School of Astrophysics (SoA)

2 year M.Sc Program in Astrophysics

Sem	Paper	Theory/*** Sessional/	FM	CA ***	End Sem	Code	Credit
I	Classical Dynamics	T	50	15	35	ASTP0701	4
	Fundamentals of Quantum Physics-I	T	50	15	35	ASTP0702	4
	Thermal and Statistical Physics	T	50	15	35	ASTP0703	4
	Mathematical and Computational Physics-I	S	50			ASTP0791	4
	Statistical Techniques and Data Analysis	S	50			ASTP0792	4
	Total (Sem I)		**250**				**20**
II	Electromagnetism and Special Relativity	T	50	15	35	ASTP0801	4
	Fundamentals of Quantum Physics-II	T	50	15	35	ASTP0802	4
	Introduction to Astrophysics	T	50	15	35	ASTP0803	4
	Mathematical and Computational Physics-II	S	50			ASTP0891	4
	Experimental Physics	S	50			ASTP0892	4
	Total (Sem II)		**250**				**20**
III*	Introduction to General Relativity	T	50	15	35	ASTP0901	4
	Theoretical and Observational Cosmology	T	50	15	35	ASTP0902	4
	**Generic Elective (extra-departmental or department specific)	T	50	15	35	ASTP0903	4
	Astrophysics Lab	S	50			ASTP0991	4
	*#Project-I: Review of Literature	S	50			ASTP0992	4
	Total (Sem III)		**250**				**20**
IV*	Project-II : Formulation of Project Proposal	S	50			ASTP1091	4
	Project-III : Dissertation	S	50			ASTP1092	4
	Project-IV : Defense Seminar and Open Viva	S	50			ASTP1093	4
	Project-V: Comprehensive Viva	S	50			ASTP1094	4
	Observatory Internship/Night Lab	S	50			ASTP1095	4
	Total (Sem IV)		**250**				**20**
	Total (Sem I+II+III+IV)		**1000**				**80**

**Not all electives will be offered every year. More electives can be added as per need.

* There may be an option for a semester exchange program to national/international institutes in the second year of our masters program through MoUs with national/international partners. The modalities of such exchange programs will be facilitated through the exchange program pipeline of Presidency University.

*# Project can be done under the supervision (individually or jointly) of faculty members from SoA/department of physics/other departments of PU/external institutions. In case the supervisor is from a different department or an institution a, co-supervisor from SoA will be required. The topic of the project can be interdisciplinary but it must have connections to astrophysics research and has to be approved by the academic committee of the School of Astrophysics.

*** All sessional papers will be evaluated in a continuous evaluation mode throughout the semester. Projects and Practicals are termed as sessionals (S). CA refers to continuous assessment.

Sem-1

ASTP0701: Classical Dynamics [50 Lectures]

Lagrangian and Hamiltonian Formulation **[14]**

Variational principle and Lagrange's equations of motion – simple applications, Lagrangian for mechanical systems with dissipation and for systems with non-holonomic constraints, Hamiltonian formulation, Small Oscillations , central force problems

Rigid Body Dynamics **[10]**

Kinematics, Euler angles, Infinitesimal rotation, Motion of heavy symmetrical top with one point fixed, other applications.

Canonical Transformations **[10]**

Generating function, Poisson bracket, Canonical invariants, Hamilton-Jacobi theory, Kepler problem.

Continuous Systems and Fields **[16]**

Introduction to tensors**,** Lagrangian and Hamiltonian formulation for continuous systems, Symmetry and conservation principles – Noether's Theorem, Fundamentals of fluid dynamics

ASTP0702: Fundamentals of Quantum Physics-I [50 Lectures]

Formalism in Quantum Mechanics **[18]**

Stern-Gerlach experiment, formulation of quantum mechanics in abstract space, representation of states and operators, uncertainty principle, Schroedinger and Heisenberg picture, Angular momentum algebra and its representations, matrix representation for j=1, spin, addition of angular momenta, Clebsh-Gordan coefficients, examples, conservation laws and degeneracies associated to symmetries, continuous symmetries, space and time translations, rotations, rotation matrices, parity and time reversal.

