M2 Astrophysics, Space science and Planetology (Science track), Toulouse
(all courses September – December)
Syllabus (English version)

UE : K5SUAE – Physics & astrophysics (15 ECTS)

- **KSUA9AA1** – Radiative processes and radiative transfer – 20h
- **KSUA9AA2** – Gravitation – 20 h
- **KSUA9AA3** – Fluid dynamics – 20 h
- **KSUA9AA4** – Space plasma physics – 20h
- **KSUA9AA5** – Formation and evolution of planetary systems - 20 h
- **KSUA9AA6** – Stellar physics - 20 h
- **KSUA9AA7** – Extragalactic astrophysics and cosmology - 20h

UE : K5SUAE – Transversal courses (9 ECTS)

- **KSUX9AC1** – Instrumentation for astrophysics – 20h
- **KSUX9AC2** – Analysing data and images – 6h
- **KSUX9AC3** — Advanced space mechanics – 12h
- **KSUX9AC4** – Engineering systems – 12h
- **KSUX9AV1** – Scientific English – 24 h

UE : K5SUAE – Astrophysics – the options : 3 modules to choose – 15h each (6 ECTS)

- **KSUA9AB1** – Interactions of planets with their environment
- **KSUA9AB2** – The interstellar medium and stellar formation
- **KSUA9AB3** – Stellar and planetary sismology
- **KSUA9AB4** – Compact objects and accretion
- **KSUA9AB5** – Cosmology and galaxy physics

UE : K5SUAE – Numerical simulations (3 ECTS)

KSUAAAA1 – Numerical simulations and data processing – 30h

Second semester : January – June (5 months)

UE : K5SUAE – Internship (27 ECTS)

●**KSUA9AA1** – Radiative processes and radiative transfer – 20h

LEARNING OBJECTIVES
Know the most frequently found radiation processes in astrophysics and acquire the basics in radiative transfer, for interpreting data

SUMMARY DESCRIPTION OF LESSONS ‘
- Reminders of electromagnetism: Liénard-Wiechert potentials; radiation emitted by charges
relativistic or non-relativistic charges: power and angular distribution; dipolar approximation
- Cyclo-synchrotron radiation: power, polarisation, ‘emission of a distribution of particles; absorption
synchrotron
- Rayleigh scattering
- Thomson and Compton scattering; inverse Compton; scattering by a distribution of particles; multiple scattering
- Bremsstrahlung; mono-energetic and thermal radiation
- Radiation transfer: definitions; transfer equation (REE) and moments of the REE
- Formal solution of the transfer equation: Kirchoff-Bunsen laws; Eddington-Barbier approximation,
Schwarzschild-Milne equations; local thermodynamic equilibrium (LTE)
- Radiative equilibrium: effective temperature; diffusion approximation; Rosseland opacity; the ‘grey case’; law of limb darkening law
- Opacities: scale balance; partition function; the H- ion, ‘statistical equilibrium’; basis of spectral classification; concepts of off-ETL transfer
- Physics of spectral line broadening
- Polarisation of spectral lines
- Digital transfer

●**KSUA9AA2** – Gravitation – 20 h

LEARNING OBJECTIVES
To introduce students to General Relativity and its initial applications.

SUMMARY DESCRIPTION OF LESSONS ‘
- Principles of relativity: Galilean, restricted, general. Principle of equivalence.
- Tensor analysis and covariance: metric, coordinate system, tensor, affine connection, geodesic, covariant erivity, parallel transport.
- Curvature of space: Riemann tensor, geodesic eviation, Bianchi identities.
- Einstein's equations, cosmological constant.
- Applications of general relativity: Schwarzschild metric, redshift, the advance of the
the Shapiro effect; introduction to Schwarzschild black holes; modern tests of relativistic relativity. tests of general relativity.
- Kinematics of the universe: cosmological principle, FRW metric, distance measurements, Hubble's law
- Dynamics of the universe: Friedmann equations, examples of solutions, cosmological parameters; standard cosmological
cosmological model.
- Introduction to gravitational waves: lin'earis'ed solution, polarisation; gravitational wave generation; optical detection.

KSUA9AA3 – Fluid dynamics – 20 h

LEARNING OBJECTIVES
The aim of this course is to train students in the elements of fluid mechanics most widely used in astrophysics. fluid mechanics most commonly used in astrophysics.

