

# Proposed revised syllabus for IUCAA Graduate School

The list of all courses for **Ph.D. Graduate School** is given below. Numbers in square brackets indicate total credits for each course.

## Core courses:

1. Introduction to Astronomy & Astrophysics [4]
2. Radiative Processes [4]
3. Astronomical Techniques [4]
4. General Relativity - I [2]
5. Research Methodology [2]
6. Fluids & Plasmas - I [2]
7. Galaxies & ISM - I [2]
8. High Energy Astrophysics - I [2]
9. Cosmology - I [2]
10. Research & Publication Ethics [2]

## Project [4]

## Elective courses:

1. Computational Astrophysics [2]
2. Fluids & Plasmas - II [2]
3. Galaxies & ISM - II [2]
4. High Energy Astrophysics - II [2]
5. General Relativity - II [1]
6. Cosmology - II [1]
7. Compact objects [1]
8. Solar and Heliospheric Physics [1]
9. Astrophysics Lab - I [2]
10. Astrophysics Lab - II [2]

## Remedial Modules:

1. Electrodynamics
2. Quantum Mechanics
3. Statistical Mechanics

*N.B: Students must complete project credit requirements as described in the detailed Course Structure.*

# Course-wise Detailed Syllabus

## 1. Introduction to Astronomy & Astrophysics

4 credits

**Astronomical Measurements:** celestial sphere, RA/DEC coordinates, Galactic coordinates, luminosity/flux magnitude scale, apparent/absolute magnitude, electromagnetic wavebands, spectroscopy, Astronomical Unit, parsec, standard candles, distance measurement by geometric means (parallax, distances to open clusters), radial velocity, binaries (visual, eclipsing, spectroscopic)

**Radiation:** radiative transfer equation and line formation, opacity and extinction, photon diffusion and scattering, LTE, departure from LTE

**Sun and solar system:** Sun as a star (qualitative): Solar spectrum, photospheric absorption lines, limb darkening; energy source: Kelvin time scale, nuclear fusion; energy transport - radiation and convection; photosphere, chromosphere, transition region, corona; X-ray emission, magnetic fields, Sunspots

**Planets and extrasolar planets:** Different types of planetary system; Detection mechanism of extrasolar planets; concept of orbital resonance

**Stellar structure and evolution:** Observed stellar properties: stellar classification based on spectra, HR diagram, main sequence, luminosity dependence on mass, Saha ionisation equation, and star clusters; Stellar models: hydrostatic equilibrium, gas/radiation pressure; theoretical main sequence: 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, CNO cycle, triple alpha reaction, nuclear resonances and elementary particle production; Pre-main sequence evolution: Jeans instability, star formation, Initial Mass Function, Hyashi track, massive stars; Post-main sequence evolution: Core He burning, shell burning, red giant phase, stellar winds, Parker's model for solar wind, planetary nebulae, compact objects (white dwarfs, neutron stars & pulsars, black holes); Binary system evolution: effective potential in rotating frame, Lagrange points, Roche lobe, mass overflow, Type Ia supernovae, X-ray binaries and accretion disk

**Extragalactic astronomy:** Inter-stellar medium (ISM): Multi-phase structure, HII region, heating and cooling mechanisms, dust and molecular clouds, basics of Circumgalactic medium; Galaxies: morphology, surface brightness profiles, colour-magnitude diagram, stellar population, kinematics, high redshift galaxies, Active galaxies; Cosmology & Structure Formation: groups, clusters and filaments, Big Bang nucleosynthesis, CMB, thermal history

*Reference books:*

- 1) The Physical Universe: An Introduction to Astronomy: Frank H. Shu
- 2) Observational Astrophysics: Robert C. Smith
- 3) An introduction to Modern Astrophysics: B. W. Carroll, D. A. Ostle
- 4) Theoretical astrophysics. Vol.1: Astrophysical processes: T. Padmanabhan
- 5) Methods of celestial mechanics: D. Brouwer, G. M. Clemence
- 6) Envisioning Exoplanets: Searching for Life in the Galaxy: Michael Carroll
- 7) An introduction to the study of stellar structure: S. Chandrasekhar
- 8) The Sun: An Introduction: Michael Stix (2004 edition).
- 9) Stellar structure and evolution: R. Kippenhahn and A. Weigert
- 10) Black holes, white dwarfs, and neutron stars: the physics of compact objects: S.L. Shapiro and S. A. Teukolsky
- 11) Galaxies and the universe: Allan Sandage, Mary Sandage, Jerome Kristian
- 12) Nucleosynthesis and Chemical Evolution of Galaxies: Bernard E. J. Pagel
- 13) Principles of Physical Cosmology: P.J.E. Peebles

## **2. Radiative Processes**

*4 credits*

**Radiative Transfer:** Specific intensity and its moments, optical depth and radiative transfer - simple approximate solutions, Thermal Radiation and Local Thermodynamic Equilibrium, scattering effects, radiative diffusion.

