Longair: Galaxy formation

[21] D. Maoz: Astrophysics in a nutshell, Princeton University Press, 2006

[22] H. Mo, F. van den Bosch, S. White: Galaxy formation and evolution

[23] P. J. E. Peebles, Physical cosmology

[24] P. J. E. Peebles, The large scale structure of the universe

[25] G. Rybicki & A. Lightman: Radiative Processes in Astrophysics

[26] F. Shu: The Physical Universe: An Introduction to Astronomy (Series of Books in Astronomy)

[27] A. R. Thompson, J. M. Moran and G. W. Swenson: Interferometry and Synthesis in Radio Astronomy

[28] S. Weinberg: Gravitation and Cosmology