Observatoire de Paris - PSL

AstroParis graduate program

MASTER 1st year

Space Science and Technology

LECTURES

up-dated on june 2025

master1.administration@obspm.fr

Contents

Chapter 1

Lectures of the 1st semestre

1.1 Quantum Mechanics

Teachers

Bess Fang (SYRTE) : bess.fang@observatoiredeparis.psl.eu

Philip Tucvkey (SYRTE) : philip.tuckey@observatoiredeparis.psl.eu

Overview

This course will provide a self-contained introduction to Quantum Mechanics, covering its foundations, the quantum description and properties of simple model systems and of elementary particles, nuclei, atoms and molecules, and the simplest approximate computational methods. The examples and applications will be chosen for their relevance to astrophysics. The objective is to provide students with the necessary background for other M1 courses (Statistical Physics, Interstellar Medium, Stellar Physics, Astroparticle Physics, Detector Physics) and for further studies in astrophysics. No prior knowledge of Quantum Mechanics is required. Basic mathematical tools such as complex numbers, linear algebra, differential equations, Fourier transform are necessary, as well as a knowledge of classical mechanics. However lengthy calculations will be avoided as far as possible in order to privilege physical interpretations.

Detailed content

- General introduction: historical context, various applications of QM, orders of magnitude of the "quantum scale", brief preview of principal concepts

- Wave and particles: particle nature of light, wave nature of (quantum) particles, duality, complementarity, wave function and its interpretation
- Quantization and quantum states: Polarisation of light and quantum states of the photon, Stern-Gerlach experiment, Dirac formalism of quantum states, Hilbert space, atomic spectra, discrete and continuous bases
- Measurement theory and observables: measurement, compatibility, complete set of commuting observables, expectation value and uncertainty, Heisenberg's uncertainty principle
- Time-independent properties : X and P operators, Hamiltonian and stationary solutions of the Schrödinger equation, particle in a box and related potentials, harmonic oscillator
- Temporal evolution of a quantum state: time dependent Schrödinger equation, solar neutrino oscillations, quantum evolution in an atomic clock, Ehrenfest theorem, constants of motion and symmetries
- Angular momentum: definition, useful relations, basis, spin, magnetic moment
- Orbital angular momentum and spherical harmonics, diatomic molecules, Hydrogen-like atoms – introduction, shell structure and periodic table
- Composite systems: direct sum, tensor product, identical particles, spin-statistics theorem (bosons and fermions), Pauli exclusion principle
- Composition of angular momentum, decomposition theorem
- Hydrogen-like atoms – precise modelling: stationary perturbation theory, fine structure, Lamb shift, hyperfine structure, external fields, Zeeman effect
- Introduction to multi-electron atoms, shell model
- Introduction to the interaction of radiation with matter: properties of the states and emission and absorption spectra of atoms, ions, molecules and nuclei relevant for astrophysics, elementary particles
- Degenerate electron gas and white dwarves (introduction to the treatment in the Statistical Physics course), Bose-Einstein condensate, superfluids and neutron stars, quantum cosmology ...

1.2 Statistical physics

Teachers

François Levrier (ENS/LPENS) : francois.levrier@ens.fr

and assistant teachers

Overview

This course is intended as a self-contained introduction to the methods of statistical physics, that allow to derive properties of systems containing a very large number of particles from properties at the microscopic scale. No prerequisite is necessary, save for a basic knowledge of classical thermodynamics. The course will extensively cover fundamental concepts relevant to a general understanding of the methods of statistical physics in systems at equilibrium, illustrated by classical examples. Extensions to out-of-equilibrum statistical physics, kinetic theory, and stochastic processes will be presented.

Contents

1. Fundamental concepts and tools : microstate and macrostates, probabilities, information, statistical entropy, ergodic principle

2. Statistical ensembles : microcanonical, canonical, and grand-canonical ensembles, thermodynamic limit

3. Quantum statistics : Fermi-Dirac and Bose-Einstein distributions for quantum gases, thermodynamics of radiation

4. Out-of-equilibrium systems : transport laws (Fick, Fourier, Ohm), Onsager's theory and thermoelectric effects

5. Kinetic theory : Liouville's theorem, BBGKY hierarchy, Boltzmann and Vlasov equations, transport coefficients, hydrodynamic limit

6. Stochastic processes : random walks, Ising's model, domain growth

1.3 Instrumentation: physics and instruments

Teachers

Elsa Huby (LESIA) : elsa.huby@observatoiredeparis.psl.eu

Benoît Mosser (LESIA): benoit.mosser@observatoiredeparis.psl.eu

Context

Astrophysics is based on highly-performing instruments that are designed in the astrophysical labs. This lecture introduces physical concepts, mostly in optics, which are necessary to understand current astrophysical instruments. The path of the observed photons is described along all processes that finally contribute to the scientific measurement.

Methodological skills

The unit is essentially methodological

Astrophysical skills

Physics for instrumentation: optics, detection, data analysis

Ongoing or future ground-based or space-borne projects

All

Detailed content

Geometrical optics, physical optics (reminders).

High angular resolution imaging

Fourier optics

Fresnel and Fraunhofer diffraction

Image formation, interferometry and coherence.

Atmospheric optics and initiation to adaptive optics.

Introduction to different instrumentation principles: astrometry, spectrometry, spectro-imaging, photometry, interferometry ...

Signal, noise, bias concepts.

Physical detection processes.

CCD imaging and image processing.

Sampling, filtering.

Thermal infrared techniques, radio observation, high-energy detection

50% lectures 50% tutorial class

Some parts of the module will be taught in flipped classroom A small project will be proposed to students, dedicated to the analysis of modern instruments.

1.4 Data Processing and associated methods 1

Teachers

Cédric Leyrat (LESIA) : cedric.leyrat@observatoiredeparis.psl.eu

Caroline Barban (LESIA) : caroline.barban@observatoiredeparis.psl.eu

and an assistant teacher.

Context

Astrophysical observations provide noisy data. Efficient methods must be used to recover the astrophysical signal.

Methodological skills

The unit is 100% methodological.

Ongoing or future ground-based or space-borne projects

All

Detailed content

1- Random variables and astrophysical signals

- Probability and statistics
- Sources of noise in astrophysical signals
- Random variables (discrete and continuous)
- Probability density
- Change of variables
- Joint distributions
- Variance, co-variance, correlation
- random vectors

2- Analysis of noisy periodic signals

- Fourier transform
- Convolution
- Wavelet analysis
- Bayesian approach
- Optimisation :
  - Estimators
  - Maximum likelihood, Gradient descent
  - Illustrations with astrophysical examples

1.5 Data Processing and associated methods 2

Teachers

Daniel Reese (LESIA) : daniel.reese@observatoiredeparis.psl.eu

Caroline Barban (LESIA) : caroline.barban@observatoiredeparis.psl.eu

Recommended prerequisite

Students are recommended to follow the "Data processing and associated methods 1" course prior to following this course.