**Basic theory of radiation fields:** electromagnetic waves, radiation spectrum, polarisation and Stokes parameters, geometrical optics

**Radiation from non-relativistic moving charges:** Single moving charges - Lienard-Wiechart potentials, velocity and radiation fields; radiation from non-relativistic system of particles, radiation reaction, radiation from harmonically bound charges.

**Continuum radiation:** Bremsstrahlung, Cyclotron and Synchrotron radiation, Comptonisation, Cerenkov radiation, Curvature radiation, plasma effects.

**Attenuation of radiation:** interaction of radiation with atoms, molecules and dust grains - reddening and extinction curves (Galactic, SMC/LMC, Starbursts), interaction of high energy radiation with matter - photoelectric absorption, Thomson and Compton scattering, pair production and pair annihilation, polarization.

*(Note: Astrophysical application should be included wherever possible.)*

*Reference books:*

- 1) Radiative Processes in Astrophysics: G. B. Rybicki, A. P. Lightman
- 2) High Energy Astrophysics: Longair, Malcolm S.

- 3) Classical Theory of Fields: L. D. Landau, E. M. Lifshitz
- 4) Astrophysics of Gaseous Nebulae and Active Galactic Nuclei: D. E. Osterbrock, G. J. Ferland

### 3. Astronomical Techniques

4 credits

Celestial sphere, astronomical coordinates and time

Astrophysical information carriers and their importance: Electromagnetic radiation, neutrinos and cosmic rays, gravitational waves

Earth's atmosphere: Effects at different bands, Extinction and reddening, ground and spaced-based telescopes

Optical/UV/IR: Telescopes: collecting area, field of view, diffraction limit, seeing and point spread function; Detectors: Turbulent atmosphere and adaptive optics; Techniques: Photometry, Spectroscopy, Timing and Polarimetry; Major Telescopes in visible/UV/IR.

Radio Astronomy: Basic Fourier optics; Signal detection at radio wavelengths - dipoles, phased arrays and single dish; Two element interferometer and aperture synthesis; Antenna electronics (LO and digitizer); Correlator and beamformer; Calibration - Hamaker-Bregman-Sault measurement equation; Imaging and deconvolution; Time domain astronomy; Polarimetry.

High Energy Astronomy: Detectors and Telescopes: X-ray/gamma-ray detectors; Source localization - collimators, coded-aperture masks, X-ray optics; Techniques: Imaging, Spectroscopy, Timing, Polarisation (optional); Major Telescopes in X-ray/gamma-ray.

**Gravitational waves**: Observational methods for gravitational waves, Michelson and Fabry Perot interferometers, Effect of gravitational waves on matter and corresponding response of a Michelson interferometer (optional), Ground-based laser interferometers as gravitational wave detectors - choice of various parameters, namely, arm length, mirror mass, laser power, vacuum level, suspensions and seismic isolation.

*Reference books:*

- 1) Astronomical Optics: D. J. Schroeder
- 2) Optical, Infrared and Radio Astronomy: From Techniques to Observation: R. Poggiani
- 3) Physical principles of Astronomical Instrumentation: Ade, Griffin, Tucker
- 4) Observational Astrophysics: P. Léna (Author), D. Rouan, F. Lebrun, F. Mignard, D. Pelat
- 5) High Energy Astrophysical Techniques: R. Poggiani
- 6) Handbook of X-ray Astronomy: Edited by K. Arnaud, R. Smith, A. Siemiginowska
- 7) The fourier transform and its applications: Ronald N. Bracewell

- 8) Tools of radio astronomy: Thomas L. Wilson , Kristen Rohlfs , Susanne Hüttemeister
- 9) Interferometry and Synthesis in radio astronomy: A. Richard Thompson , James M. Moran , George W. Swenson Jr.
- 10) Fundamentals of Interferometric Gravitational Wave Detectors, 2nd Edition, Peter Saulson, World Scientific (2017)
- 11) General Relativity and Gravitational Waves: Essentials of Theory and Practice, Dhurandhar & Mitra, Springer (2022)

