

Université Côte d'Azur  
Observatoire de la Côte d'Azur

# MAUCA

Leaflet of available METEORS  
2026-2027

UNIVERSITÉ  
CÔTE D'AZUR 

 **Observatoire**  
de la CÔTE d'AZUR



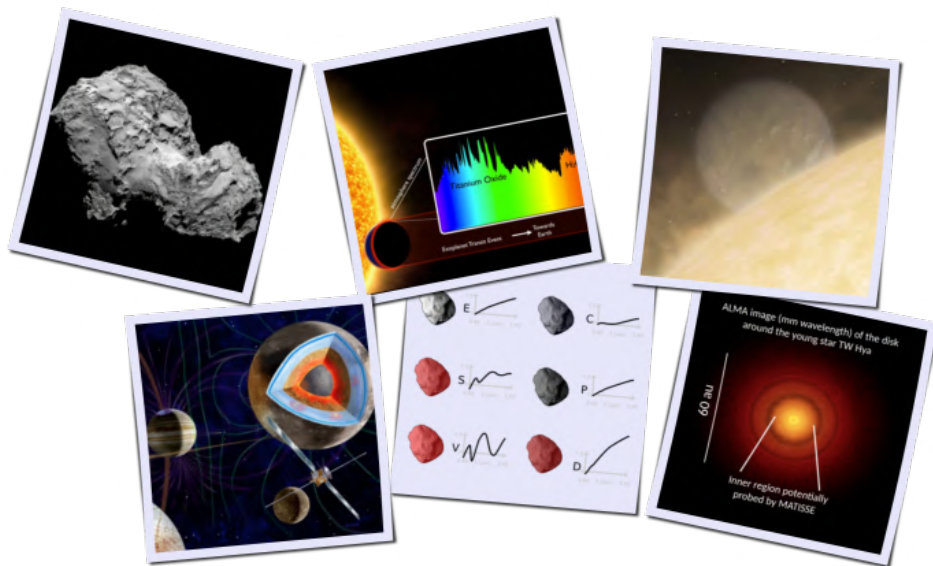


# Contents

<b>Table of content</b>	<b>2</b>
<b>I Planetary sciences</b>	<b>3</b>
1 Rosetta and ExoMars . . . . .	4
2 Planet-disk interactions . . . . .	5
3 JUICE - JUpiter ICy moons Explorer . . . . .	7
4 Polarimetry of Asteroids . . . . .	8
5 Atmospheres of exoplanets and stars . . . . .	9
<b>II Stellar and galactic physics</b>	<b>10</b>
1 Planetary Dynamics and Stellar Evolution . . . . .	11
2 Astrophysics of Gaseous and Dusty Nebulae . . . . .	12
3 Galactic Archeology . . . . .	13
4 Stellar Pulsation and Evolution . . . . .	14
5 Infrared spectroscopy in the Galactic center . . . . .	15
<b>III Extragalactic, cosmology &amp; relativity</b>	<b>16</b>
1 Relativistic Gravitation and Astrophysics . . . . .	17
2 The Bepi-Colombo mission . . . . .	19
3 Formation et Evolution of Galaxies . . . . .	21
4 Galaxy clusters as multiwavelength astrophysical laboratories . . . . .	24
5 Star clusters: a looking glass into galaxy evolution . . . . .	25
<b>IV Signal processing &amp; numerical methods</b>	<b>26</b>
1 LISA data analysis . . . . .	27
2 High Performance Computing for Fluids . . . . .	28
3 Machine Learning for Stellar SEDs . . . . .	29
4 RFI masking recast as a supervised segmentation problem . . . . .	30
<b>V Astronomical optics &amp; instrumentation</b>	<b>32</b>
1 Stellar amplitude interferometry . . . . .	33
2 Photonics for high angular resolution astronomy . . . . .	34
3 Co-phasing Segmented Optics . . . . .	36
4 Imaging Exoplanets . . . . .	38
5 Ground to Space Laser Links for Space applications . . . . .	40
6 Astronomical Adaptive Optics . . . . .	41
7 Graviational Wave Detector . . . . .	42

# Chapter I

## Planetary sciences



### Contents

---

1	Rosetta and ExoMars . . . . .	4
2	Planet-disk interactions . . . . .	5
3	JUICE - JUpter ICy moons Explorer . . . . .	7
4	Polarimetry of Asteroids . . . . .	8
5	Atmospheres of exoplanets and stars . . . . .	9

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# ExoMars and the Molecular Traces of the Origins of Life



## SUMMARY.

A decade ago, ESA's Rosetta mission had made spectators from all over the world dream: In 2014, the Rosetta mission tried to pose the little robot Philae on the nucleus of comet 67P/Churyumov-Gerasimenko. The Rosetta Space Probe collected information about the composition of the comet nucleus during its spectacular approach to the sun. Our gas chromatograph coupled to a mass spectrometer was on board and delivered precious data. Since 2008 our research group has been actively involved in an international team for the design and construction of the ExoMars mission of the European Space Agency (ESA). In particular, we are implied in the scientific team of the Mars Organic Molecule Analyzer (MOMA) instrument. Our work is particularly linked to the chirality of molecules that we intend to identify on the surface and sub-surface of Mars after landing planned for 2028/2029. The technique again will be a gas chromatograph coupled to a mass spectrometer. The lecture will briefly summarize the main successes of the cometary Rosetta mission and then focus on the ongoing development and evolution of ESA's ExoMars mission.

## — OBJECTIVES —

Students will learn how to design scientific instruments for space missions, how to accompany space missions with the help of laboratory experiments and how to treat space mission data. Gas chromatography, mass spectrometry and circular dichroism spectroscopy will be taught along with enantiomers, chirality, and concepts and theory of stereochemistry. History and evolution of planet Mars will be treated.