Context

In many situations, measurements/observations only provide indirect information on underlying physical phenomena and are furthermore affected by noise and convoluted by instrumental effects. Accordingly, in order to study such phenomena, it is necessary to invert the data in order to extract the information they contain. This typically leads to ill-posed inverse problems where a naive application of simple resolution techniques leads to poor results. Inverse techniques provide a way to handle these problems by damping the effects of noise and injecting prior information. The goal of this course is to introduce students to these techniques by providing both a theoretical basis as well as numerous practical applications. Applications range from astrophysics (e.g. probing the internal structure of stars via stellar pulsations, probing planetary atmospheres, deconvolving images, super-resolution imaging etc.) geophysics (probing the earth's structure through earthquakes), industry (sounding building structure), to medical applications (X-ray tomography, ultrasound imagery, etc.).

Detailed content

Introduction: reminders on linear algebra

- Introduction

- Direct vs. inverse problems - definitions
- First notions on ill-posed problems
- Illustrations from different domains

- Reminders on algebra

- Reminders on linear algebra
- vectors, matrices, eigenvalues, eigenvectors
- symmetric and orthogonal matrices
- vector and matrix norms

Classical methods

- Least-squares method/linear regression
- Singular value decomposition

Ill-posed problems

- Definition/illustration
- Condition number - direct definition - formula based on SVD

Regularisation strategies

- Regularised Least-Squares

  - General regularisation matrix
  - Tikhonov regularisation

- Truncated SVD/spectral truncation
- Generalisation: regularising filters

  - Link with truncated SVD
  - Link with Tikhonov method

Localised inversion methods

- MOLA, SOLA
- Illustrations/comparisons with RLS methods/robustness

Probabilistic approach (if time permits)

- Bayesian approach
- The RLS method as a specific application for Gaussian noise

3 practical sessions

- Matrix construction (discretisation of integral equations)

- Inversion/least-squares inversion
- Condition number and SVD
- Illustrate how reducing the discretisation step can lead to a worse matrix conditioning
- Regularised inversions: Truncated SVD, Tikhonov method
- Regularised image deconvolution using 2D Fast Fourier Transform
- RLS and SOLA seismic inversion in a solar model

1.6 Hydrodynamics

Teachers

Guillaume AULANIER (LPP) : guillaume.aulanier@lpp.polytechnique.fr

and an assistant teacher.

Detailed content

Each chapter is illustrated with various astrophysical objects and phenomena.

Introduction to (astrophysical) fluid mechanics

Chapter 1. Fundamental compressible fluid equations

- 1.1. Continuity equation, convergence and divergence
- 1.2. Momentum equation, pressure, gravity and other forces
- 1.3. Energy equation(s), adiabatic, and with heating or radiative cooling

Chapter 2. Compressibility: sound & shock waves

- 2.1. Sound wave equations, dispersion relation
- 2.2. Sound interaction with other terms, gravitational instability
- 2.3. Properties of shocks, steepening, jump conditions, blast waves

Chapter 3. Incompressible flows

- 3.1. The incompressible limit, low-Mach flows
- 3.2. Stream function, stream lines, stagnation flows
- 3.3. Vortical flows, pressure balance in vortices
- 3.4. Irrotational (and incompressible) flows, flows around obstacles
- 3.5. Kelvin-Helmholtz (K-H) instability, dispersion relation with imaginary frequencies

Chapter 4. Bernoulli principle & engineering applications

- 4.1. Bernoulli equation, causality issues between velocity and pressure
- 4.2. Incompressible applications, the origin of lift, and of acceleration in Venturi tubes
- 4.3. Compressible application, supersonic propulsion and magnetized winds

Chapter 5. Gravitationally stratified fluids

- 5.1. Buoyancy force & standing gravity (not gravitational) waves
- 5.2. Oscillatory behavior and convective instability, atmospheric clouds and stellar interiors
- 5.3. Interface/surface propagating waves, the science of beaches
- 5.4. Parker winds & Bondi accretions around stars and other objects

Chapter 6. Numerical practical work

- Using an existing cartesian uniform-grid f95 code,
- Basic programming of initial conditions and setting some physical (and numerical) parameters, Running quicklook programs for visualizations.

1.7 General Astronomy

Teachers

Pierre Kervella (LESIA) : pierre.kervella@observatoiredeparis.psl.eu

Andreas Zech (LUTH) : andreas.zech@observatoiredeparis.psl.eu

Detailed content

This course is designed as an introduction to the vocabulary and concepts of astronomy. It will include developments on selected exciting fields of modern research in astrophysics, with the goal to foster the interest and curiosity of the students for research fields that they may not be familliar with initially.

Part I (Pierre Kervella) :

Historical perspective

- Overview of astronomy in history and culture.

The sky and its observation

- Spherical astronomy, coordinate systems, astrometry, parallaxes, proper motions.
- Matter and radiation, telescopes, detectors.
- Observational photometry, magnitude systems, spectroscopy.

The Solar system

- Overview of the structure of the Solar system.
- Terrestrial and giant planets, physical properties.
- Minor bodies as witnesses of the primordial Solar system.
- The Solar system in view of planets in other stellar systems.

Stars

- Stars and the cosmos,
- What is a star ? Source of energy.
- Structure and evolution of the Sun and stars.
- Spectral classifcation, Hertzsprung-Russell diagram, extreme stellar objects.
- Open and globular clusters, star formation.
- Stellar rotation and pulsation.

Part II (Andreas Zech) :

The Milky Way Galaxy

- The Galactic morphology (disk, spiral arms, central bar, halo)
- Mass and energy content of the Galaxy (stellar populations, interstellar medium, cosmic rays, magnetic field morphology, dark matter)
- Galactic dynamics and kinematics
- The Galactic Center (central black hole, central region - recent observations EHT, Gravity, Fermi, radio, ...)

Galaxies

- Classification of Galaxies (Hubble sequence; spiral, elliptical, irregular galaxies; dwarf galaxies)
- Evolution of galaxies and their interactions (starburst galaxies, ...)
- dark matter halos (rotation curves, velocity dispersion, virial mass)
- Active Galaxies (physics of the central engine: accretion, jet formation; Seyfert galaxies, radio galaxies, quasars, blazars, unified model..)
- Galaxy Clusters (Local Group, types of clusters, cooling flow, intracluster gas, superclusters ...)

Cosmology

- the cosmological principle (cosmological principle, Olbers's paradox, obs. of large scale structure, ...)
- the big bang and the expansion of the universe (big bang nucleosynthesis, recombination, reionisation,...)
- observational cosmology (Hubble law, redshift measurements, CMB ...)
- introduction to the lambda CDM model (energy content of the univers, curvature, characteristics of dark matter, cosmological constant ...)

1.8 Mathematical Physics

Teachers

Quentin Kral (LESIA) : Quentin.Kral@observatoiredeparis.psl.eu

and an assistant teacher.