SUMMARY DESCRIPTION OF TEACHING
- A brief review of fluid dynamics in astrophysics. Flow stability: generalisations; local analysis, global or modal analysis; planar sheared flows, Squire's theorem.
- Thermal convection: introduction; Schwarzschild criterion; Boussinesq approximation; Rayleigh-B'enard instability. turbulent convection: two simple approaches to mixture length theory, boundary layer model.
- Rotating fluids: introduction; reminders of Rossby and Ekman numbers and of geostrophic flow, waves and eigenmodes of rotating fluids; Ekman boundary layer; examples.
- Introduction to turbulence: route to turbulence; developed turbulence - possible symmetries; two-point velocity correlations; spectra; dynamics of universal turbulence (Kolmogorov's theory) Karman-Howarth and Kolmogorov equations
- Shock waves: introduction; formation of a shock wave; conditions for the passage of a discontinuity.
- Fluid dynamos: reminder of conductive fluids; how to amplify the magnetic field - the antidynamic theorems. basics of turbulent dynamo.

KSUA9AA4 – Space plasma physics (G. Fruit, V. Genot) – 20h

LEARNING OBJECTIVES
Presentation of the mathematical foundations of plasma physics (kinetic and fluid theory) and of some of the major applications in astrophysique and geophysics. An important part of the course is devoted to the propagation of waves and electromagnetic waves and plasma instabilities. An introduction to the ’epineux’ problem of magnetic reconnection and shock physics.

SUMMARY OF TEACHING
- Kinetic description of a plasma: Vlasov equation - Liouville theorem; application to the Harris layer.
- Fluid description of a plasma: derivation of the fluid equations; closure problem; MHD (review).
- Waves in plasmas: Langmuir ‘electrostatic’ modes; ‘electromagnetic’ waves in cold plasma; Alfv'en waves; electrostatic waves in hot plasma - Landau damping.
- Introduction to magnetic reconnection: problematics; Sweet-Parker model.
- Astrophysical shocks

KSUA9AA5 – Formation and evolution of planetary systems – 20 h

LEARNING OBJECTIVES
This course aims to provide a fundamental grounding and a broad view of our knowledge of the formation and evolution of planetary systems, both in terms of the models proposed and the observations made, particularly through the latest results of space exploration missions, as well as from the analysis of the data we have collected and analysis of meteorites.

SUMMARY DESCRIPTION OF LESSONS
A/ Formation and evolution of planetary systems
1/ Properties of gas and dust in protoplanetary disks. Thermal, chemical and dynamic evolution of the disks.
2/ Formation of telluric and giant planets via the accretion of planetes. Atmosphere of (exo)planets. Internal and orbital evolution of planets (planetary migration, interactions with the star). Comparison of models of planet formation and evolution with observations of exoplanetary systems.
B/ Formation of planets in the solar system through the study of meteoroids and small bodies
Study of the early history of the solar system based on small bodies (asteroids, comets, satellites). Presentation of the periological, mineralogical and chemical diversity of meteoroids, and their origin in relation to current space missions. missions. Reconstruction of the chronology of the early solar system (formation of the first solids, internal differentiation) and the astronomical properties of solar particles (asteroids, comets and KBO).

KSUA9AA6 – Stellar physics - 20 h

LEARNING OBJECTIVES
Deepen knowledge of the physics of stars

SUMMARY DESCRIPTION OF TEACHING
- Overview of the place of stellar physics in modern astrophysics
- Reminder of the standard model: why do we need non-standard processes?
- Microscopic processes: atomic diffusion, gravitational sorting and radiative acceleration
- Macroscopic processes: convective/radiative zone boundaries (penetrative convection, overshoot), rotation and meridian circulation in radiative zones, turbulent transport and anisotropic turbulence, binary stars, tidal forces
- Other transport processes: internal waves and the magnetic field
- The standard model of stellar atmospheres: radiative transfer :
- radiative equilibrium, mechanics, statistics - static 1D atmospheres and LTE - fundamental parameters, abundances, (pg-pe-T) relationship - microturbulence, line bisectors, line blanketing, current digital resources current digital resources
- Beyond standard models: new abundances
- Polarimetric measurement: overview, M¨uller matrices, polarimeter formation, spatial and temporal modulations, applications modulations, applications
- Exploitation of polarised stellar spectra: extraction of polarised signals, astrophysical exploitation