## — PREREQUISITES —

A bachelor degree in physics, astrophysics or chemistry.

## — THEORY —

by UWE MEIERHENRICH

The aim of this Meteor is to better understand the molecular composition of the surface and subsurface of planet Mars. We are particularly interested in the concept of molecular chirality. Chirality and stereochemistry of molecules under investigation will be taught; they contain important hints on their formation pathway and chemical evolution.

## — APPLICATIONS —

by UWE MEIERHENRICH

Based on current knowledge on the

mineralogical and chemical composition of surface of planet Mars, students will experimentally and systematically investigate different samples of Mars analogues available in the laboratory. Gas chromatography coupled to mass spectrometry will be experimentally used to resolve enantiomers and to investigate the phenomena of chirality and stereochemistry. The identification of organic species in these mass spectra will be envisaged. The Mars Organic Molecule Analyzer (MOMA) instrument onboard ExoMars that we developed in an international partnership lead by the Max Planck Institute for Solar System Research, is an identical gas chromatograph using four stationary phases coupled with a mass spectrometer ion trap type. Data will be interpreted in view of the ExoMars mission and landing on Mars scheduled for 2028.



## — MAIN PROGRESSION STEPS —

- **Week 1:** Courses Mars and ExoMars

- **Week 2:** Courses Chirality
- **Week 3:** Courses GC-MS
- **Week 4:** Exercices
- **Weeks 5-7:** Project

## — EVALUATION —

- **Theory grade [30%]** including theoretical understanding of lectures, critical spirit in discussions, and scientific thoughts and insight during exchange.
- **Practice grade [30%]** based on laboratory experiments, technical skills, initiative, progress of the project, data analyses.
- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

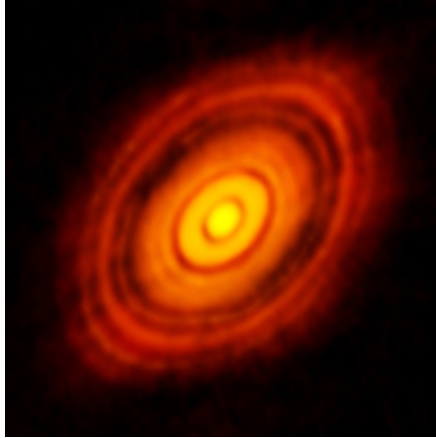
## — BIBLIOGRAPHY & RESOURCES —

- JL Vago, UJ Meierhenrich et al. Habitability on early Mars and the search for biosignatures with the ExoMars Rover. *Astrobiology* 17 (2017), 471-510.
- ExoMars website

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## Planet-Disk-Interactions



### SUMMARY.

Planets form in protoplanetary disks around young stars, like the one around HL-Tau imaged by ALMA shown on the adjacent picture. Such disks are mainly made of gas, with  $\sim 1\%$  dust, from which planets grow. As a consequence, planets must interact with the gas while they form. Actually, the structures seen on the image may be due to planets in formation. In turn, the perturbed disk acts on the planets, which leads to a modification of their orbits: they migrate! Migration is a key ingredient in planet formation, which shapes the final solar and extrasolar systems. In this METEOR, we will explore the theory and the various applications of planet-disk interactions.

### — OBJECTIVES —

- Get a global picture of planetary formation, the physics of protoplanetary disks, the dynamics of planet-disk interactions (restricted three-body problem, notion of torque, pressure wave propagation).
- Use a complex hydrodynamics code. Run simulations on the observatory local cluster. Analyse the results of these simulations using `python` scripts that can be adapted. Develop a critical mind about these results to decide the set-up of the next simulations in the frame of the chosen project.

### — PREREQUISITES —

- ✗ S1. Numerical methods
- ✗ S2. Dynamics & Planetology
- ✗ S2. General mechanics

Note: these lectures are not absolutely mandatory, but their good understanding would be of considerable help for this METEOR.

### — THEORY —

by A. CRIDA

Physics of gas disks around stars: vertical hydrostatic equilibrium, equilibrium rotation velocity. Dust behaviour: sedimentation, radial drift. Planet formation: streaming instability,  $s_0$  accretion, gaz accretion, formation of satellites. Planetary migration: Lindblad and corotation torques, gap opening. Applications to the solar system, and other systems.

by H. MÉHEUT

Fluid dynamics to model the gas of protoplanetary disks, Euler equations that will be solved by the code FARGOCA, perturbative approach and wave propagation in astrophysical disks.

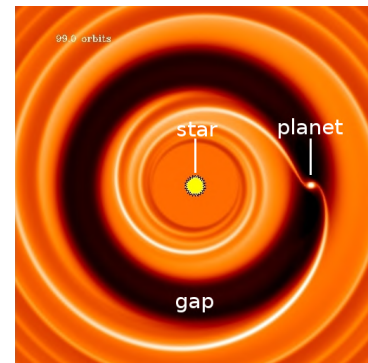
by E. LEGA

Classical numerical methods for the integration of Navier-Stokes equations and for the N-body problem (finite difference, Runge-Kutta) and their use in the code FARGOCA. The code is specifically designed for the study of protoplanetary disks and for planet-disk interactions. Learn how to use the code and to run simulations on the local cluster.

### — APPLICATIONS —

by A. CRIDA, E. LEGA, H. MÉHEUT

- **Common project:** Make a numerical simulation with our code FARGOCA, of a protoplanetary disk with an embedded terrestrial planet. Produce a gas density map and notice the spiral wake. Compare the numerical simulation with the theoretical spiral curve. Explore the parameter space to test the theory (or the code).



Gas density map from a numerical simulation with a giant planet on a fixed, circular orbit. A spiral wake (white) and a deep gap (black) are clearly visible, due to planet-disk interactions.

- **Personal project:** Choose among the following possible personal studies.