Detailed content

1 - Functional analysis

- First-order partial derivative equations (characteristics, geometric interpretation). Homogeneous and non-homogenous linear equations
- Phase space, global properties of ordinary differential equations, surfaces of section
- Calculation of perturbations (polynomial roots, stability of a differential systems)
- Linear operators (eigenvalues, eigenvectors, orthogonal basis, example: heat equation)
- Variational calculus (Example: Lagrange equations, central field)
- Basics of Hamiltonian systems
- Fourier series and Fourier transform
- Measurements - Convolution, Correlation, Self-correlation

2 - Linear algebra (matrices)

- Reminder: vectors, matrices, operations, vector bases, eigenvectors, eigenvalues, decomposition into singular values
- Norms, orthogonality
- Singular and non-singular matrix properties
- Transformations, projections, base changes, kernel
- Optional: Linear algebra in the function space

Examples: regression in spaces with N dimensions, Principal Component Analysis

3 - Probability theory and statistics

- Reminders: discrete and continuous random variables, probability distribution function, joint distributions, variance, co-variance, moments, mean value, expectation, marginal probabilities
- Main laws (1D, 2D, ...): binomial, Poisson, uniform, normal, ...
- Estimators (least squares, chi2 tests, parameter estimation)
- Bayesian approach

1.9 Classical Gravitation

Teachers

Daniel Hestroffer (IMCCE) : Daniel.Hestroffer@observatoiredeparis.psl.eu

and an assistant teacher.

Context

Starting from a reminder of Newton's law of gravitation, we will analyse the orbital motion in the basic 2 body problem. This will include several applications in astronomy and astrodynamics for natural celestial and artificial bodies. It also covers various representation of Keplerian orbits, the determination of orbits, and first approach to various perturbation sources and perturbed 2-body problem. The lecture is completed by an analysis of the rotation of rigid bodies and satellites' attitude.

Detailed content

Nota: "+" means short introduction, or connection to other courses

Dynamics under Gravitation

- Reference frames - Galilean inertial frame
- Fundamental principle of dynamics

- Kinetic energy and potential energy - virial theorem
- Central force and gravitational potential

The 2body problem

- Historical context from epicycles to Newton
- Properties of conics and energy
- Cauchy problem
- Orbital elements and state vector
- Motion in 2D and 3D - Reference frames
- Perturbed 2-body problem
- +Introduction to N-body problem

Orbital position as a function of time

- Different representation of the trajectory and orbit True orbit - Apparent orbit
- Kepler equation - and solutions
- Ephemerides
- Approximate computation of coordinates

Determination of orbits (preliminary orbit determination)

- Lambert problem
- Characterisation of binary systems (binary stars, exoplanets, ...)
- Modern astrometry - observational data to characterise orbits
- Methods with 2 or 3 observations - principles
- Determination of masses and different associated measurements
- + introduction to methods with N»1 observations

Astrodynamic basics

- Escape velocities - horizon
- Satellites and bounded orbits (galaxies, planets, ...)
- Change of orbits - orbital manoeuvres
- Hohman transfer of orbits
- Two-impulse rendez-vous manoeuvres

Rotation - Rigid-body dynamics

- Euler angles
- Moments of inertia
- Equations of dynamics rotation of rigid body
- Free rotation Euler top
- NPA rotators
- Quaternions ; Satellite attitude
- +Introduction to precession+nutation, and non-rigid bodies

1.10 Computer science

Teachers

Christian Balança (LERMA) : Christian.Balanca@observatoiredeparis.psl.eu

Caroline Barban (LESIA) : Caroline.Barban@observatoiredeparis.psl.eu

Daniel Reese (LESIA) : Daniel.Reese@observatoiredeparis.psl.eu

Context

The use of computer-based techniques for problem solving has become ubiquitous in many domains including astrophysics and industry. Accordingly, in order to be competitive on the job market in today's world, it is necessary to acquire a number of computer skills. The goal of the following two courses is to equip students with basic skills in Unix as well as some of the most popular programming languages, namely C and python, and to provide an overview of the some of the most widely-used numerical analysis techniques.

Detailed content

The module Computer Science will provide basic skills in Unix, C and Python.

* Unix (20%) - console, basic package of commands - files and directories, tree, archive, connection and copy through network - permissions, filters, redirection, pipes, environment variables, special characters

* C (40%) C89 norme ANSI - variables, types, operations, compilation, headers - input/output, control structures, loops - static arrays and functions - pointers and dynamic memory allocation Applications: analysis of astronomical data from a catalog

* Python (40%) - syntax: instructions, types, constructs, comments, documentation (including the use of sphinx) - interactive mode and use of scripts - functions, objects, packages - libraries: numpy, matplotlib Applications: plotting data with matplotlib, basic image treatment

Chapter 2

Lectures of the 2nd semestre

2.1 Numerical analysis

Teachers

Christian Balança (LERMA) : Christian.Balanca@observatoiredeparis.psl.eu

Caroline Barban (LESIA) : Caroline.Barban@observatoiredeparis.psl.eu

Emeric Bron (LERMA) : Emeric.Bron@observatoiredeparis.psl.eu

Daniel Reese (LESIA) : Daniel.Reese@observatoiredeparis.psl.eu

Detailed content

The module Numerical Analysis will improve the level in Unix, C and Python. Most of the time will be focus on learning by practice with strong support of the teachers.

* Unix (20%) scripts, Makefile and Git variables, command substitution, positional parameters, tests, control structures, arithmetic

* Numerical Analysis (C & python) (80%) - Interpolation et extrapolation. Context: Large parts of astrophysics rest on empirical datasets (experimental results, astronomical observations) and interpolation in multidimensional data is often necessary to make efficient use of these datasets.

- Minimization and model fitting Context: Model fitting is a central part of data analysis in astrophysics. Moreover, modern massive astronomical dataset open new possibilities through Machine Learning methods, which rely on efficient minimization techniques in high-dimensional spaces.

- Mini-project: Fitting astrophysical spectra

- Non-linear algebraic equations Context: Astrophysical modeling often requires solving large nonlinear systems, and even the most advanced solvers will often encounter convergence problems, so that the students will need to know the relative advantages of different methods and the role of tweaking parameters.

- Ordinary differential equations Context: Most astrophysical models relie on differential equation, we will limit ourselves to ordinary differential equations in this course. Stiff equations often arise in astrophysics (e.g. astrochemical systems) and we will introduce the problem and the use of implicit methods to overcome it.

- Mini-project: The chemical evolution of giant molecular clouds

- Multidimensional data analysis Context: Massive datasets, often in high dimensions, are becoming the norm in astrophysics. This chapter will present an introduction to a few common data science methods and a first contact with Machine Learning.

2.2 Gravitation of extended bodies and Galactic dynamics

Teachers

Andrea Cattaneo (LERMA) : andrea.cattaneo@observatoiredeparis.psl.eu

Gary Mamon (IAP) : gam@iap.fr

Nicolas Rambaux (IMCCE) : Nicolas.Rambaux@observatoiredeparis.psl.eu

Detailed content

This course is devoted to the effect of the gravitation on N-body systems interacting together. It is an introduction to the dynamics of continuous (extended) bodies and galactic dynamics with a description of methods and observations.

FIRST PART (extended bodies)

Prerequisite:

Classical mechanics, reference system, angular velocity, angular momentum, inertia tensor, Euler angles, two-body problems.

Lesson Plan (9h):

Introduction: Review on extended bodies in Astronomy and Astrophysics (objects, theory, models, observations with focus on space missions). Links between extended bodies, point-mass N-body and Galaxies.