KSUA9AA7 – Extragalactic astrophysics and cosmology – 20h

LEARNING OBJECTIVES
Understand the basics of cosmology and galaxy physics

SUMMARY DESCRIPTION OF LESSONS
Cosmological parameters
Dark matter: galaxies, clusters, large scales, direct and indirect searches, gravitational lensing.
Large-scale structure: 2-point, angular and 3D correlation functions, estimators. Cell counting, scaling.
Structure formation theory: Linear Newtonian perturbations, Jeans scale, sound horizon, nonlinear regime, virialisation, structure mass function, scaling laws, theory and numerical observations/simulations.
Galactic dynamics (general considerations) : Relaxation of stellar systems, Jeans equations, mass distribution models.
Galaxy dynamics: Scale relations, rotation curves, disc dynamics, spiral structure, special cases.
Chemical evolution and spectro-photometry of galaxies: Basic equations, IMF, simple analytical models, spectro-photometric models, population synthesis models, digital models and public tools for determining the physical parameters of galaxies from spectra
Active galactic nuclei (AGN): Properties, types of AGN, standard model, radiation mechanisms, formation of super-massive black holes, co-evolution.

KSUX9AC1 – Instrumentation for astrophysics - 20h

LEARNING OBJECTIVES
Acquisition of a solid general knowledge of observation systems for astronomy beyond the visible: Radio, Infrared, sub-mm, X- and Gamma-ray, non-photonic astronomy, Astroparticles.

SUMMARY DESCRIPTION OF COURSES
observation systems for *submillimetre, *infrared, *UV, *X and *Gamma astronomy :
* optical (mirrors, radio astronomical antennas, Wolter telescopes, grazing incidence/multilayer, cod'es masks, Compton telescopes, hodoscopes, gamma lenses, Cerenkov telescopes), * detectors (bolometers, CCDs, arrays, heterodyne chains, microchannel wafers, microcalorimeters, gas detectors, scintillators, photomultipliers, semiconductors, bolometers)* spectroscopy (dispersive, non-dispersive), imaging, polarim'etrie* Mission requirements (type(s) of orbit, attitude, pointing performance, thermal control, etc.)
Astroparticles: cosmic ray detectors, neutrino telescopes; gravitational wave detectors; instruments for direct detection of dark matter.

KSUX9AC2 – Analysing data and images – 6h

LEARNING OBJECTIVES
Instruments in the sciences of the Universe acquire data corresponding to the observation of astrophysical objects. This data does not generally consist of a direct measurement of physical quantities of interest, which requires the data to be processed.
The aim of this course is to introduce the tools needed to exploit this data.
The emphasis will be on tools for estimating parameters and will be illustrated by concrete examples of data processing in the sciences of the Universe

SUMMARY DESCRIPTION OF COURSES ‘
I. Introduction to estimation and optimisation
II Spectral analysis of signals and the case of irregular sampling
III. Sparsimonious representations of signals and images and applications in the sciences of the Universe ;
IV. Econvolution, inverse problems and applications in the sciences of the Universe.
Illustrated with practical examples of numerical estimation and optimisation methods for data processing
with applications such as :
- Estimation of the PSF from the observation of an unresolved object
- Estimation of morphology parameters from the observation of a galaxy
- Search for periodicity in irregularly sampled signals
- Estimation of a high-resolution PSF from several low-resolution images
- Improving image resolution through deconvolution

In these Matlab practical exercises, students will have the opportunity to program simple methods and exploit existing libraries for more complex methods.

KSUX9AC3 — Advanced space mechanics - 12h

LEARNING OBJECTIVES
After a reminder of the basics of Space Mecanics (M1 SUTS) the objective is to obtain a general culture in SCAO: know the basic control problems, familiarise yourself with physical phenomena and their scale.

SUMMARY DESCRIPTION OF COURSES
Space Mechanics
Keplerian motion. Earth satellites. Orbits. Perturbation theory. M1 SUTS reminder.
SCAO : System Attitude Commande and orbital definition of attitude control referentiels used in space science, attitude representations (Euler, transition matrix, quaternion), kinematic and dynamic equations.
Space environment and perturbing couples: aerodynamic forces, atmospheric density, solar pressure, Earth's magnetic field, gravitational gradient.
Reminder of the most common sensors/actuators and how they work (solar sensors, terrestrial sensors, star sensors, magnetometer, gyroscope, nozzles, reaction wheels, and magn'eto-couplers.)
Review of several attitude control concepts: passive stabilisation by

spin/gravity gradient, triaxial control with or without kinetic energy bias, magnetic modes
Introduction to automatic control and application to space: PID, phase advance, filtering, stabilisation of linear systems, Laplace transforms, applications to flexible modes (solar panels).