#### **4. General Relativity - I**

*2 credits*

Equivalence principle and physical basis for GR

Tensor analysis

Geodesics, connection and curvature

Energy-momentum tensor

Einstein equations

Schwarzschild metric: orbits and classical tests of GR

Linearized gravity

*Reference books:*

- 1) A First Course in General Relativity: B. Schutz
- 2) Gravity: An Introduction to Einstein's General Relativity: J. Hartle
- 3) Gravitation: C. W. Misner, K. S. Thorne, J. A. Wheeler
- 4) A Relativist's Toolkit: E. Poisson

#### **5. General Relativity - II**

*1 credit*

Gravitational waves

Black holes and event horizons

Action principle approach to gravitation

Basic differential geometry

Introduction to numerical relativity

*(Gravitational waves will be included each year. Any 1 or 2 of the remaining topics will be included in any given year.)*

*Reference books:*

- 1) Gravitation: C. W. Misner, K. S. Thorne, J. A. Wheeler
- 2) The Classical Theory of Fields: L. D. Landau, E. M. Lifshitz
- 3) Numerical Relativity: T. W. Baumgarte, S. L. Shapiro
- 4) The Mathematical Theory of Black Holes: S. Chandrasekhar

## 6. Research Methodology

*2 credits*

Probability and Statistics: discrete and continuous distributions, Bayes' theorem, moment and cumulant generating Functions, multivariate Gaussian statistics, non-Gaussian distributions, Central Limit Theorem

Python revision: Numpy and Scipy, data structures and precision

Random number generation

Statistical tests of randomness: Kolmogorov-Smirnov, Chi-squared, mean and variance of a data set

Basic parameter inference: least squares fitting, linear Gaussian problem in Bayesian framework, model comparison theory

Differential equations: basic finite differencing schemes, implementation of one of the methods [*first and second order Runge Kutta, Crank Nicholson*], PDE solvers, implementation of one of the methods [*method of characteristics, LAX*]

Fourier techniques: FFT and DFT

*Reference books:*

- 1) Data Reduction and Error Analysis: P. R. Bevington, D. K. Robinson
- 2) Probability, Random Variables and Stochastic Processes: A. Papoulis, S. U. Pillai
- 3) The Art of Computer Programming, vol.1: fundamental algorithms: D. E. Knuth
- 4) Numerical Methods that (usually) Work: Forman S. Acton
- 5) Numerical Recipes: W. H. Press, B. P. Flannery, S. A. Teukolsky, W. T. Vetterling
- 6) [Bayesian methods in Cosmology](https://arxiv.org/pdf/1701.01467.pdf): Roberto Trotta, online notes - <https://arxiv.org/pdf/1701.01467.pdf>
- 7) The Fourier Transforms and its Applications: Ronald N. Bracewell

## 7. Computational Astrophysics

*2 credits*

Numerical implementations of basic linear algebra: matrix inversion, LU and singular value decompositions

Parameter inference and model comparison: bootstrapping, Markov Chain Monte Carlo techniques, nested sampling, MCMC implementations using open-source packages, e.g., Cobaya + GetDist, EMCEE

Timing Analysis: power spectrum, bispectrum, cross-spectrum, cepstrum, wavelets

Computation of gravitational forces: particle-mesh approach, tree algorithm, Tree-PM algorithm

N-point statistics of discrete data sets: estimators of 2-point function, brief discussion of 3-point function

HPC @ IUCAA (by sysadmin staff): practical aspects, concept of multithreaded computation, shared vs distributed memory architecture

*(3 to 4 of the above topics will be included in any given year.)*

*Reference books:*

- 1) Numerical Methods that (usually) Work: F. S. Acton
- 2) Numerical Recipes: W. H. Press, B. P. Flannery, S. A. Teukolsky, W. T. Vetterling
- 3) [Bayesian methods in Cosmology](#): Roberto Trotta, online notes - <https://arxiv.org/pdf/1701.01467.pdf>
- 4) The Fourier Transforms and its Applications: Ronald N. Bracewell
- 5) [Invitation to the Bispectrum](#): M. Wolinsky, online notes - [https://web.iucaa.in/~dipankar/CMA2020/MF\\_files/Invitation\\_to\\_the\\_Bispectrum.pdf](https://web.iucaa.in/~dipankar/CMA2020/MF_files/Invitation_to_the_Bispectrum.pdf)
- 6) Wavelet Methods for Time Series Analysis: D. B. Percival & A. T. Walden (e-book accessible from IUCAA)
- 7) Computer Simulation Using Particles: R. W. Hockney, J. W. Eastwood

## 8. Fluids & Plasmas - I

*2 credits*

### Ideal Fluids:

Definition of fluid as continuum, mean free path, collision time, local thermal equilibrium, perfect gas equation of state, convective/Lagrangian derivative, Euler equation, fluid equations in conservation form, vorticity, circulation theorems, Hydrostatic equilibrium of plane parallel atmosphere: isothermal, isentropic; Fluid equations in rotating reference frames