I Planetary rotation (3 hours)

I-1 Rotational equations: Euler-Liouville equation with an application to the free rotation of the Earth this part allows to recall: angular velocity, angular momentum, moment of inertia (discrete and continuous), Euler angles. Introduction of rotation matrices.

I-2 Forced rotation: precession-nutation, introduction of the gyroscope (description of the gyroscopic effect), solid body potential (spherical harmonics, links with moment of inertia), tidal potential. Applications to the Precession-Nutation of the Earth and to the spin-orbit motion of the Moon, resonance spin-orbit and libration in longitude.

II Tides (3 hours)

II-1 Equilibrium tides in non-rigid planet, Love number and variable moment of inertia

II-2 Tidal evolution in the Earth-Moon system (angular momentum exchange).

III Equilibrium Figures (3 hours)

III-1 formulation of the gravitational potential in terms of quadratic function, MacLaurin ellipsoid

III-2 Equilibrium shape of bodies in fast rotation, bifurcation and symmetry breaking, Jacobi ellipsoid

Reference books (for extended bodies):

- Murray, C., and Dermott, S., Solar System Dynamics, ed. Cambridge 2000

- Goldstein, Poole, Safko, 2000, Classical Mechanics, ed.Adison Wesley

SECOND PART (galactic dynamics)

1. Galaxy properties: an observational overview (1h30) AC

2. Newton's theorems. Poisson's equation. Potential-density pairs - I: spherical systems (power-law, Hernquist, NFW and Sérsic profiles) (1h30) AC

3. Potential-density pairs - II: ellipsoidal systems, discs. Rotation. Astrophysical application: discovery of dark matter in spiral galaxies (1h30) AC

4. Stellar orbits in non-rotating and rotating systems. Epicyclic motion (1h30) AC

5. Distribution functions. Jeans theorem. Collisionless Boltzmann equation. Liouville's theorem. Eddington's formula (1h30) GM

6. Equilibria of collisionless systems: Jeans equations, virial theorem (1h30) GM

7. Structural and kinematic projection and deprojection. Measurements of mass and mass profiles. Galaxy units. Applications to globular clusters, elliptical galaxies and galaxy clusters. Dark matter distribution (1h30) GM

8. Local stability of stellar and gaseous systems. Jeans instability. Toomre criterion. Global stability of spherical and uniformly rotating systems (1h30) AC

9. Galaxy formation. Formation and violent relaxation of dark matter haloes. Dissipational infall. Origin and sizes of disc galaxies. Characteristic galaxy mass. Evolution across the Hubble sequence (1h30) AC

10. Star formation. Feedback. Dissipationless and dissipational mergers. Supermassive black holes (1h30) AC

11. Galaxy evolution in dense environments - I. Infall, two-body relaxation. Dynamical friction (1h30) GM

12. Galaxy evolution in dense environments - II. High speed encounters. Tides by extended perturbers. Mergers, merger rates and growth by mergers (1h30) GM

13. Internal evolution of disc galaxies. Formation of spiral arms and bars. Density waves. Oort's constants. Lindblad resonances. Stellar diffusion, radial migration (1h30) GM

14. Evolution of globular clusters. Dynamical evaporation. Core collapse and gravothermal catastrophe. Three-body problem and application to stars interacting with a binary system. Effects on the host galaxy (1h30) GM

Reference books (for galactic dynamics):

- Binney, J., and Tremaine, S. Galactic Dynamics, Princeton University Press, 2008.

2.3 Physics of the Interstellar medium

Teachers

Franck Le Petit (LERMA) : Franck.LePetit@observatoiredeparis.psl.eu

Emeric Bron (LERMA) : Emeric.Bron@observatoiredeparis.psl.eu

Detailed content

Part 1 - Introduction

Notions of physics used in this part are: Hydrodynamics, thermodynamics principles, Virial theorem, wave propagation, perturbation computation in hydrodynamic equations.

1 - Overview

1.1 - Composition of the ISM

1.2 - Dust properties

1.3 - Phases of the ISM

2 - Molecular clouds

2.1 - Virial theorem analysis

2.2 - Hydrodynamical analysis

2.3 - Gravitational and thermal Instabilities (Eber-Bonnor mass, Jeans mass, WNM and CNM)

Part 2 - Physical processes in the ISM

In this part, small scales processes are presented and several notions of physics are used:

- Quantum physics and statistical physics: quantum levels of atoms and molecules (electronic states, rotational and vibrational levels, fine and hyperfine structure, ionization, recombination), radiative transitions, Einstein coefficients, collisional processes, collision rates, ionization potential.

- Detailed balance in quantum levels: how to estimate level populations (at Local thermodynamical equilibrium (LTE) and at non-LTE.

- Gas kinetics and the role of supra-thermal particules (such as electrons ejected from grains or atoms) on their environment. This will be an opportunity for a reminder about the Maxwell distribution and the link with macroscopic quantities such as kinetic temperature. In this part, the radiative transfer equation is presented. We will focus on the most common processes in the ISM.

3 - Heating and Cooling of the ISM

3.1 - Heating mechanisms (Photo-electric effect on grains, cosmic ray ionization, other heating mechanisms)

3.2 - Cooling mechanisms (two-level system, critical density, atomic and molecular transitions, main coolants)

4 - The radiation field and its interaction with interstellar matter

4.1 - Radiative transfer equation and its solutions

4.2 - Sources of radiation field

4.3 - Absorption, emission, diffusion by grains and gas

4.4 - Spectra : how to link observations and theory

5 - Atomic and molecular composition

5.1 - Chemical composition of the neutral ISM

5.2 - Ionisation : from ionized gas to neutral gas

5.3 - H2 formation in the Galactic ISM and in low metallicity galaxies

5.4 - Role of cosmic rays for the formation of some main molecules (ex: CO, H2O)

5.5 - Other molecules - a link towards Life ?

Part 3 - From Clouds to Stars

In parts 3 and 4, the lecture comes back to macroscopic physics. Notions used in this part are: momentum conservation, hydrodynamics and shocks (Rankine-Hugoniot jump conditions), role of magnetic field on the acceleration of particles (ambipolar diffusion). We will also discuss the various pressure terms (thermal, radiative, magnetic) and the global equilibrium in the ISM. In part 3, the H II regions section deals with atomic physics and radiative transfer.

7 - Cloud collapse

7.1 - Cloud equilibrium and stability

7.2 - Collapse and ambipolar diffusion

7.3 - Disks and Jets (Time scales of the processes at large scales and small scales)

Part 4 - Impact of Stars on their environment

8 - H II regions

8.1 - Strömgren sphere

8.2 - Processes in H II regions

9 - Dynamical processes induced by stars and supernovae

9.1 - Wind generation

9.2 - Shocks and turbulence

9.3 - Photo-evaporation

10 - Extragalactic environments

10.1 The different roles of UV photons and X-rays

10.2 Impact of the metallicity on the composition of the ISM

10.3 Molecular clouds in low metallicity galaxies and star formation rate

10.4 Cosmo-chemistry and the first stars

2.4 Physics of Satellite Navigation Systems

Teachers

Philp Tuckey (SYRTE) : philip.tuckey@observatoiredeparis.psl.eu

Overview

This course is strongly motivated by modern time-frequency and length metrology applied to positioning and navigation, and teaches various aspects of satellite navigation physics and engineering: orbits, on-board clocks, observational data, communication with ground stations, ... These topics are illustrated with the satellites of Global Navigation Satellite Systems (GNSS), but the concepts are easily applicable to other positioning and navigation systems, such as geodetic satellites, the Deep Space Network, ...