- Mean motion resonance of several planets in convergent migration
- Fourier decomposition of the spiral and link with mean motion resonances with the planet
- (In)stability of a disk cavity and planet trap
- Energy equation and role of the corotation torque
- Effect of the indirect term on the stability of the disc and the dynamics of the planet

### — MAIN PROGRESSION STEPS —

MAUCA – METEOR in Planetary sciencesPlanet-Disk-Interactions

- Weeks 1-2: Theory lectures
- Week 3: Learn to use FARGOCA, study of the spiral wake + written exam
- Weeks 4-7: Personal projects
- Week 7: preparation of the defense

– EVALUATION –

- **Theory grade [30%]**
  - Production of the student's own lecture on Fluid mechanics with H. MÉHEUT.

- Written exam. Theoretical questions, exercices based on the examples seen in lectures by A. CRIDA and E. LEGA.

- **Practice grade [30%]**  
Evaluation based on the students attitude and progresses during the practical work.

Criteria are curiosity, autonomy, achievements, ease with the numerical tools, understanding of the physics and the numerics, general scientific attitude and critical mind.

- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

– BIBLIOGRAPHY & RESOURCES –

- Crida (2023)
- Baruteau et al. (2014) (video)

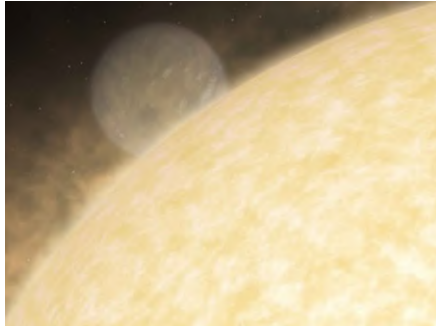
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# Atmospheres of exoplanets and stars



## SUMMARY.

The largest information content from astrophysical objects comes from their spectra. Particularly, stellar and exoplanet spectra allow us to measure stellar and exoplanet atmospheres' thermal, chemical and dynamical properties.

We will first learn the fundamental physical processes that shape stellar and planetary atmospheres' temperature and chemical structure. Then we will learn how spectra are formed in planetary atmospheres and how their observations can be used to determine physical and chemical state of the atmospheres.

The METEOR will be divided into coursework, homework, practical and project. At the end the students will be able to use numerical codes to produce stellar and planetary spectra that can be directly compared to ground- and space-based observations.

## — OBJECTIVES —

- Understand the thermal structure, the chemical properties and the formation of spectra in stellar and planetary atmospheres.
- Use numerical codes to calculate the thermal structure and spectra of stellar and planetary atmospheres and compare them to space-based (JWST) and ground-based (VLT) telescope observations.

## — PREREQUISITES —

- ✗ S2. Stellar physics
- ✗ S2. Dynamics & Planetology

## — THEORY —

by VIVIEN PARMENTIER, ANDREA CHIAVASSA, JULIA SEIDEL

- Radiative/convective equilibrium
- Equilibrium and disequilibrium chemistry
- Opacity
- Formation of emission and transmission spectra for exoplanets and stars
- Confounding factors (stellar contamination, 3D effects, instrumental effects)

## — APPLICATIONS —

Then the students will pick a project with a focus on exoplanet or stellar spectra.

by VIVIEN PARMENTIER

Estimate the chemical abundance and thermal structure of an exoplanet based on its observed spectrum by the James Webb Space Telescope using a 1D radiative/convective code.

by JULIA SEIDEL

Extraction and study of the atmospheric signal of the sodium line from high-spectral observation from the HARPS spectrograph

by ANDREA CHIAVASSA

Interpretation of stellar spectra with a grid of state-of-the-art 3D stellar models.

- Tier 1: Theory of atmospheres: radiative transfer, hydrodynamics, chemistry.
- Tier 2: Formation of emission and transmission spectra and tools to observe them.
- Tier 3: project

## — EVALUATION —

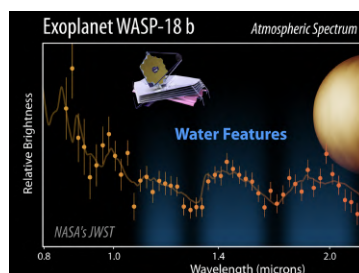
- Theory grade [30%]
  - Written exam on coursework
- Practice grade [30%]
  - Presentation of an article relevant for the project (30%)
  - Project (70%): initiative, progress, analysis
- Defense grade [40%]
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

## — BIBLIOGRAPHY & RESOURCES —

- WASP-18b JWST observation
- TOI-1518b Gemini/MAROON-X observation

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## — MAIN PROGRESSION STEPS —

# Chapter II

## Stellar and galactic physics



### Contents

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1	Planetary Dynamics and Stellar Evolution . . . . .	<b>11</b>
2	Astrophysics of Gaseous and Dusty Nebulae . . . . .	<b>12</b>
3	Galactic Archeology . . . . .	<b>13</b>
4	Stellar Pulsation and Evolution . . . . .	<b>14</b>
5	Infrared spectroscopy in the Galactic center . . . . .	<b>15</b>

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# PLANetary Dynamics and Stellar Evolution PLADYSE



**SUMMARY.**

Stellar evolution for star with mass between 1 and 8 solar masses is, at the end of the Main Sequence, a period of drastic transformations both for the star itself but also for the circumstellar environment. The travel from the Red Giant (RG) phase to the White Dwarf (WD) ultimate one (through AGB, post AGB and planetary nebulae (PN) stages) is a fast and violent transformation during which up to 1 solar mass of the star can be expelled in 10 000 years and the star luminosity can increase of several order of magnitude. The circumstellar environment is hence deeply modified during these phases. The dynamics of planets and small bodies around the central star will be deeply modified by these events and many non gravitational perturbations have to be considered in the dynamical equations. The student will develop numerical integrators to describe and study the pertubated dynamics of planets and small bodies during the late phases of stellar evolution.