### Linear Waves and Instability:

Sound, Internal gravity, Surface gravity, Schwarzschild criterion for convective instability, Rayleigh-Taylor and Kelvin-Helmholtz instabilities, Jeans instability

### Non-ideal fluids:

Energy equation, Navier-Stokes equations, Boundary layers, Reynolds number, Stokes flow, Molecular origin of viscosity

### Turbulence:

transition to turbulence, homogeneous and isotropic turbulence: Kolmogorov (K41) phenomenology

### Supersonic Flows:

Hydrodynamic shocks, Rankine-Hugoniot jump conditions

**Plasma:** Definitions of cold and warm plasmas, Plasma orbit theory: magnetic mirrors, gradient drift, curvature drift, 2-component plasmas, Debye length, Cold plasma oscillations

**Kinetic theory:** Distribution functions, Vlasov Equation, Landau Damping (collisionless plasma)

**Magnetohydrodynamics:** regime of its validity, induction equation, flux freezing, MHD waves

**Solar winds:** Parker spiral

### *Reference books:*

- 1) Elementary Fluid Dynamics: D J Acheson
- 2) Physics of Fluids and Plasmas: A R Choudhuri
- 3) Fluid Mechanics: Landau & Lifshitz
- 4) Physics of Plasmas: T J M Boyd & J J Sanderson
- 5) Introduction to Plasma Physics and Controlled Fusion: F F Chen
- 6) Magnetohydrodynamics (of Laboratory and Astrophysical Plasmas): H Goedbloed, R Keppens, S Poedts
- 7) Principles of Astrophysical Fluid Dynamics: C Clarke & B Carswell
- 8) Astrophysical Flows: J Pringle & A King

## 9. Fluids & Plasmas - II

*2 credits*

Viscous flows with heat conduction

Rotating flows: geostrophic flows, Taylor-Proudman theorem, Rossby waves, Ekman Pumping

Couette flow: Rayleigh's criterion

Sedov-Taylor blast wave

Convection: Rayleigh-Benard convection, mixing length theory, Solar convection (conundrum)

Turbulence: structure functions, intermittency, turbulent viscosity

Relativistic dynamics of a perfect fluid, shock waves in relativistic flows

Magnetorotational instability: Shakura-Sunyaev alpha-viscosity for accretion

Cowling's anti-dynamo theorem, Astrophysical dynamo: elementary turbulent dynamo theory (alpha-squared)

magnetic reconnection: Sweet-Parker model

Elementary aspects of MHD turbulence

Radiation Hydrodynamics and GRMHD

*(First 4 topics will be included each year. Any 2 or 3 of the remaining topics will be included in any given year.)*

### *Reference books:*

- 1) Fluid Mechanics: Landau & Lifshitz
- 2) Modern Classical Physics: K S Thorne & R D Blandford
- 3) Plasma Physics for Astrophysics: R M Kulsrud
- 4) Magnetohydrodynamics (of Laboratory and Astrophysical Plasmas): H Goedbloed, R Keppens, S Poedts
- 5) Principles of Astrophysical Fluid Dynamics: C Clarke & B Carswell
- 6) Astrophysical Flows: J Pringle & A King
- 7) Foundations of Radiation Hydrodynamics: D Mihalas & B Mihalas

## 10. Galaxies & ISM - I

2 credits

Milky Way and its neighbourhood: Basic structure of our Galaxy, solar neighbourhood, Andromeda and their satellites e.g., LMC, SMC

Galaxy morphology: Classification of galaxies: spirals, ellipticals, lenticulars, irregulars, dwarfs, peculiar galaxies; Active galactic nuclei, Hubble sequence and Hubble Types; Methods of galaxy classification: visual inspection, colour-based

Photometry and Surface Brightness distribution: Basic filter system; photometry; Point spread function; Surface brightness profiles: radial and vertical; colors, colour-bimodality, colour-magnitude diagram

Stellar population: Simple stellar population models; mass-to-light ratio estimation; stellar mass estimation

Potential of galaxies: Solving Poisson equation for spherical galaxy models; Kuzmin disk and exponential disk models

Kinematics: Galaxy spectra; Rotation curve - ionized gas and stellar rotation, cold HI 21 cm, CO rotation; Modelling dark matter profiles; stellar velocity dispersion and its measurement.