Detailed content

- Metrology of positioning: different methods available for positioning on Earth; analysis of positioning requirements for a given application; design of a positioning system that can satisfy such requirements.

- Orbits: physics of orbits and Kepler's laws; types of orbits around the Earth; orbit parametrization, Keplerian elements, perturbations, ...

- Atomic clocks: historical development of clocks; physics (quantum mechanics) of atomic clocks such as atomic energy levels, Schrödinger's equation, Rabi/Ramsey interrogation, analysis of interference signal in clocks; different types of atomic clocks.

- Time and frequency metrology of clocks: basic notions of uncertainty, stability and accuracy; Allan variance and power spectral density; systematic effects, in particular in atomic clocks.

- Relativistic chronometry: reference systems; space-time diagram and related concepts such as world line, light cone, proper time, space-time interval, simultaneity conventions, ... ; calculation of coordinate time and proper time for simple trajectories.

- Geodesy and geographic maps: notion of ellipsoid, geoid and map projection; conversion between geographic coordinates and Cartesian coordinates; classes of map projections.

- Physics of the atmosphere: influence of different atmospheric layers on GNSS signal propagation, in particular the ionosphere and troposphere; modelling of dispersion; tropospheric and ionospheric delays, orders of magnitude; rejection of ionospheric effects; correction of tropospheric effects.

- Physics of signals: general concepts such as pseudo-random code, communication capacity of a channel, carrier and modulation; GNSS signals, structure, codes (C/A, P and navigation message), frequency bands, separation of signals from different satellites, RINEX file format; measurement of pseudo-distance, code and phase, differential positioning.

- GNSS data analysis: use of GNSS-Laboratory (gLab), study of two positioning solutions, Standard Point Positioning and Precise Point Positioning, and various corrections applied.

2.5 Analytical mechanics

Teachers

Pierre Auclair-Desrotour (IMCCE) : pierre.auclair-desrotour@observatoiredeparis.psl.eu

Adrien Bourgoin (SYRTE): adrien.bourgoin@observatoiredeparis.psl.eu

Context

Two dominant branches of analytical mechanics are the Lagrangian mechanics (using generalized coordinates and corresponding generalized velocities in the state space) and the Hamiltonian mechanics (using coordinates and corresponding momenta in phase space). The two formulations are complementary. The first one is more general and allows the modeling of both dissipative and conservative systems. The second formulation is restricted to conservative systems but offers more geometrical properties providing general theorems and powerful algorithms. The course presents the basic principles of classical mechanics within the framework of the variational approach. The knowledge of these principles is necessary for a deeper penetration into the structure of the classical mechanics itself, and also for a proper understanding of statistical mechanics, quantum mechanics, etc. Furthermore, the methods of analytical mechanics can serve as a set of efficient tools for the analysis of the majority of hard problems in mechanics and related topics, such as dynamical systems.

Detailed content

I. Lagrangian formalism

- Newton's second law of motion
- Constraints
- D'Alembert principle
- Generalised coordinates and velocities
- Principle of least action
- Lagrange multipliers
- Conservation laws

II. Hamiltonian Equations

- Generalised momentum
- Legendre transform
- Hamiltonian
- Hamiltonian equations

III. Pendulum

- Model
- Fixed points

3. Phase space

- Small oscillations

IV. Canonical transformation

- Canonical variables
- Cyclic coordinates and conservation theorem

- Poisson brackets
- First integrals
- Integrable systems
- Canonical transformation

V. Hamilton-Jacobi theory

- Hamilton-Jacobi equation
- Action-angle variables

2.6 Relativity and cosmology

Teachers

Adrien Bourgoin (SYRTE): adrien.bourgoin@observatoiredeparis.psl.eu

Aurélien Hees (SYRTE) : aurelien.hees@observatoiredeparis.psl.eu

Detailed content

In italic, we indicate the topics that we are planning to offer as tutorials.

Part 1:

- historical introduction on the notions of relativity and inertia from Antiquity, Galileo, Newton and Einstein.
- quick demonstration that Maxwell equations (or more simply the wave equation) are not invariant under Galilean transformation and that this highlights a problem.
- Presentation and interpretation of the Michelson and Morley experiment.
- speed of light constant in any frame: first simple and intuitive examples of the implications (such as the loss of the notion of simultaneity).

Part 2:

- quick general introduction of the geometric background: 4D spacetime, 4-vectors, example of Newtonian spacetime.
- introduction of the notions of event and worldine in a 4D spacetime.
- introduction of the metric tensor as the mathematical tool for computing spacetime distances; Minkowski metric.
- introduction of the relativistic invariant ds^2 as the infinitesimal spacetime distance between events.
- introduction of the notion of proper time ; 4-velocity as a first concrete example of 4-vector.
- *easy manipulations of 4-vectors and metric tensor in Minkowski spacetime (scalar product, norm of a vector) ; introduction of the notions of timelike/spacelike/null vectors; light cone.*

Part 3:

- demonstration of the Lorentz transformation from the invariance of ds^2.
- space-time diagrams: notion of simultaneity.
- notion of observer.
- *applications and illustrations: length contraction, time dilation, relativistic aberration and applications in astrophysics, relativistic Doppler, beaming.*
- illustration of all this with pedagogical " relativistic images " as that published by Daniel Weiskopf at the University of Tubingen.

Part 4 :

- introduction of the relativistic action, derivation of momentum and energy.
- relativistic equations of motion.
- introduction of 4-momentum and conservation.
- *application of $E = \gamma mc^2$ to particles accelerators and to cosmic rays.*
- *application to desintegration of 2 particles, collisions of 2 particles, nuclear fusion/fission, Cerenkov radiation.*

Part 5:

- historical introduction to general relativity (GR) and the ideas that led Einstein to GR.
- emphasis on the equivalence principle and experimental confirmation (MICROSCOPE, GRAVITY S2 star test)
- consequences of the equivalence principle: geodesic motion; weak-field derivation of the behavior of clocks, redshift
- *illustration with the example of the GPS*
- application: gravitational redshift and experimental verification (ACES, GRAVITY S2 star measurement)

Part 6:

- presentation of the Schwarzschild metric (no derivation)
- conserved quantities along geodesics (energy and angular momentum at infinity)
- timelike and null geodesics in Schwarzschild spacetime; effective potential
- *emphasis on circular timelike geodesics, innermost stable circular orbit; illustration by the discussion of accretion disks around compact objects (focus on Sgr A* and M87).*

Part 7:

- fundamental effects linked to geodesic motion in Schwarzschild spacetime:

  - *advance of periastron* and experimental verification (in the Solar System and using the S2 star around Sgr A* with GRAVITY)