Approximate Methods in Quantum Mechanics **[32]**

Time independent non-degenerate perturbation theory, first order and second order corrections to the energy eigenvalues, first order correction to energy eigenfunction, degenerate perturbation theory, some applications-relativistic mass corrections of hydrogen spectra, spin-orbit coupling , Zeeman and Stark effects, Variational principle and its applications . Basic idea of WKB method, Construction of wave function, Connection formula, Some applications, Formulation of time dependent perturbation theory, Examples, transition probability, Rabi oscillations, selection rule. Fermi's golden rule, Atom in an electromagnetic field, Dipole selection rules, Einstein’s A and B coefficients

ASTP0703: Thermal and Statistical Physics [50 Lectures]

Review of Thermodynamics **[8]**
Concepts of thermal equilibrium and equation of state, laws of thermodynamics, Internal energy, Thermodynamic variables, Thermodynamic potentials, Maxwell relations, Entropy and disorder, limitations of thermodynamic approach

Fundamentals of Statistical Mechanics **[12]**
Introduction; thermalization, ergodicity, Microcanonical Ensemble; Entropy and the Second Law; Temperature; Canonical Ensemble; Energy Fluctuations; Chemical Potential; Grand Canonical Ensemble, Examples and applications

Classical and Quantum Gas **[30]**
Classical Partition Functions; Ideal Gas; Equipartition; Maxwell Distribution; Diatomic Gas; Interactions; van der Waals Equation of State; Density of States; Bose-Einstein Distribution and Bose-Einstein Condensation; Fermi-Dirac Distribution and ideal Bose and Fermi Gas, Applications (e.g., Saha Equation and its application in Stellar Astrophysics, Statistical Mechanics and theory of compact objects, Boltzmann equation and early Universe Cosmology).

ASTP0791: Mathematical and Computational Physics-I [50 Lectures]

Complex Analysis **[15]**
Complex variables, Analytic functions, Cauchy -Riemann conditions,
Cauchy's theorem, Cauchy's integral formula, Derivatives of analytic functions, Singularities, Taylor and Laurent series, Branch points and cuts, calculus of residues, Evaluations of integrals using residue theorem, Principal value of an integral.

Vector Spaces **[10]**
Infinite dimensional spaces, examples, Cauchy sequences, completeness, Norms,
Inner products, Hilbert spaces, Applications in Physics.

Review of Python Programming Language (Fortran, C or C++ may also be used) **[9]**

Numerical Methods **[16]**
Interpolation (Lagrange, Newton-Gregory), Derivative (first order and higher order methods), Integration (Trapezoidal method, Simpson's Rule, Gaussian Quadrature, Romberg Method), Ordinary Differential Equation (Euler Method, Modified Euler Method, Runge Kutta, simultaneous ODEs, second order ODEs), Algebraic Equation (Bisection, Newton-Raphson Method), Set of Linear Algebraic Equations (Gauss Elimination, Gauss Jordon, LU decomposition, Inverse of a matrix, Eigenvalues and Eigenvectors), Analysis of Numerical Error.

ASTP0792: Statistical Techniques and Data Analysis

Propagation and reporting of uncertainties **[10]**
Characterisation of uncertainties present in various basic instruments in the lab. Effect of uncertainties in the final result, Instrumental, random, and systematic uncertainties in various experiments in labs. Concept of different moments: mean, standard deviation. Standard deviation on the mean, Scientific visualizations.

Probability Distributions: **[10]**
Probability theory, PDF, CDF, Moments of a distribution, Binomial, Poisson. Gaussian/Normal**,** Central limit theorem , population and sample statistics

Curve Fitting: **[18]**
Straight line. Polynomial. Arbitrary function. Uncertainties from fit, goodness of fit, Confidence intervals, Chi-squared test, Degrees of freedom, Reduced Chi-square, Correlation and covariance, F test, Monte-Carlo test

Introduction to Bayesian Statistics : **[12]**
Bayes theorem, frequentist versus Bayesian approach, Introduction to Parameter Estimation, Markov Chain Monte Carlo, Optimization techniques
Extensive Computer programs and statistical packages will be used for the lab.

Sem-2

ASTP0801: Electromagnetism and Special Relativity [50 lectures]

Electrostatics and Magnetostatics **[10]**
Laplace and Poisson Equations, Green's Functions Boundary Value Problems, Multipole Expansion, Scalar and Vector Potential, Electrostatic and magnetostatic energy

Time varying Fields **[15]**
Maxwell's equations, electromagnetic waves, gauge transformations, Poynting's theorem, conservation laws, motion of a charged particle in E and B fields, concept of a plasma, Maxwell's equations in media, basics of waveguides

Relativistic Formulation of Electrodynamics **[10]**
Vacuum Maxwell equations for potentials and their symmetries; origin of special relativity and Lorentz invariance; relativistic energy and momentum, relativistic kinematics; relativistically covariant form of Maxwell's equations for potentials, covariant form of Lorentz force equation.