Interstellar medium (ISM) Overview: Multi-phase structure of ISM

Basics of interstellar dust: Extinction and reddening of star light; Galactic reddening correction, extinction curve

HII regions: Ionization structure: static; heating and cooling; Nebular diagnostic: BPT diagram; Hot gas: heating and cooling curve

HI clouds: Two-phase medium: 21 cm line; HI distribution: in-plane and perpendicular to the plane - bending and breathing waves, corrugation

*Reference books:*

- 1) Galaxies in the Universe: An Introduction: L. S. Sparke, J. S. Gallagher
- 2) Galactic Astronomy: Binney, Merrifield
- 3) Theoretical Astrophysics Vol. 3, Galaxies & Cosmology: T. Padmanabhan
- 4) Galaxy Formation and Evolution: H. Mo, F. van den Bosch, S. D. M. White
- 5) Galactic Dynamics: Binney, Tremaine
- 6) Galaxies and cosmology: F. Combes, P. Boisse, A. Mazure, A. Blanchard, M. Seymour
- 7) Physical Processes in the Interstellar Medium: L. Spitzer Jr.

- 8) Astrophysics Of Gas Nebulae and Active Galactic Nuclei: D. E. Osterbrock, G. J. Ferland
- 9) Physics of the Interstellar and Intergalactic Medium: B. T. Draine

## 11. Galaxies & ISM - II

*2 credits*

**Galaxies as Collisionless system:** Stellar encounters; Concept of relaxation and its time scale for different stellar systems. Jeans theorem and its application; moments of CBE - Jeans equation, tensor virial theorem and their application to galaxies; Dynamical friction and its application

**Galaxy environment:** Local group and beyond; groups and clusters of galaxies; filament and voids. Tidal interaction and application to binary galaxy interaction; Impact of environment on galaxy properties

**Galaxy morphology:** Quantitative morphology; morphology density relation and its application to nearby cluster of galaxies; Galaxy luminosity function

**Stellar population and stellar mass:** Spectra energy distribution (SED) and its modelling. Star formation rate and star-formation history; Star-formation law

**Scaling relations:** Tully-Fisher relation, Faber-Jackson relation; Kormendy relation; Fundamental plane relation

**Kinematics and dynamics of Galaxies:** Stellar orbits; Schwarzschild modelling; Disk dynamics. Bars and spiral structures, disk instability.

**Galaxy formation and Evolution:** Angular momentum problem; SMBH-galaxy connection; high-redshift galaxies; top-down and bottom-up scenario

**ISM dust:** Composition and geometry of interstellar dust; extinction curve revisited; Scattering of optical and UV photons by dust grains; emission of infrared, submillimeter, and microwave radiation by dust; the evolution of interstellar dust.

**HII regions:** Ionization structure - dynamics

**Magnetic field:** Faraday rotation; cosmic rays

**Supernovae:** Three phase model; shocks; supernovae remnants; acceleration of cosmic rays by shock waves;

**Nebular diagnostics:** planetary nebulae, chemical enrichment; alpha abundance;

**Gas phase metallicity:** methods to measure metallicity and its distribution in the galaxy

**Molecular hydrogen:** Formation and destruction; UV radiation from OB associations; turbulence in interstellar clouds; giant molecular clouds - star-formation

**Initial Mass Function:** Salpeter, Kroupa; connection to metallicity; massive star formation including Pop-III models.

*(40% of the topics will be included in any given year.)*

*Reference books:*

- 1) Galactic Dynamics: Binney, Tremaine
- 2) Galaxies in the Universe: An Introduction: L. S. Sparke, J. S. Gallagher
- 3) Galactic Astronomy: Binney, Merrifield
- 4) Theoretical Astrophysics Vol. 3, Galaxies & Cosmology: T. Padmanabhan
- 5) Galaxy Formation and Evolution: H. Mo, F. van den Bosch, S. D. M. White
- 6) Galaxy formation: M.S. Longair
- 7) Principles of stellar dynamics: S. Chandrasekhar
- 8) Astrophysics Of Gas Nebulae and Active Galactic Nuclei: D. E. Osterbrock, G. J. Ferland
- 9) Physics of the Interstellar and Intergalactic Medium: B. T. Draine
- 10) The Origin of Cosmic Rays: V. L. Ginzburg and S.I. Syrovatskii

## 12. High Energy Astrophysics - I

*2 credits*

**Introduction to the high-energy sky:** Experimental tools for high energy astrophysics, high energy telescopes, high energy sky, X-ray transients

**Brief review of relevant radiation processes:** (taught as part of Radiative Processes course)

**Accretion of plasma:** Basics of accretion, Eddington limits, Bondi-Hoyle accretion, Roche lobe geometry in binaries and accretion from a companion star, formation of a disk

**High Energy sources:** Cataclysmic variable stars; supernova explosions and supernova remnants; neutron stars, radio pulsars, X-ray pulsars and magnetars; gamma-ray bursts, X-ray binaries with neutron stars and black holes, active galactic nuclei - basic classification.