  - *lensing* and experimental verification (quasar double images, *black hole shadow* and M87 image by EHT)

  - *Shapiro time delay* and application (Cassini, microlensing)
- introduction to Einstein Equation (no demonstration; intuitive introduction of Riemann tensor and stress-energy tensor and special case of a perfect fluid for later use in the cosmology section)

Part 8:

- linearized Einstein Equation and gravitational wave (GW) propagation (no demonstration
- discussion on the two polarizations of GW; link between the gravitational luminosity and the derivative of the source quadrupole (no demonstration);
- *waveform of a circular binary system*: orders of magnitude for the frequency and amplitude of the GW;

Part 9:

- geodesic motion in FLRW spacetime; cosmological redshift; Hubble and acceleration parameters; *derivation of Hubble law*; discussion of experimental measurements of Hubble and acceleration parameters (supernovae, cepheids)
- proper distance; luminosity distance; angular distance; what is observable and how
- components of the cosmological fluid: matter, radiation, vacuum (cosmological constant)
- Friedmann equations for the evolution of the scale factor, taking into account a perfect fluid for the stress-energy content (no demonstration, but explaining that they are the special case of Einstein Equation for the FLRW metric);
- derivation of the evolution equation for density, explicit solution for p=w*rho equation of state, for matter, radiation, and vacuum; Friedmann equation in terms of density parameters

Part 10:

- discussion on few possible evolutions of the scale factor (big bang, big crunch, expansion, contraction, accelerated expansion...); quick introduction of dark energy for accelerated expansion; presenting the Euclid project in a nutshell.
- quick introduction of CMB: recombination, *blackbody temperature evolution T(z) derived from the density evolution of radiation, derivation of today's CMB temperature from its temperature at recombination* ; presenting the Planck and LiteBIRD projects in a nutshell.
- quick introduction of dark matter; *understanding its necessity from galaxy rotation curves*; probing dark matter with weak lensing.
- how the LambdaCDM model incorporates all the above; its parameters (at least the part of these that can be understood at this point); experimental determination of the cosmological parameters.

2.7 Stellar physics

Teachers

Caroline Barban (LESIA) : Caroline.Barban@observatoiredeparis.psl.eu

Laia Casamiquela (GEPI) : Laia.Casamiquela@observatoiredeparis.psl.eu

Rhita-Maria Ouazzani (LESIA) : Rhita-Maria.Ouazzani@observatoiredeparis.psl.eu

Detailed content

1) Stellar Observables

Introduction to stellar Observations: how do we quantify the basic parameters of stars? Spectrometric, astrometric and asteroseismic constraints on stellar parameters (brightness, magnitudes, temperature, mass, radius, etc), Hertzsprung-Russel diagram (HRD). Large surveys (Gaia)

2) Stellar Atmospheres

How does radiation interact with matter at the surfaces of stars, to produce the observables we measure? Reminders of atomic physics concepts, Stellar spectra, Excitation & Ionization, Describing the Radiation Field, Radiation & Matter, Radiative Transfer, Model Atmospheres, Opacity Sources, Line broadening, Eddington-Barbier relation, Examples of applications

3) Stellar Interiors

what processes determine the interior structure, composition and evolution of stars? Equation of state of the gas, conservation of mass, hydrostatic equilibrium, radiative and convective energy transport, nuclear energy source, comparison of a star's structure at different stages (HR diagram).

2.8 (Astro)-particle physics

Teachers

Andreas Zech (LUTH) Andreas.Zech@observatoiredeparis.psl.eu

Detailed content

lessons 1-4 : phenomenological introduction to the standard model of elementary particles

- elementary and constitute fermions

  - characteristics of quarks and leptons, spin-statistics theorem, anti-particles
  - baryons, decays and resonances

- bosons, gauge bosons and fundamental interactions

  - characteristics of gauge bosons, the Higgs boson, mesons
  - characteristics of fundamental interactions, conservation rules
  - interaction cross section and Feynman diagrams
  - Klein Gordon wave equation, Yukawa theory

- structure of nuclei and atoms

  - liquid drop model for nuclei
  - shell model for nuclei and atoms, Pauli principle

- beyond the standard model

  - super-symmetry, grand unified theories, theory of everything
  - dark matter candidate particles: WIMPs, axions
  - direct dark matter searches (e.g. Edelweiss, ...)

lessons 5-6 : gamma-ray astrophysics

- astrophysical sources and emission mechanisms, dark matter searches

  - Inverse Compton radiation, pion decay
  - the link with particle acceleration and cosmic rays
  - Galactic sources, extragalactic sources, diffuse background

- indirect dark matter searches with gamma-rays

- direct detection : pair production telescopes

  - a look at the Fermi-LAT telescope (pair production, detector layout)
  - the gamma-ray sky seen with Fermi-LAT

- indirect detection : electromagnetic air showers, Cherenkov emission

  - introduction to electromagnetic air showers, Cherenkov emission
  - a look at the HESS Cherenkov telescopes (indirect detection method, layout)
  - the very-high-energy sky

journal club : discussion of recent detections with Fermi-LAT and a Cherenkov telescope array

lessons 7-8 : cosmic-ray physics

- potential astrophysical sources and emission mechanisms

  - cosmic ray spectrum, Hillas diagram
  - cosmic ray composition
  - cosmic ray propagation
  - cosmic ray accelerators, the link with dark matter

- direct detection : mass spectrometers (e.g. AMS, ...)

  - a look at the AMS detector (layout)
  - results from AMS: particle spectra, antiparticles, dark matter searches

- indirect detection : hadronic air showers, fluorescence emission (e.g. Auger,...)

  - introduction to hadronic air showers, fluorescence emission
  - a look at the Pierre Auger Observatory (surface detectors, fluorescence detectors)

- results from Auger: spectrum, composition, origin of UHECRs

journal club : discussion of recent detections with AMS and Auger

lessons 9-10 : neutrino astronomy

- potential astrophysical sources and emission mechanisms, the link with dark matter

  - neutrino production in weak decays
  - neutrino interactions with matter, neutrino oscillations
  - known and potential sources of neutrinos

- direct detection : solar neutrinos, SN1987A

  - neutrino detectors at MeV energies (e.g. SuperKamiokande, SNO,...)
  - observations of solar neutrinos and neutrinos from SN1987A

- indirect detection : large-scale neutrino detectors

  - neutrino detectors at TeV/PeV energies (e.g. IceCube, Antares,...)
  - results from IceCube
  - neutrino detection at ultra-high energies (e.g. Auger, Anita,...)

journal club : discussion of recent detections with IceCube

" journal club " : An important methodological component of the course will be the lecture and presentation of recent scientific articles. Appropriate papers, corresponding to the topics of the lectures, will be proposed to the students, who, after selection of a paper, have two weeks to prepare a presentation to be given in front of the class.