**— OBJECTIVES —**

- Students will be able to
- model gravitational forces in N body problem
- model non-gravitational forces in N body problems
- use SSE (Single Star Evolution) code for stellar evolution
- couple gravitational code and SSE to study small body dynamic with respect with stellar evolution

**— PREREQUISITES —**

- ✗ S1. Data Sciences
- ✗ S1. Numerical methods
- ✗ S2. Stellar physics
- ✗ S2. Dynamics & Planetology

**— THEORY —**

by PH. BENDJOYA  
 Restricted three body problem. !  
 N body problem (N small).  
 Non gravitational forces : friction, wake , mass loss, Yarkovsky...  
 numerical ODE integration,  
 Rebound + ReboundX  
 SSE code use

**— APPLICATIONS —**

by PH. BENDJOYA  
 Analytical derivation of equations of motion of gravitational and non gravitational perturbation interactions

Numerical coding of 2 body problem, restricted 3 body problem, general N body problem,  
 Numerical coding of non grvitaional perturbation.  
 Coupling stellar evolution in previous simulation



(Photo : Pixabay/Terranaut) JWST's Glimpse into the Future: Predicting Solar System's Fate through Exoplanet Observations

**— MAIN PROGRESSION STEPS —**

- First half of the period : theoretical courses : Revision 2 body and restricted 3 body problem.
- First half of the period in parallel: Numerical exercises. Introduction of different non gravitational forces
- Second half of the period : numerical project: application on student's

chosen problem. Critical analysis of the simulations

- Last week : preparation of the final oral presentation.

**— EVALUATION —**

- Theory grade [30%]
  - base calculus from lectures
- Practice grade [30%]
  - Exercices (30%): thought-process and results
  - Project (70%): initiative, progress, analysis
- Defense grade [40%]
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

**— BIBLIOGRAPHY & RESOURCES —**

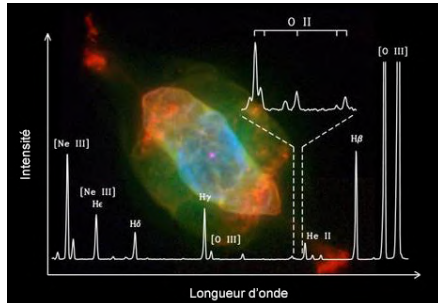
- Solar System Dynamics, Carl D. Murray, and S. F. Dermott, Cambridge University Press (Book)
- SSE
- SSE
- Rebound
- Reboundx

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# Astrophysics of Gaseous and Dusty Nebulae



**SUMMARY.**

Gaseous nebulae and dusty environments play an important role in astrophysics. H II regions and Planetary Nebulae, ionized by hot stars, can provide informations related to stellar formation and evolution, in connection to the chemical evolution of galaxies. In addition, dust formation can hamper the derivation of physical properties of such objects.

Keywords: Stellar physics and evolution - Diffuse medium - HII/HI regions - Dust and gas in circumstellar envelopes

**OBJECTIVES**

- This METEOR aims at making the students familiar with the physical study of gaseous and dusty environments from theoretical and high-resolution observational points of view.
- The theory of ionization and thermal equilibria associated to radiative transfer in nebulae will be presented. Practical projects based on high-resolution images of circumstellar environments and collected with ESO/VLT instruments will also be proposed.

**PREREQUISITES**

- ✗ S1. General astrophysics
- ✗ S2. Stellar physics

**THEORY**

by PATRICK DE LAVERNY

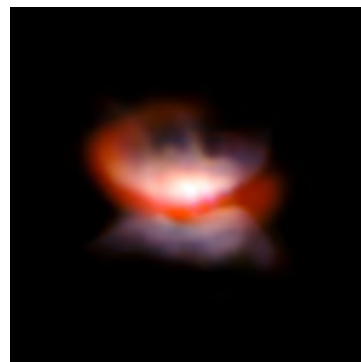
All stars are formed from interstellar material and synthesize new chemical elements during their life. These newly formed elements can then be injected back to the interstellar medium during the ultimate phases of stellar evolution. Understanding star formation and the final stages of their evolution is thus a key to understand the chemical evolution of the Universe. During their ejection phases, stars can be surrounded by circumstellar material (ionized or neutral gas and dust). As all the informations we can obtain from these objects come from their emerging light, we need to study how photons interact with gas and dust.

This first part will allow to understand the different types of gaseous

nebulae, to study the physics of gas ionisation by hot photons, to understand the formation of emission spectra for these objects and how we can determine physical properties and chemical abundances.

by ERIC LAGADEC

Dust particles play also an important role in circumstellar envelopes of evolved stars. The students will also become familiar with dust radiative transfer, to study the interaction of light with circumstellar dust particles.



The dusty circumstellar envelope of L2 Pup.

**APPLICATIONS**

by ERIC LAGADEC

The students will then get their hands on state of the art data and modeling codes. They will be taught how to analyse data taken with the Very Large Telescope (VLT) in Chile with instruments like VISIR and SPHERE. They will learn how to derive the morphological, physical and chemical properties of circumstellar environments. This will be done by using the dust radiative

transfer code DUSTY and optical and infrared diffraction limited images using extreme adaptive optics. They will thus learn how to measure physical parameters of the circumstellar environment via modeling of the observations, thus directly applying the theoretical knowledge they acquired before.