Radiation **[15]**
Lienard-Wiechert potentials; Fields due to moving charge, dipole radiation, Larmor's formula and its relativistic generalisation; Bremsstrahlung; Synchrotron radiation; Thomson and Compton scattering, Radiative transfer equations and simple solutions, radiation reaction and the limitations of classical electrodynamics.

ASTP0802: Fundamentals of Quantum Physics-II [50 Lectures]

Scattering theory **[15]**

Laboratory and centre of mass frames, differential and total scattering cross-sections, scattering amplitude; Scattering by spherically symmetric potentials; Partial wave analysis and phase shifts; Scattering by a rigid sphere and square well; Coulomb scattering; Formal theory of scattering — Green's function in scattering theory; Lippman-Schwinger equation; Born approximation

Identical Particles **[4]**

Symmetric and antisymmetric wavefunctions; Slater determinant; Symmetric and antisymmetric spin wavefunctions of identical particles.

Relativistic Aspects **[15]**

Klein-Gordon equation, Feynman-Stuckelberg interpretation of negative energy states and concept of antiparticles; Dirac equation, Spin and magnetic moment of the electron; Non relativistic reduction; Helicity and chirality; Properties of γ matrices

Atomic and Molecular Spectroscopy **[16]**

Fine structure of spectral lines; Selection rules; Lamb shift. Hyperfine interaction and isotope shift; Hyperfine splitting of spectral lines and broadening; selection rules, Many electron atoms, Born- Oppenheimer approximation, Electronic states of diatomic molecules, Approximation methods for the calculation of electronic Wavefunction, Shapes of molecular orbital and bond, Term symbol for simple molecules, Rotation and Vibration of Molecules, diatomic molecule, models for polyatomic molecules, Raman transitions and Raman spectra.

ASTP0803: Introduction to Astrophysics [50 Lectures]

Astronomical Observations **[16]**

Our current understanding of the Universe (broad idea of cosmology, galaxy clusters, galaxies, stars, and planets), Astronomical coordinates, Flux, Luminosity, Magnitude, Astronomical distance scale (AU, light year, parsec, megaparsec) and mass scale, Refracting and reflecting telescopes, Concept of angular size and its relation to physical size, Diffraction limit, Astronomical seeing, Need for Space Telescopes, Basic observational techniques in optical, radio and high-energy (Xray/ Gamma-ray) astronomy, outlines of spectroscopic and polarimetric observations, Stellar parameters (mass, radius, temperature) from binary systems, Extrasolar planets, Continuous, emission, and absorption spectra, Formation of spectral lines, HR diagram, Main sequence.

Stellar Astrophysics **[18]**

Virial theorem, Hydrostatic equilibrium, Concept of Opacity, Stellar energy sources, Solar neutrino, Jeans Criterion, Interstellar medium, Formation of protostars, evolution of stars before, during and after their location on the main sequence, HII region, Stromgren Sphere, Supernovae, Stellar Pulsation, Degeneracy pressure, White dwarfs, Chandrasekhar limit, Neutron stars, Pulsars, Black holes, Close binary systems, accretion disks

Galactic Astrophysics **[10]**

Spiral, elliptical and irregular galaxies (rotation, spiral structure, dark matter), Interaction and evolution of galaxies (evolutionary relation of spirals and ellipticals), Supermassive black hole (MBH vs. Mbulge, Black hole-galaxy coevolution), Morphology, Kinematics, Galactic centre.

Extragalactic Astrophysics **[6]**

Galaxy clusters, Cosmic distance ladder (Parallax, Cepheid variables, Hubble's law, Type IA supernovae), Observations of active galaxies all over the electromagnetic spectrum, Unification model, Importance in galaxy formation and evolution, Gamma-ray bursts.

ASTP0891: Mathematical and Computational Physics-II [50 Lectures]

Differential Equations **[12]**

Sturm-Liouville theory; Hermitian operators; Completeness; Simple applications;
Inhomogeneous equation: Introduction to Green's functions and its application.

Integral Transforms **[9]**

Fourier and Laplace transforms; Transform of derivative and integral of a function; Solution of differential equations using integral transforms.

Introductory Group Theory [5]

Preliminaries; group representation, finite groups

Computational Algorithms **[8]**

Fourier transform (Discrete Fourier transform, Fast Fourier transform); Partial Differential Equation (Relaxation, Over-relaxation, Gauss Seidel, FTCS, Spectral Method).