2.9 (Exo)planetary physics

Teachers

Emmanuel Lellouch (LESIA): Emmanuel.Lellouch@observatoiredeparis.psl.eu

Cédric Leyrat (LESIA) : Cedric.Leyrat@observatoiredeparis.psl.eu

Bruno Sicardy (LESIA) : Bruno.Sicardy@observatoiredeparis.psl.eu

Quentin Kral (LESIA) : Quentin.Kral@observatoiredeparis.psl.eu

Detailed content

Formation of planetary bodies (B. Sicardy)

1) gravitational instability (effects of pressure, rotation and self-gravity on a disk, Toomre's stability parameter)

2) grain growth, coagulation (from grains to planetesimals, focusing parameter)

3) dynamical evolution, collision processes (runaway growth, streaming instability)

4) planet migration, resonances, stability (migrations of type I and II, connection with course on resonance effects: gravity)

Planetary interiors (B. Sicardy)

1) equation of state, hydrostatic equilibrium (basics of internal structure, respective effects of thermal and Fermi pressure from a simple point of view, figures of equilibrium: Maclaurin and Jacobi solutions)

2) gaseous and telluric planets (applications of the above to the current planets in the solar system, importance of radiogenic heating for solid bodies)

3) differences between planets and dwarf planets

Planetary surfaces (C. Leyrat)

1) Formations and evolutions

- Planetary Surfaces formations (cooling, Al. radioactivity effects during post-formation times, crusts formation and differentiation)
- Planetary surfaces evolutions :

- Craterisation (impact processes, craters shapes, energy exchange, viscous relaxation, absolute/relative age counting, impactors)

- Evolution of atmosphereless surfaces (space weathering, energetic particles, thermal stresses, migrations of volatiles)

- Erosion and sedimentation of surfaces with atmospheres (winds, transports of regolith w.r.t size grains, ice sublimation, coupling with dust, dunes formations, sediments...)

- Tectonic and volcanism + cryovolcanism

All previous effects will be detailed with the most recent spacecraft discoveries.

2) Processes of radiations

- Radiative transfer inside regolith (effects of grain size, phase angle, composition and spectroscopic measurements) - Hapke, Skuratov formalism
- Thermal emission of surfaces :

- Conduction (approximations, boundary conditions)

- Radiative transfer inside subsurface

- Thermal emission at long wavelengths and Jeans approximations :

Polarizations effects ; Dust contamination effects ; Dielectric constants ; Notions of skin depths ; Several examples and exercises.

- **(Exo)Planetary atmospheres (E. Lellouch)**

1) basic concepts, nomenclature

2) diversity of atmospheres

3) effects on solar/stellar radiation

4) methods of investigation

5) photochemistry, thermochemistry, transport

6) radiative balance, vertical structure, greenhouse effect

7) global warming

8) atmospheric dynamics, climate models, habitability

2.10 MHD & Space plasmas

Teachers

Olga Alexandrova (LESIA) : Olga.Alexandrova@observatoiredeparis.psl.eu

Arnaud Zaslavsky (LESIA) : Arnaud.Zaslavsky@observatoiredeparis.psl.eu

Context

Plasmas and ionised gases are the major part of the visible universe, and are relevant to a broad range of astrophysical objects, electricity in the Earth's atmosphere, and the space environment of the Earth, as well as applications in terrestrial laboratories. This course is to provide the basic physics of plasmas, starting from the fluid description and discussing the more general context of statistical physics.

Methodological skills

theory, modelling

Astrophysical skills

Understanding the structure and dynamics of a wide range of astrophysical environments and processes: stellar atmospheres and winds, interstellar medium, origin and propagation of energetic particles, magnetic fields and their interaction with matter.

Ongoing and future ground-based and space-borne instruments

Solar Orbiter, Parker Solar Probe, Bepi Colombo; Magnetospheric Multiscale Mission (MMS); Taranis; LOFAR, SKA, solar radio observations; Auger, H.E.S.S., CTA

Detailed content

Domains of illustrations are within parentheses.

- An introduction to ionised gases and plasmas

  - Plasmas in the Universe
  - Binary collisions vs long-range interactions; collision frequencies (stellar interior, stellar atmospheres and winds)
  - What is a plasma? Collective behaviour, Debye shielding, Debye length, plasma oscillations, plasma frequency

- Particle motion in magnetic fields

  - Test-particle motion; cyclotron frequency, Larmor radius
  - Particle drifts (Earth's magnetosphere, propagation of cosmic rays)
  - Adiabatic invariants; application: Fermi acceleration (SNR)

- The MHD description of a plasma

  - Fluid description of a plasma: motion of a conductive fluid in a magnetic field (stars, planetary magnetospheres, Heliosphere)
  - MHD approximations
  - Lorentz force and Maxwell's equations in non-relativistic approximation
  - Plasma electric conductivity
  - Induction or Advection-diffusion equation for magnetic field
  - Magnetic Raynolds number
  - Resistive MHD
  - Ideal MHD
  - Frozen-in magnetic field in ideal MHD
  - Magnetic field line and flux tube
  - Magnetic forces: magnetic pressure, magnetic tension (examples in different magnetic configurations, i.e., current sheet, x-type field lines)
  - MHD waves: Alfven waves, fast and slow magnetosonic waves (introduction to Alfvenic turbulence)
  - Conservation relations in ideal MHD

- Kinetic description of a plasma

  - Introduction to the statistical description of a plasma - connection with statistical physics course; distribution function
  - Maxwellian distribution and alternatives in a tenuous plasma (measurements in the solar wind)
  - The evolution of the distribution function: Boltzmann, Vlasov, Fokker-Planck
  - Illustration of the transition from the statistical description to the fluid picture: equation of continuity, pressure tensor (+reference to plasma physics M2 for further developments)

2.11 Observational techniques and Data analysis

Teachers

Laia Casamiquela (GEPI) : Laia.Casamiquela@observatoiredeparis.psl.eu

Stéphane Erard (LESIA) : Stephane.Erard@observatoiredeparis.psl.eu

Miguel Montarges (LESIA) : miguel.montarges@observatoiredeparis.psl.eu

and collaborators

Context

Astrophysics is based on the data analysis of highly-performing instruments. This lecture provides skills to carry out observations in the visible with classical techniques (imaging, spectroscopy) and to master the associated data reduction.

Sky observations are planned between monday and friday from january to march, weather permitted.

Methodological skills

The unit is essentially methodological

Astrophysical skills

Physics for instrumentation: optics, detection, data analysis

Ongoing or future ground-based or space-borne projects

All

Detailed content

A first part is devoted to courses introducing the tools (instruments, cameras). Then a second part is devoted to the observations and to the corresponding data reduction, in Python.

Nightly observations are performed at the Meudon Observatory, using 0.3-1m class telescopes and semi-professional instruments.

Topics

- Pointing a telescope, celestial coordinates, telescope optics.
- Data reduction of observational data, using of professional software tools (python).

Practical exercises at least on two topics:

- CCD imaging. Introduction to the following notions: point spread function, aberrations, bias and noise, spatial resolution, acquisition and processing of digital data.
- Spectroscopy: principle of the spectrograph , spectral resolution, bias and noise, acquisition and processing of digital data.

Optional practical work on speckle imagery: atmospheric turbulence, seeing, point spread function, speckle, spatial resolution, acquisition and processing of digital data.

Up to three possible themes will be covered: imaging, spectroscopy and speckle imaging. Each of these themes will be the subject of observations on several telescopes at Meudon.