**MAIN PROGRESSION STEPS**

- Tiers 1 & 2: courses A & B and exercices
- Tier 3: personal project

**EVALUATION**

- Theory grade [30%]
  - Written exam (70%): theoretical questions from lectures
  - Presentation of an article (30%): critical spirit and answer to questions
- Practice grade [30%]
  - Exercices (30%): thought-process and results
  - Project (70%): initiative, progress, analysis
- Defense grade [40%]
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

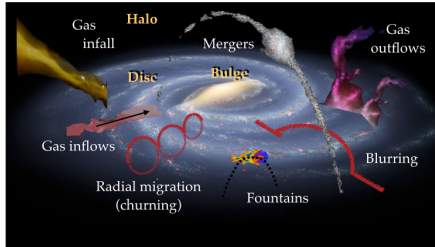
**BIBLIOGRAPHY & RESOURCES**

- *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, D.E. Osterbrock & G.J. Ferland

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## Galactic Archaeology and the Gaia mission



### SUMMARY.

Galactic Archaeology consists in deciphering the Milky Way formation and evolution history through the study of the stars composing its different Galactic populations. Such studies are now possible on large scales thanks to devoted Galactic ground-based and space surveys, as the ESA Gaia mission. This METEOR will particularly focus on the Gaia spectroscopic survey that collects tens of millions of stellar spectra of any type. Thanks to such unique data, our Galaxy is mapped spatially, kinematically and chemically.

Keywords: Near field cosmology - The Milky Way as a spiral galaxy. Stellar populations and local environment

### — OBJECTIVES —

- The students will have a global view of the Milky Way formation and evolution history, thanks to lectures on Galactic stellar populations. In particular, they will study how kinematics and chemical information allow for the exploration of the Milky Way and its history. The main recent results obtained on Galactic Archaeology and based on the Gaia survey will also be described.
- Practical applications of Galactic data analysis will be performed by the students, focussing on observations collected with Gaia.

### — PREREQUISITES —

- ✗ S1. General astrophysics
- ✗ S2. Stellar physics

### — THEORY —

by ALEJANDRA RECIO-BLANCO

Galactic Archaeology aims to reconstruct the history of the Milky Way by analyzing stars, just as the history of life was deduced by examining rocks. Stars record their past in their ages, chemical compositions and kinematics and can thus provide unprecedented constraints on the early phases of galaxy formation back to redshifts greater than two (a look-back time of about 10 billion years). How did our galaxy form? What is its place and ours in the cosmic evolution? We will also deeply discuss how these questions could be addressed through many ongoing and planned spectroscopic surveys of the Milky Way, culminating in the Gaia mission, which have been

revolutionizing our knowledge about Galactic stellar populations during the last two decades.

by PATRICK DE LAVERNY

We will focus on the analysis of stellar spectra and stellar parameterization, including reviews on stellar evolution. Then, we will study how to kinematically characterize stars belonging to the Milky Way and how to identify the different stellar populations of the Galaxy.

by PEDRO ALONSO PALICIO

The Galactic chemical evolution will be studied, including lectures on stellar nucleosynthesis, chemical yields and chemical evolution models. The origin and chemo-dynamical properties of Galactic populations, as revealed by current surveys, will be also introduced.



The ESA Gaia mission mapping the Milky Way

### — APPLICATIONS —

Practical studies on Galactic stars characterisation based on Gaia astrometric, photometric and spectroscopic data will be proposed. The main topics covered will be: (i) Statistical analysis of large samples of stellar chemo-dynamical properties, (ii) Derivation of

Galactic chemical gradients and metallicity distributions and (iii) Modelling of the Galactic Chemistry.

### — MAIN PROGRESSION STEPS —

- Tiers 1 & 2: courses A/B/C and exercises
- Tier 3: personal project

### — EVALUATION —

- Theory grade [30%]
  - Written exam (70%): theoretical questions from lectures
  - Presentation of an article (30%): critical spirit and answer to questions
- Practice grade [30%]
  - Exercices (30%): thought-process and results
  - Project (70%): initiative, progress, analysis
- Defense grade [40%]
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

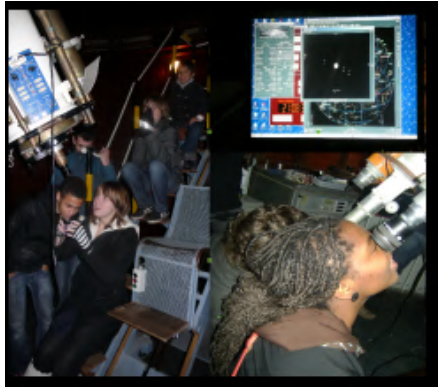
### — BIBLIOGRAPHY & RESOURCES —

- The ESA/Gaia website and archive
- *The Milky Way*, Combes & Lequeux, 2016
- *The origin of the Galaxy and Local Group*, Bland-Hawthorn, Freeman & Matteucci, 2013, Springer

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## Stellar Pulsation and Evolution Polar and Space Missions



**SUMMARY.**

Stellar Pulsation and Evolution –SPE– based on Polar and Space Missions, gives rise to two interesting stellar physics fields, (1) the theory of the pulsation and evolution of various stellar classes accross Hertzsprung–Russell diagram towards an understanding of the origin of the Universe, and (2) the observation and data analysis techniques, such as Astrometry, Photometry and Spectroscopy from Polar and Space Telescopes. The theoretical topics are shared among stellar interiors and atmosphere structure, stellar energy and transport mechanisms, and mechanisms of the pulsation and the hydrodynamical phenomena induced by shock waves. Whereas, the application themes are founded on frequency detections, mode identification, stellar parameters determination, and time-series data interpretation from light and Radial Velocity Curves.

— OBJECTIVES —

- This Meteor provides students with the knowledge and research ability for a career in Astronomy towards an improving the research development for new generations.
- The students learn how to relate stellar models to observable quantities by use of observation and theoretical methods, and they will be able to deal with the Stellar Evolution and Structure challenges.

— PREREQUISITES —

Uncomment the Fundamental Courses that are required for your METEOR.