Applications **[16]**

Monte-Carlo Techniques (Statistical methods of integration, Importance sampling, MCMC method); Equation of Motion and Trajectories (Leap-Frog, Verlet Method), N-body dynamics Solar system; Oscillatory motion and Chaos; Solution of Laplace, Poisson, Schrodinger equation.

ASTP0892: Experimental Physics

The Following Experiments are part of the lab. The topics in brackets indicate the theoretical module that is connected to the experiment.

1. Studying Michelson's Interferometer *(Waves and Optics)*
2. Characteristics of optical fibres *(ENM: Wave Guides)*
3. Determination of the dissociation energy and anharmonicity constant of the iodine molecule by analysing its absorption spectrum *(Molecular Physics: Diatomic Molecule)*
4. Study of Zeeman pattern of the green line of mercury *(Quantum Physics)*

5. Measuring charge to mass ratio (e/m) of electron *(ENM: Motion of a charge particle)*
6. Velocity of ultra-sonic waves in a liquid by ultra-sonic diffraction grating *(Waves, Optics and Fluid dynamics)*
7. Studying Faraday effect for an optically active material *(ENM: Polarization of EM waves)*
8. Studying a Fabry Perrot interferometer *(Waves and Optics)*
9. Characterizing noise in electronic signals *(Electronics and Signal Processing)*

Sem-3

ASTP0901: Introduction to General Relativity [50 Lectures]

Introduction: [5]
Introduction to gravitational physics; Space, time and gravity in Newtonian physics; Scope of General Relativity. Minkowski spacetime; Four vectors; The null cone; Variational principle approach to relativistic mechanics – relativistic free particle dynamics; Covariant formulation of relativistic mechanics and electromagnetic theory - Lorentz force law and energy momentum conservation.

The Geometry of Curved Spaces and Spacetime [8]
Manifolds and coordinates - Curves and surfaces; Transformation of coordinates – contravariant, covariant and mixed tensors; Elementary tensor algebra; Partial derivative of a tensor; Affine connection; Parallel Transport and covariant differentiation; Metric tensor; Geodesics; Isometries – Killing vectors and conserved quantities; Solution of geodesic equation – simple examples; Riemann tensor; Geodesic deviation; Ricci tensor and scalar.

The Principles of General Relativity and Field Equation [12]
Mass in Newtonian theory; The principle of equivalence, general covariance and minimal gravitational coupling. The vacuum field equation of general relativity; Derivation from action principle; Bianchi identity; Stress Energy tensor - incoherent matter, perfect fluid, electromagnetic field and scalar field; The structural properties of the equation; Derivation of the FLRW line element.

Schwarzschild Solution and Black Hole [10]
Einstein's equation for weak gravitational fields; Newtonian limit; Schwarzschild solution – exterior and interior; Properties of the metric - symmetries and conserved quantities; Concept of black hole – event horizon, its properties and significance; Singularities; Particle and photon trajectories in Schwarzschild spacetime.

Experimental Tests of Einstein's Theory [10]
Gravitational redshift; Precession of planetary orbits; Bending of light; Gravitational lensing.

Gravitational Waves [5]
The covariant formulation of electromagnetic waves and polarization vectors; The linearized Einstein equations - plane wave solutions; Production of weak gravitational waves; Cosmic sources of gravitational waves; The quadrupole formula for energy loss; Detection methods.

ASTP0902: Theoretical and Observational Cosmology [50 Lectures]

Standard Model of Cosmology **[10]**

Historical development of cosmology, Observational triumphs of cosmology, Olber's paradox, Hubble's law and the expanding Universe, Big Bang theory, redshift, scale factor, FRW metric, Cosmological principle, homogeneity and isotropy, Newtonian cosmology, Friedmann equation, conservation and acceleration equations, different components of the Universe, Distance measures in cosmology

Thermal History of the Universe **[18]**

Thermal Equilibrium in Expanding Cosmology, Boltzmann equation, Out of equilibrium, Relic abundance, neutrino decoupling, Cosmic Neutrino Background, Big Bang Nucleosynthesis, Baryon Asymmetry, Recombination and decoupling of photons, surface of last scattering, temperature fluctuations in the CMB, acoustic oscillations, primary and secondary temperature anisotropies, measuring the CMB temperature anisotropy, CMB as a probe of cosmology

Growth History of the Universe **[22]**

Gravitational instability, linear perturbation theory, linear growth equation, Statistics of density fluctuations, matter power spectrum, large scale structure in the Universe, 2-point correlation function, observations of large scale structures, hot versus cold dark matter, cosmological simulations, Inflationary Paradigm and the initial conditions of the Universe.