Chapter 3

Lectures and majors

Instrumental astrophysics : InstrA   Observational astrophysics : ObsA

Numerical astrophysics : NumA   Theoritical astrophysics : TheoA

Digital engineering : DigEng   Instrumental engineering : InstrEng

SEMESTRE 1: 1 semestre = 30 ECTS

Lectures	ECTS	InstrA	ObsA	NumA	TheoA	DigEng	InstrEng
Optionnal lectures							
Quantum Mechanics	6			X	X		
Statistical physics	6			X	X		
Instrumentation: physics and instruments	6	X	X			X	X
Data Processing and associated methods 1	3	X	X			X	X
Data Processing and associated methods 2	3	X	X			X	X
Hydrodynamics	3			X	X		
General Astronomy	3	X	X			X	X
Mathematical Physics	3			X	X		
Classical Gravitation	3			X	X		
Mandatory lectures							
Computer Science	3	X	X	X	X	X	X
Lab Insertion Unit	6*	X	X	X	X	X	X

* A Lab Insertion Unit of 3 ECTS + PSL course of 3 ECTS might be possible in specific cases.

For the first semestre:

each studend has to choose 2/2.5/3 lectures for a total of 12/15/18 ECTS among the following ones:

- Quantum Mechanics 6 ECTS

- Statistical physics 6 ECTS

- Instrumentation: physics and instruments 6 ECTS

- Data processing and associated methods (3+3) ECTS

each studend has to choose 3/2/1 lecture(s) for a total of 9/6/3 ECTS among the following ones:

- Fluid mechanics 3 ECTS

- General astronomy 3 ECTS

- Mathematical physics 3 ECTS

- Classical gravitation 3 ECTS

SEMESTRE 2: 1 semestre = 30 ECTS

For the 2nd semestre, each student has to choose a number of lectures depending on the duration of the training period. For example, for a 2-month training period, the student has to choose 7 lectures (3 ECTS each) for a total 21 ECTS.

- Instrumental astrophysics : InstrA

- Observational astrophysics : ObsA

- Numerical astrophysics : NumA

- Theoritical astrophysics : TheoA

- Digital engineering : DigEng

- Instrumental engineering : InstrEng

Lectures	ECTS	InstrA	ObsA	NumA	TheoA	DigEng	InstrEng
Optionnal lectures							
Numerical Analysis	3			X		X	
Gravitation of extended bodies and Galactic dynamics	3						
Physics of the Interstellar medium	3						
Metrology of satellites	3						
Analytical Mechanics	3						
Relativity and Cosmology	3				X		
Stellar physics	3						
(Astro)-particle physics	3						
(Exo)planetary physics	3						
MHD & Space plasmas	3						
Mandatory lectures							
Observational techniques & Data analysis	3	X	X	X	X	X	X
Training periode	9, 15 or 21	X	X	X	X	X	X

Chapter 4

Lectures and M2 projects

Here are the recommended lectures depending on the M2 project.

For the M2 IRT, no specific lectures are recommanded.

Some lectures that are recommanded for a specific M2 project could be followed by student with other M2 project after approval by the M1 pedagogical team.

SEMESTRE 1: 1 semestre = 30 ECTS

Lectures	ECTS	AADC	PES	OSAE
Optionnal lectures				
Quantum Mechanics	6	X	X	
Statistical physics	6	X		
Instrumentation: physics and instruments	6			X
Data Processing and associated methods 1	3	X	X	X
Data Processing and associated methods 2	3	X	X	X
Hydrodynamics	3	X	X	
General Astronomy	3	X	X	X
Mathematical Physics	3	X		
Classical Gravitation	3	X	X	
Mandatory lectures				
Computer Science	3	X	X	X
Lab Insertion Unit	6*	X	X	X

* A Lab Insertion Unit of 3 ECTS + PSL course of 3 ECTS might be possible in specific cases.

Examples of lectures choices for the 1st semestre depending on the M2 project. Other choices are possible according to the M1 pedagogical team approval.

M2/AADC, 1st semestre :

One choice example:

Quantum mechanics (6 ECTS) + Statistical physics (6 ECTS)

General Astronomy (3 ECTS) + Mathematical Physics (3 ECTS) + Gravitation (3 ECTS)

Another choice example:

Quantum mechanics (6 ECTS) + Statistical physics (6 ECTS)

Hydrodynamics (3 ECTS) + Mathematical Physics (3 ECTS) + General Astronomy (3 ECTS)

Another choice example:

Quantum mechanics (6 ECTS) + Statistical physics (6 ECTS) + Data processing (3 ECTS)

Mathematical Physics (3 ECTS) + Gravitation (3 ECTS)

Another choice example:

Quantum mechanics (6 ECTS) + Statistical physics (6 ECTS) + Data processing (3 ECTS)

Mathematical Physics (3 ECTS)

Another choice example:

Quantum mechanics (6 ECTS) + Statistical physics (6 ECTS) + Data processing (3 ECTS)

Gravitation (3 ECTS) + General Astronomy (3 ECTS)

Another choice example:

Quantum mechanics (6 ECTS) + Instrumentation (6 ECTS) + Data processing (6 ECTS)

General Astronomy (3 ECTS)

M2/PES, 1st semestre :

One choice example:

Quantum mechanics (6 ECTS) + Statistical physics (6 ECTS)

Hydrodynamics (3 ECTS) + Mathematical Physics (3 ECTS) + General Astronomy (3 ECTS)

Another choice example:

Quantum mechanics (6 ECTS) + Statistical physics (6 ECTS) + Data processing (3 ECTS)

Gravitation (3 ECTS) + General Astronomy (3 ECTS)

Another choice example:

Quantum mechanics (6 ECTS) + Instrumentation (6 ECTS) + Data processing (6 ECTS)

General Astronomy (3 ECTS)

M2/OSAE, 1st semestre :

One choice example:

Instrumentation (6 ECTS) + Data processing (6 ECTS)

Hydrodynamics (3 ECTS) + Mathematical Physics (3 ECTS) + General Astronomy (3 ECTS)

Another choice example:

Instrumentation (6 ECTS) + Data processing (6 ECTS)

Hydrodynamics (3 ECTS) + Gravitation (3 ECTS) + General Astronomy (3 ECTS)

Another choice example:

Instrumentation (6 ECTS) + Data processing (6 ECTS)

Mathematical Physics (3 ECTS) (3 ECTS) + Gravitation (3 ECTS) + General Astronomy (3 ECTS)

SEMESTRE 2: 1 semestre = 30 ECTS

Lectures	ECTS	AADC	PES	OSAE
Optionnal lectures				
Numerical Analysis	3	X	X	X
Gravitation of extended bodies and Galactic dynamics	3	X		
Physics of the Interstellar medium	3	X	X	X
Metrology of satellites	3	X		
Analytical Mechanics	3	X		
Relativity and Cosmology	3	X		
Stellar physics	3	X	X	X
(Astro)-particle physics	3	X	X	X
(Exo)planetary physics	3		X	
MHD & Space plasmas	3	X		
Mandatory lectures				
Observational techniques & Data analysis	3	X	X	X
Training periode	9, 15 or 21	X	X	X