- ✗ S1. Fourier Optics
- ✗ S1. Data Sciences
- ✗ S1. Numerical methods
- ✗ S2. Stellar physics

— THEORY —

by MERIEME CHADID

The theoretical goal is to provide a background in stellar physics specially in pulsation and evolution. After a recapitulation of the observational properties of stars, the physical conditions in stellar interiors and atmosphere are taught, in particular the usual conservation equations of stars in general. Then, nuclear sources of the

stellar radiation and the energy transport are studied with driving mechanisms of the pulsation and hydrodynamical phenomena induced by shock waves. The stellar evolution is studied by the use of the simple analytical models, and the equations of stellar pulsation is derived for radial and non radial pulsations.

— APPLICATIONS —

by MERIEME CHADID

The application field is based on mode detections, frequency analysis and stellar parameters determination by the use of ground-based observations, time-serie Antarctica observations (PAIX) and Space Telescopes (CoRoT, KEPLER, GAIA and PLATO). The student will learn and experiment the observation techniques by use of Polar and Space Telescopes with various optical instruments.

Use the following code to insert a figure



PAIX Polar Antarctica Telescope  
@Chadid

— MAIN PROGRESSION STEPS —

The students will progressively get deeper insight on the main properties of stars by first deriving simple models and by further performing experiments with observing runs and data analysis algorithms.

— EVALUATION —

Oral presentation (50%) and a global mark from the supervisor (50%) to evolute the student on the Objectives described above.

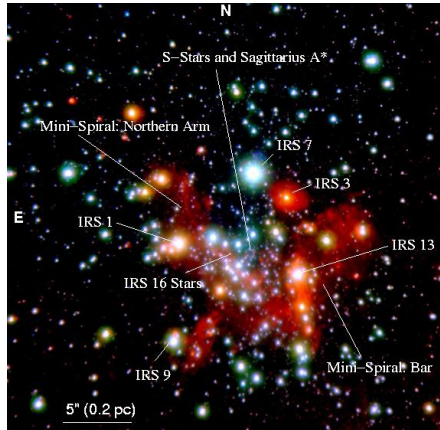
— BIBLIOGRAPHY & RESOURCES —

- Communiqué de presse
- Asteroseismology C. Aerts, J. Christensen and Kurtz 2010
- HDR Stellar Pulsation and Evolution, M. Chadid 2014
- An introduction to stellar astrophysics, F. Leblanc Willey 2010
- Stellar Structure and Evolution R. Kippenhahn and A. Weigert 2012

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## Infrared spectroscopy in the Galactic Center



The Center of our Milky Way is the only nucleus of a Galaxy which we can study in detail as we can resolve there individually the stellar populations. Together with the existence of the supermassive black hole of Sgr\*, this part of our Galaxy is one of the most extreme environment where star formation can happen. Crowding, heavy interstellar reddening obliges to work in the infrared. Recently, many developments in infrared spectroscopy has been obtained. With the upcoming KMOS large survey at ESO starting in ten thousand of objects will be observed. This METEOR proposes to analyse these spectra and derive stellar parameters as well as alpha-abundances

In this METEOR, the focus will be on the analysis of KMOS spectra which will be obtained this summer 2026 at the VLT (ESO, Chile) within a large accepted ESO program lasting at least three years. The goal of this large survey is to get the largest spectroscopic dataset so far in the Galactic Center region. Courses about infrared spectroscopy and data reduction will be taught and during the practical work, the newest data from the ESO KMOS large survey (VLT/Chile) will be analysed.

— OBJECTIVES —

- The student will learn the complex structure of the Galactic center, its stellar populations and the basic theoretical aspects of the formation of the Galactic Center
- A specific focus will be done to the two main structures in the Galactic Center: the nuclear star cluster and the nuclear stellar disc.
- The student will learn to use infrared spectroscopy as a powerful tool to study the dust obscured population in the Center of our Galaxy and run the stellar parameter pipeline.

— PREREQUISITES —

- ☒ S1. Data Sciences
- ☒ S2. Stellar physics
- ☒ S2. Statistics

— THEORY —

by MATHIAS SCHULTHEIS

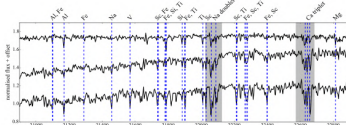
The nucleus of the Milky Way is the most extreme environment in our Galaxy. It is hosting a massive star cluster of 30 million solar masses coexisting with a supermassive black hole of 4 million solar masses. This central star cluster is a typical representative of a very common class of objects called nuclear star clusters (NSCs), the densest stellar systems in the universe so

know of. Given their position at the center of the potential well of a galaxy and their coexistence with black holes, nuclear star clusters potentially play a key role in the formation and certainly in the growth of the central supermassive black holes. In addition, a course on galactic Archeology as a powerful tool to trace the chemical evolution history of the Milky Way will be given.

— APPLICATIONS —

by MATHIAS SCHULTHEIS & GEORGES KORDOPATIS

The student will work a stellar reduction pipeline STARKIT allowing to fit simultaneously the observed spectrum with a grid of synthetic spectra for cool M giants. An important role is the prior assumption for Starkit as well as the choice of the masked regions. A comparison sample of high-resolution spectra ( $R = 45.000$ ) will be used to do a detailed comparison.



A typical KMOS spectrum in the center of the Milky Way in the K-band at around 2.2 micron.