*Reference books:*

- 1) Exploring the X-ray Universe - Frederick D. Sward, Philip A. Charles
- 2) Introduction to High Energy Astrophysics - Stephan Rosswog, Marcus Brüggen
- 3) High Energy Astrophysics - Fulvio Melia
- 4) High Energy Astrophysics - M. S. Longair

## 13. High Energy Astrophysics - II

*2 credits*

**Active Galactic Nuclei:** central engines, optical/UV emission line regions in Seyferts and quasars, Radio galaxies and blazars, AGN statistics and evolution, Link between AGN and host galaxies.

**Accretion disks:** Standard accretion disks, accretion columns, thick disks, radiatively inefficient flows; Hot corona - physical condition, possible geometries, radiation spectrum, X-ray reflection including relativistic iron line.

**Particle acceleration:** Cosmic ray spectrum, Fermi acceleration processes, highest energy particles, astrophysical sites for particle acceleration: SNR and jets.

**Ejection, outflows and relativistic jets:** applications in X-ray binaries, GRBs and AGNs.

*Reference books:*

- 1) High Energy Astrophysics - M. S. Longair
- 2) Introduction to High Energy Astrophysics - Stephan Rosswog, Marcus Brüggen
- 3) High Energy Astrophysics - Fulvio Melia
- 4) Accretion power in Astrophysics - Frank, King and Raine

## 14. Cosmology - I

*2 credits*

**Expanding Universe:** Cosmological principle, homogeneity and isotropy, maximally symmetric spaces with and without curvature, Friedmann Lemaitre Robertson Walker (FLRW) metric, expansion of the Universe, redshift and distances in an expanding Universe - angular diameter distance, luminosity distance

**FLRW Dynamics:** Einstein tensor of the FLRW metric, Energy-momentum tensor of dust, Friedmann equations, critical density of the Universe, special case solutions, horizons in the Universe, standard model of Cosmology

**Brief thermal history of the Universe from  $T = 1 \text{ GeV}$  to  $T = 900 \text{ K}$ :** number density, energy density, pressure and entropy density of particles in thermal equilibrium, relativistic and nonrelativistic limits, effective number of degrees of freedom and its evolution, particle freeze out, temperature of decoupled relativistic species, cosmic neutrino background, Big Bang nucleosynthesis, Helium abundance, cosmic microwave background (CMB) and discovery of temperature fluctuations

Observational evidence for dark matter: Kinematics of galaxies in galaxy clusters, rotation curves of galaxies, growth of structure.

Structure Formation: Linear growth of perturbations, Nonlinear evolution of perturbations - Zeldovich approximation, spherical top hat, basic idea of simulation results

Brief introduction to physics of galaxy formation

Basic discussion of cosmological observations: geometrical probes, CMB anisotropies, late-time cosmic web, intergalactic medium

*Reference books:*

- 1) An Introduction to Cosmology: J. V. Narlikar
- 2) Cosmology: J. A. Peacock
- 3) Theoretical Astrophysics Vol. 3, Galaxies & Cosmology: T. Padmanabhan
- 4) The Early Universe: E. Kolb, M. Turner
- 5) Physical Cosmology: P. J. E. Peebles

## **15. Cosmology - II**

*1 credit*

Very early Universe and inflation, quantum seeds of perturbations

Models of dark matter

CMB anisotropies and observations

Large-scale structure: cosmic web, halo mass function and 2-point correlation function, large-volume surveys

Gravitational lensing

Galaxy groups, clusters and superclusters

Structure of IGM: Gunn-Peterson effect, quasar absorption systems

High redshift galaxies

Alternatives to standard cosmological model.

*(2 to 3 of the above topics will be included in any given year.)*

*Reference books:*

- 1) Structure Formation in the Universe: T. Padmanabhan
- 2) Modern Cosmology: S. Dodelson
- 3) Galaxy Formation & Evolution: H. Mo, F. van den Bosch, S. D. M. White
- 4) The Large Scale Structure of the Universe: P. J. E. Peebles
- 5) Cosmological Inflation and Large Scale Structure: A. R. Liddle, D. H. Lyth
- 6) An Introduction to Cosmology: J. V. Narlikar

## 16. Compact Objects

1 credit

Brief introduction to compact stars: white dwarfs, neutron stars, black holes.