ASTP0903A: Extragalactic Astrophysics [50 Lectures]

The World of Galaxies **[12]**

Morphological classification; Elliptical galaxies (Classification, Brightness profile, Composition of elliptical Galaxies, dynamics of elliptical galaxies); Spiral galaxies (Trends in the Sequence of Spirals, Brightness Profile, Rotation Curves and Dark Matter, Stellar Populations and Gas Fraction, Spiral Structure); scaling relations (Tully-Fisher, Faber-Jackson, the fundamental plane); Black holes at the center of galaxies; luminosity function of galaxies (Schechter Luminosity Function, Bimodal Color Distribution of Galaxies); Population synthesis

Clusters and Groups of Galaxies **[18]**

The Local Group; Galaxies in clusters and groups (luminosity function of cluster galaxies, morphological classification of clusters, spatial distribution of galaxies in a cluster, dynamical mass of clusters, morphology-density relation of clusters); X-ray emission from clusters (observation, model, cooling flow problem, SZ effect); Scaling relation in clusters (mass-temperature, mass-luminosity, near IR luminosity as mass indicator); Active galaxies (brief overview, Interaction of AGN with cluster and ICM, quasar luminosity function, quasar absorption lines); Clusters as gravitational lenses

Cosmological Application of Extragalactic Astrophysics **[14]**

Preliminaries (success and problems of the standard model); Redshift survey of galaxies (power spectrum, angular correlation, peculiar velocities); Cosmological parameters from clusters (number density, mass-to-light ratio, baryon content, large scale structure of clusters); Lyman Alpha forest (phenomenology, model, application as a cosmological tool)

Universe at High Redshift **[6]**

Galaxies at high redshift (Lyman break galaxies, photometric redshift, Hubble Deep Field(s)); New types of galaxies (starburst galaxies, Extremely Red Objects, Damped Lyman alpha systems); Cosmic IR and X-ray background, Cosmic star formation history, final words on galaxy formation and evolution

ASTP0991: Astrophysics Lab

The Following Experiments are part of the lab. The topics in brackets indicate the theoretical module that is connected to the experiment.

Data Analysis Experiments

1. Introduction to Astrophysical Software: IRAF, IDL *(imaging and spectroscopy)*
2. Determining parameters of Extra-Solar planets *(Transit method in exo-planet detection)*
3. Main sequence fitting of a star cluster *(Stellar astrophysics)*
4. Statistics of the Cosmic Microwave Background Radiation *(Cosmology)*
5. Galaxy Spectral Fitting *(Observational Techniques)*
6. Obtaining parameters of the Hulse-Taylor Binary System *(General Relativity)*
7. Modelling gravitational waveforms *(General Relativity)*

Instrument Based Experiments

1. Studying Solar Limb Darkening *(Stellar Astrophysics)*
2. Characterizing a radio antennae. *(Classical Radiation)*
3. Characterization of a Charged Coupled Device *(Detector Instrumentation)*
4. Designing a Spectrograph *(Instrumentation)*

ASTP0992: Project-I: Review of Literature

In this module the student will undertake background studies or learn experimental/observational techniques that are needed to do the project work. At the end of the semester, the student will provide a literature review report (not exceeding 2000 words) and make a presentation of the study followed by an open viva-voce

Sem-4

ASTP1091: Project-II: Formulation of Project Proposal

In this module the student will formulate the techniques and global goal of their project work. At the middle of the semester the student will make an open presentation to propose the project and show preliminary results to justify the feasibility of the work. The student will also submit a synopsis (not exceeding 500 words) where they will provide the methodology/techniques and the global goal for their project work.

ASTP1092: Project-III: Dissertation

A final dissertation (not exceeding 5000 words) pertaining to the project work undertaken by the student will be submitted for evaluation of the work.

ASTP1093: Project- IV Defense Seminar and Open Viva

Students will be expected to defend their thesis in an open seminar and a viva voce will follow.

ASTP1094: Project-V Comprehensive Viva

Students will be examined through a comprehensive viva by a board of examiners consisting internal and external members on the basis of the submitted dissertation.

ASTP1095: Astrophysics Night Lab/Observatory Internship

Students will either need to opt for night lab observations with small telescopes or at least a four week internship to a national observing facility where they would learn to do hands-on observations with research purpose telescopes. The student will have to keep regular records of observations and do the necessary analysis and present it in a report form. At the end students will have to go through a viva-voce on the observational/instrumental work that they performed.