KSUX9AC4 – Engineering systems – 12 h

SUMMARY DESCRIPTION OF LESSONS
This course introduces the notion of System, the technical and organisational complexity associated with its realisation, and introduces the concepts of System Engineering, which covers all the activities involved in moving from an expressed need to a solution. The following aspects are addressed:
- The technical point of view: how do you build a system that meets the customer's expectations?
- The organisational point of view: the life cycle of space projects, project management processes, work breakdown structure (WBS), etc., planning, risk management, communication management.

The course is illustrated by examples of major space systems (e.g. GALILEO navigation system).
The course is punctuated by exercises to enable students to assimilate the various concepts covered as they progress.
In order for the students to concentrate on the methodology and not on the content, these exercises are deliberately chosen from outside the space discipline.

KSUX9AV1 – Scientific English – 24 h

LEARNING OBJECTIVES
Communicate (written and spoken) scientific and technical ideas
Understand scientific and technical presentations

SUMMARY DESCRIPTION OF TEACHING
- Write a summary of an article or proposal in English
- Writing a scientific article in English
- Writing a proposal in English
- Evaluating proposals in English
- Applying for a job (CV, covering letter) in English
- Interviewing in English
- Presenting work orally in English
- Asking questions in English
- Presenting written work (poster) in English
- Lead a debate in English
- Understand an article/presentation in English
- Write a press release in English

KSUA9AB1 – Interactions of planets with their environment

LEARNING OBJECTIVES
The aim of this course is to learn the concepts, physical processes and methods of analysis relating to the study of solar-planetary relationships, often referred to as ‘heliophysics’. The solar atmosphere is not in hydrostatic equilibrium and continuously emits a wind of particles associated with a magnetic field. This solar wind interacts with all the objects in the solar system.
These interactions are modulated not only by the high variability of the wind, but also by the nature of the bodies encountered, in particular whether or not they are magnetised or not. This course will present different models for the evaluation of the diversity of space data acquired over the last fifty years.

SUMMARY DESCRIPTION OF LESSONS
- General introduction to heliophysics
- Generation of the solar wind and the interplanetary magnetic field - Parker model, kinetic model
- Transient solar wind events: coronal mass ejections, co-rotating interaction regions
- Boundary formation: shocks, magnetopause
- Description and dynamics of the magnetospheric system: Dungey cycle, solar wind-magnetosphere-ionosphere coupling, substorms, space meteorology.
- Analysis of multi-satellite in-situ data using online tools

KSUA9AB2 – The interstellar medium and stellar formation

LEARNING OBJECTIVES

Deepen knowledge of cosmology and the physics of galaxies

SUMMARY OF TEACHING

Thermal history of the primordial universe: relic abundances, cold and hot dark matter, asymmetry, antimatter, baryogenesis

Physics of the primordial universe: Limits of the standard model, Dynamics of a scalar field, Inflation, Quintessence, Modified gravity

Perturbation theory: relativistic perturbations, transfer functions (CDM, HDM), cosmological background fluctuations, polarisation

Formation of galaxies and the first structures: physics of the intergalactic medium, cooling and heating processes, first objects, overcooling, reionisation

Measurement of the physical parameters of galaxies: Physics of star-forming regions, determination of metal abundances, spectral diagnostics, measurement of the star formation rate, modelling and adjustment of spectralenergy spectral distributions

Formation and evolution of galaxies (in-depth) : The universe traced by Lyman alpha, the Lyman forest, properties of large redshift galaxies, construction and analysis of large samples.