Stellar collapse and formation of compact stars: nuclear physics of core collapse supernova

Physics of neutron star interior: internal structure and composition, Lane Emden equation, TOV equations, calculation of NS observables

Dense matter equation of state: white dwarfs, neutron stars. Effects of rotation, magnetic fields, superfluidity.

Compact stars as gravitational wave sources: GW from isolated and binary neutron stars, physics of neutron star mergers, multi-messenger signatures

Constraints on equation of state models: multi-messenger data, nuclear experiments and theoretical calculations

*Reference books:*

- 1) Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects: S. L. Shapiro, S. A. Teukolsky
- 2) The Physics and Astrophysics of Neutron Stars: Editors: L. Rezzolla, P. Pizzochero, D. I. Jones, N. Rea, I. Vidana
- 3) Pulsars as Astrophysical Laboratories for Nuclear and Particle Physics: F. Weber
- 4) Compact Stars: Nuclear Physics, Particle Physics, and General Relativity: N. K. Glendenning
- 5) Compact star physics: J. Schaffner Bielich

## 17. Solar and Heliospheric Physics

1 credit

Introduction to the Sun

Solar Interior: energy generation and standard solar model including ZAMS

Solar Radiation Spectrum: Radiative Transfer, formation of absorption and emission lines

Solar Dynamics: Solar Convection: Granulation and reverse granulation; Solar Oscillation and Helioseismology; Solar Rotation; Long-term Variability and Climate

Solar Magnetic Field: Generation and measurements, Zeeman and Hanley Effect, Spectro-polarimetry, Magnetic elements, Sunspots

Chromospheric and Coronal Heating: Different modes of MHD waves, their dispersion relation, Wave dissipation (phase mixing, resonance absorption, MHD Alfvénic turbulence), Braiding of magnetic field and formation of current sheet, ohmic heating, magnetic reconnection

Sun-Earth Connection: CMEs and Space Weather

Explosive and eruptive phenomena: Flares, CMEs, and explosive events (observations and theory), power law distribution of events

Solar Wind: Parker Solution, Fast and slow solar wind, possible origin of wind on the Sun and their signature in heliosphere

*(In a given year, only one of Solar Dynamics or Chromospheric & Coronal Heating will be covered, the other will be given as homework.)*

*Reference books:*

- 1) TBD

## **18. Research & Publication Ethics**

*2 credits*

**Scientific Ethics:** definition, moral philosophy, nature of moral judgements and reactions; Need for responsible research activity

**Scientific conduct and misconduct:** Intellectual honesty and research integrity; Defining problems, formulation of testable hypotheses, exploring alternatives, breaking a problem into parts; Research reports and presentations; Writing observing/funding proposals; collection of data, its management and tagging; conducting collaborative research

**Scientific misconduct:** Falsification, Fabrication, and Plagiarism (FFP) of data; redundant publications; selective reporting of data; plagiarism of ideas

**Publication ethics:** definition, introduction and importance; conflicts of interest; publication misconduct, unethical behaviour in publishing; violation of publication ethics, authorship and contributorship; plagiarism in publications

**Use of Research funds:** responsibilities of scientists, understanding rules for use of public funds, cooperation to ensure proper use of research funds, obtaining corporate social responsibility funds, examples of misconduct

**Quality improvement of research:** Peer review and its role in publication and acceptance of grants, challenges in peer review;

**Raising the alarm on observing scientific or publication misconduct**

**Databases and research metrics:** reviewing literature, accessing journals, impact factor of journals, understanding different research metric indices (h-index, g-index, i10 index, altmetrics)

*References:*

- 1) Bird, A. (2006). *Philosophy of Science*. Routledge
- 2) Macintyre, Alasdair (1967) *A Short History of Ethics*. London
- 3) P. Chaddah, (2018) *Ethics in Competitive Research: Do not get scooped; do not get plagiarized*, ISBN:978-9387480865

- 4) National Academy of Sciences, National Academy of Engineering and Institute of Medicine. (2009). *On Being a Scientist: A Guide to Responsible Conduct in Research: Third Edition*. National Academies Press.
- 5) Resnik, D. 8. (2011). What is ethics in research & why is it important. *National Institute of Environmental Health Sciences*, 1-10. Retrieved from <https://www.oiehs.nih.gov/research/reso~eslbioethics/whatis/index.cfm>
- 6) Beall, J. (2012). Predatory publishers are corrupting open access. *Nature*, 489(7415), 179-179. <https://doi.org/10.1038/489179a>
- 7) Indian National Science Academy (INSA), *Ethics in Science Education, Research and Governance* (2019), ISBN:978-81-939482-1-7. [http://www.insaindia.res.in/pdf/Ethics\\_Book.pdf](http://www.insaindia.res.in/pdf/Ethics_Book.pdf)
- 8) For the Sound Development of Science -The Attitude of a Conscientious Scientist ([https://www.jsps.go.jp/j-kousei/data/rinri\\_e.pdf](https://www.jsps.go.jp/j-kousei/data/rinri_e.pdf))

## 19. Astrophysical Laboratory - I, II

*2 credits (part I), 2 credits (part II)*

A total of 10 experiments will be offered each year, 5 in part I and 5 in part II.