— MAIN PROGRESSION STEPS —

- Tier 1: Courses about the Galactic Center and infrared spectroscopy and exercises
- Tier 2: project
- Tier 3: project

— EVALUATION —

- Theory grade [30%]
  - Oral exam (50%): questions about the Galactic Center and infrared spectroscopy
  - Presentation of an article (50%): critical spirit
- Practice grade [30%]
  - Exercises (30%): thought-process and results
  - Project (70%): initiative, progress, analysis
- Defense grade [40%]
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

— BIBLIOGRAPHY & RESOURCES —

Two review papers about these topics:

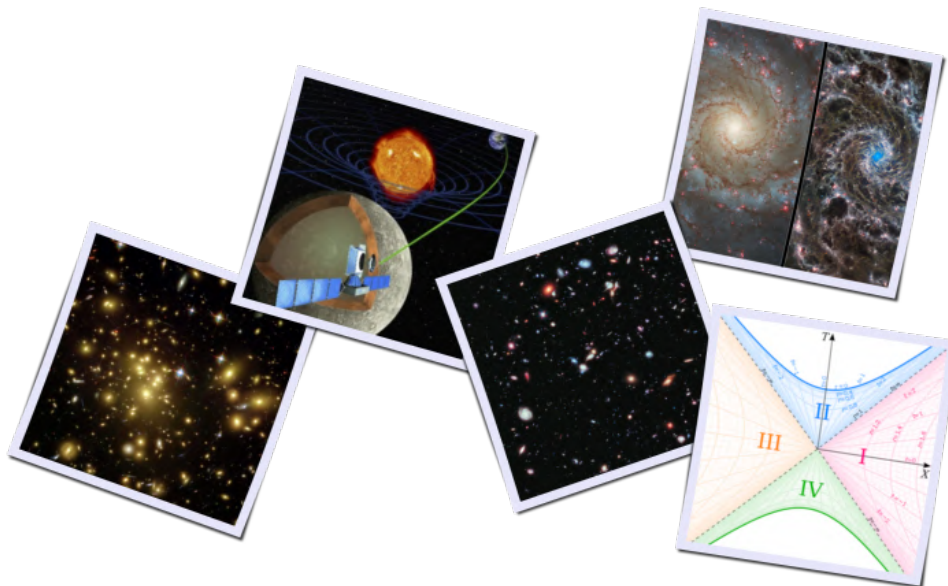
- Schultheis2025
- Neumayer2020

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# Chapter III

## Extragalactic, cosmology & relativity



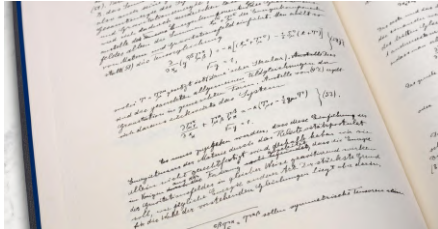
### Contents

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1	Relativistic Gravitation and Astrophysics . . . . .	17
2	The Bepi-Colombo mission . . . . .	19
3	Formation et Evolution of Galaxies . . . . .	21
4	Galaxy clusters as multiwavelength astrophysical laboratories . . . . .	24
5	Star clusters: a looking glass into galaxy evolution . . . . .	25

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# Relativistic Gravitation and Astrophysics



... their tools and methods ...  
 ... and applications to astrophysics and cosmology.

**SUMMARY.**

Geometric gravity theories: General Relativity (GR) and alternatives ...

**OBJECTIVES**

Improving your knowledge in GR and in some related astrophysical applications.

It mainly consists in the acquisition of the skills required in geometric gravity and relativistic astrophysics. This includes mastering the mathematical tools required to be conversant in these fields. Special attention will be paid to exact GR solutions.

Schwarzschild-de Sitter), Robertson-Walker, Kasner, axial symmetry, Kerr, ...

• **Relativistic Astrophysics**

Perfect fluids in astrophysics, examples of relativistic stars.  
 Black holes and their environment (dynamics, optics).  
 Gravitational radiation.  
 Backgrounds on cosmology.

(about 60h, planned on 3/4 sessions a week).

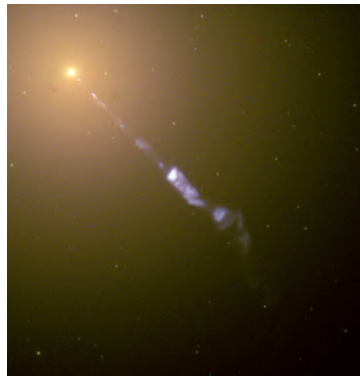
Reading of some review and/or pedagogical papers.

- Last 2/3 weeks  
 Some specific points (courses and exercises, more specifically related to the project).  
 Focus on a specific topic and preparation of the oral presentation (project part).

**PREREQUISITES**

- ✗ S2. Gravity & relativity

**CARE:** it is of first importance the student not to be scared by the formal issues involved in this course (tensor calculus, Riemannian geometry, ...).



**THEORY**

by BERTRAND CHAUVINEAU

• **Mathematics**

Tensor calculus  
 Riemannian geometries: metrics, geodesic curves, covariant derivatives, curvature.  
 Advanced topics (Killing vectors, ...).

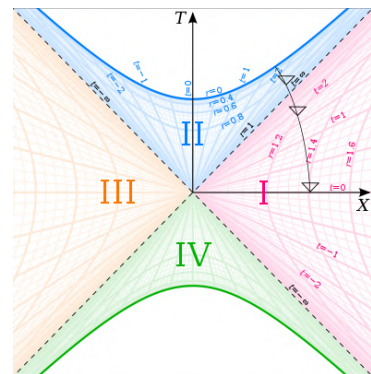
• **Gravitation theories**

GR, scalar-tensor gravity, ...  
 Lagrangian formalism, matter description, stress tensor.  
 Linearized theory, gravitational waves. Conservation laws.  
 Exact solutions: Schwarzschild, Reissner-Nordström, de Sitter (&

**APPLICATIONS**

by BERTRAND CHAUVINEAU

For the "project part" of the METEOR, the student will choose a part of the lectures, or a specific topic related to them, and make a presentation that shows his mastering of its different aspects, including technical issues.