●**KSUA9AB3** – Stellar and planetary sismology

LEARNING OBJECTIVES
An introduction to seismology of stars and (telluric) planets

SYNTHETIQUE DESCRIPTION DES ENSEIGNEMENTS ‘
Introduction: Reasons to study the seismology of stars and planets
Wave equations in a fluid / in an ‘elastic’ medium: acoustic waves (p), gravitational waves (g), volume waves (P, SV, SH), surface waves (Love, Rayleigh).
o JWKB approximation, theory of lines, equations, asymptotic formulae
o Green's functions: modal representation, decomposition into propagating waves, reconstruction by cross-correlation of random fields
o Asteroseismology and planetary seismology: nature of observables
o Inverse problems: effects of a first-order perturbation, variational principle, Fréchet derivatives, sensitivity kernels. Expressions in the form of inverse problems.
o Applications: Inversion of the internal rotation profile of stars (Sun, giant stars), Inversion of the internal structure of stars (rotation profile), Inversion of the internal structure of stars (rotation profile), Inversion of the internal structure of stars (sound velocity profile), 3D volume wave tomography of the Earth's mantle and core, surface wave dispersion curves for crustal and lithospheric imaging.
o Current developments in asteroseismology and planetary seismology

●**KSUA9AB4** – Compact objects and accretion

LEARNING OBJECTIVES
This module deals with the physics of compact objects (white dwarfs, neutron stars and stellar and supermassive black holes) and the accretion/ejection phenomena associated with them. The aim of the module is to provide the key points (vocabulary, order of magnitude and framework) for understanding the rich and complex physics of these objects & their importance in various fields of modern astrophysics (e.g. cosmology, galaxy physics, stellar physics) and fundamental physics (e.g. nuclear and particle physics, gravitational waves).The major issues in the field will be discussed using examples.

SUMMARY DESCRIPTION OF COURSES ‘
* Formation scenarios, formation sites and physical properties.
* Basics on supernovae and their links with compact objects
* Physics of accretion phenomena without (Bondi-Hoyle and Hoyle-Lyttleton accretion) and with angular momentum (accretion discs) around these objects.
Examples: X binaries and active galactic nuclei

* Standard emission model for accretion disks, the role of relativistic effects, disk instability models and the accretion/ejection links (jets and winds)
* Impact of jets/winds on the interstellar and intergalactic environment
* Discussion of some open questions
* Examples of observation techniques used to study them

●**KSUA9AB5** – Cosmology and galaxy physics

LEARNING OBJECTIVES
Deepen knowledge of cosmology and the physics of galaxies

SUMMARY OF TEACHING
Thermal history of the primordial universe: relic abundances, cold and hot dark matter, asymmetry, antimatter, baryogenesis
Physics of the primordial universe: Limits of the standard model, Dynamics of a scalar field, Inflation, Quintessence, Modified gravity
Perturbation theory: relativistic perturbations, transfer functions (CDM, HDM), cosmological background fluctuations, polarisation
Formation of galaxies and the first structures: physics of the intergalactic medium, cooling and heating processes, first objects, overcooling, reionisation
Measurement of the physical parameters of galaxies: Physics of star-forming regions, determination of metal abundances, spectral diagnostics, measurement of the star formation rate, modelling and fitting of spectral energy distributions
Formation and evolution of galaxies (in-depth) : The universe traced by the Lyman alpha forest, properties of galaxies at high redshift, construction and analysis of large samples

UE : K5SUAE – Numerical simulations

LEARNING OBJECTIVES
Provide tools for the numerical solution of partial differential equations encountered in various fields of astrophysics, acquire notions about the quality of methods (convergence, rapidity, efficiency) and apply these methods to concrete problems using computer-based practical exercises.

SUMMARY DESCRIPTION OF TEACHING ‘
Part: Digital simulations
- Introductory course on numerical methods for solving partial differential equations: the different types of numerical simulations and their applications.
types of numerical simulations in astrophysics, ‘elements of theory on numerical methods, proprerties of some finite-difference schemes, comparison of the efficiency of two schemes in a simple case, limitations of digital simulations.

- Practical 1 on digital methods
- Practical 2 on the dynamics of stellar interiors
- Practical 3 on Landau damping in non-collidisional plasmas

Part : Practical Astronomy :

A wide range of subjects will be proposed to the students who must ‘eventail de sujets sera propos'e aux ’etudiants, who will thenh present their work on these subjects to the class in order to introduce students to different instrumental methods in astrophysics. Each mini-project is supervised by a contact scientist. These mini-projects can cover a wide range of subjects such as: setting up observations with the IRIS telescope, using archival data to determine the light curve of a transit, etc. of an exoplanet transit, determining the detection limit in deep observations with the HST, etc ...