### Experimental subject codes:

1. RA - Radio Astronomy
2. OA - Optical Astronomy
3. GW - Gravitational Waves
4. AI - Astronomical Instrumentation
5. GL - Gravitational Lensing

### List of experiments:

1. RA1: Johnson Noise measurement
2. RA2: Faraday Rotation
3. RA3: Observation of HI Line using a horn antenna
4. RA4: Astronomical data analysis (e.g., ORT observations of Vela pulsar)
5. RA5: Determine the dipole antenna power pattern and sea-cliff interferometry
6. RA6: Characterizing radio telescope receiver chain including LNA, superheterodyne receiver and filters
7. OA1: CCD Characterisation
8. OA2: Determining temperature of an artificial star
9. OA3: Determining temperature of stars
10. OA4: Determining night-sky brightness
11. OA5: Determining atmospheric extinction

- 12. GW1: Suspension damping
- 13. GW2: Dither lock of a laser to a rigid Fabry-Perot Cavity
- 14. AI1: Polarimetry
- 15. AI2: Shack-Hartmann wavefront sensor
- 16. GL1: Mimicking Gravitational lensing using optical lenses

## 20. Remedial Electrodynamics

Principle of relativity; Relativistic mechanics; Charges in electromagnetic (EM) fields; EM field equations; constant EM fields; EM waves; propagation of light; field of moving charges

*References:*

- 1) Classical Theory of Fields: Landau & Lifshitz vol 2. (chs 1-9)

## 21. Remedial Quantum Mechanics

Heisenberg uncertainty principle; Schrodinger's equation; 1-d potentials; Linear algebra, Hilbert spaces; Simple harmonic oscillator; Hydrogen-like atoms; Angular momentum algebra; Identical particles and symmetry, Pauli exclusion; Time-independent perturbation theory, Zeeman effect, Stark effect; Time-dependent perturbation theory, Fermi's golden rule, electric dipole transitions, Selection rules, Decays and lifetime, natural line-width, transition probability, Einstein coefficients.

*References:*

- 1) "Introduction to quantum mechanics", David J. Griffiths, Cambridge University Press
- 2) "Lectures on Quantum Mechanics", Ashok Das, World Scientific
- 3) "Quantum Mechanics Theory and Applications", Ajoy Ghatak and S. Lokanathan, Springer
- 4) "Physics of atoms and molecules", B. H. Bransden and C. J. Joachain, Pearson
- 5) "Modern Quantum Mechanics", J. J. Sakurai, Cambridge University Press
- 6) "The Physics of Astrophysics: Radiation", Frank H. Shu, Univ Science Books
- 7) "Principles of Quantum Mechanics", R. Shankar, Springer

## 22. Remedial Statistical Mechanics

Kinetic theory, Boltzmann equation, H-Theorem. Classical statistical mechanics, microcanonical, canonical, grand canonical ensembles, derivation of thermodynamics. Quantum statistical mechanics, density matrix, Bose and Fermi statistics, ideal gases; Photons and the Planck spectrum, Saha ionisation equilibrium, phase transitions, basic theory of white dwarfs.

*References:*

- 1) "*Thermodynamics: Concepts and Applications*" - Stephen R. Turns, Cambridge University Press
- 2) "*Statistical Mechanics*" - K. Huang, John Wiley & sons
- 3) "*Statistical Mechanics*" - R. K. Pathria, Butterworth Heinemann
- 4) "*Fundamentals of Statistical and Thermal Physics*", - F. Reif, McGraw Hill International Edition (1985)
- 5) "*Introduction to Modern Statistical Mechanics*" - David Chandler, Oxford University Press
- 6) "*Equilibrium Statistical Physics*" - M. Plischke and B. Bergersen, World Scientific
- 7) "*Statistical Physics, Vol. 5 in Course in Theoretical Physics*", L. D. Landau and E. M. Lifshitz, Elsevier
- 8) "*Principles of Condensed Matter Physics*", P. M. Chaikin and T. C. Lubensky, Cambridge University Press