**EVALUATION**

- **Theory grade [30%]** Written exam.
- **Practice grade [30%]** Student's investment during the whole period.
- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

**MAIN PROGRESSION STEPS**

- Whole period theoretical courses and exercises

— BIBLIOGRAPHY & RESOURCES —

Any GR book/online course designed for undergraduate and/or graduate students is welcome.

More specifically, let me suggest (plenty of books ... Dozens new books every year! Hard to choose ...):

C.W. Misner, K.S. Thorne, J.A. Wheeler, "Gravitation" (San Francisco, Freeman, 1973).

> THE reference in the field, even if a bit old. Different levels of reading. An about 1000 pages book!

R.M. Wald, "General Relativity" (The University of Chicago Press, 1984).

> In two parts: 1. Fundamentals (about 150 pages), 2. advanced topics (about 300 pages).

H. Stephani, "General Relativity" (Cambridge University Press).

> Different editions. I like the second one (1990).

L. Landau, E. Lifchitz, "Field theory" (Mir Editions, 1970).

> Of course, the 2cd volume of their renowned course of physics! The second part (of this 2cd volume) is devoted to GR.

S. Weinberg, "Gravitation and Cosmology" (John Wiley & Sons, 1972).

> Another (old) reference book. Maybe easier to understand than Wald's book for the introduction to tensors.

H.C. Ohanian, "Gravitation and spacetime" (W. W. Norton & Company, 1976).

> Basics + a bit more.

E. Schrödinger, "Spacetime structure" (Cambridge University Press, 1950).

> I like so much this little book !!! (By the way, he is THE Erwin S., the guy you know as one of the creators of the quantum theory.) He introduces the concepts from nothing, all seems very natural. However, he first defines affinely connected spaces (ie the theory of spaces endowed by an affine connexion), and only later introduces metrics. So maybe not the most directly useful for your need ... and clearly, astrophysics is not his concern: not a single word about the Schwarzschild metric, black holes, planetary motions and so on. Just interested in field equations ... but so splendidly! Just amazing !!!

All of these books present relativity and gravitation from scratch, sometime going up to an advanced level. They all first thing (or after a short introduction, as I do in my lectures)

present the required formalism. Many of these books are not recent, but are still references nevertheless.

Let me also suggest some french books:

P. Tournenc, "Relativité et gravitation" (Armand Colin, 1997).

> A very pedagogical book.

H. Andrillat, "Introduction à l'étude des cosmologies" (Armand Colin, 1970).

> A very pedagogical introduction to GR, cosmology (in those times ... but ok for understanding the basics nevertheless) and to tensor calculus. (Henri Andrillat introduced GR in the French university teaching. With specific attention to pedagogy, as I said ...)

D. Gialis, F.-X. Désert, "Relativité Générale et Astrophysique" (EDP Sciences, 2015).

> mainly compilations of exercices, with corrections.

A. Barrau, J. Grain, "Relativité Générale" (Dunod, 2016).

> mainly compilations of exercices, with corrections.

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Cosmo/Extragalactics:Relativity

## THE BEPI-COLOMBO MISSION



### SUMMARY.

The Bepi-Colombo mission is an ESA large mission of exploration of Mercury. Its main goal is the characterization of the internal structure of the closest to the sun planets together with the tests of general relativity. In this METEOR, we will firstly see how the solar system can be a very efficient tool for testing general relativity. We will then focus on Mercury and see how the Bepi-Colombo mission can contribute in testing alternative theories of gravity.

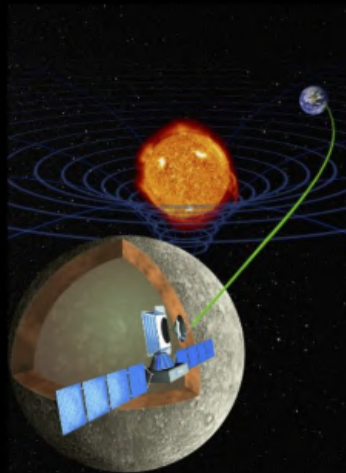
### OBJECTIVES

There 2 main objectives:

- to learn how, in the solar system, the law of gravity ruled by General Relativity can be studied and how alternative theories of gravity can be also tested in the low gravitational regime of the solar system.
- to understand how spacecraft are navigated and how radio science measurements can be used from constraining the motion of the major bodies of the solar system and how the knowledge can be used for benchmarking laws of gravity.

### PREREQUISITES

Dynamics and Planetology; Numerical methods; General Relativity, Extragalactics and Cosmology; Maths/Stat Interesting complementarity with the METEOR JUICE.



### THEORY

by A. FIENGA (O. MINAZZOLI)

We will introduce different theories of gravity starting from the foundation of general relativity with the definition of the metrics, the geodesics and the different time-scales to tensor-scalar theories and phenomenological approaches such as MOND theory. We will see how these diverse models impact the mod-

elization of the light path and the equations of motion for spacecraft and solar system objects.

### APPLICATIONS

by A. FIENGA

The practical works will be done in the frame of the mission of Mercury exploration, Bepi-Colombo and of the instrumental experiment MORE. This experiment of radio science aims at constraining the accuracy on the s/c orbit and the Mercury orbit. Simulations will be done considering different alternative theories of gravity to measure if the MORE experiment will be sensitive to the modifications induced by the studied alternative theories.

### MAIN PROGRESSION STEPS

- First part of the first half of the period : theoretical courses introducing the construction of the equation of motions with GR lagrangian and generalization in considering alternative theories.
- Second part of the first half of the period : lectures introducing the

A MAUCA METEOR.  
 ✦ <http://mauca.unice.fr>

navigation of a spacecraft and the MORE experiment.

- Second half of the period : Each student has a different theory to implement in the equations of motion and in the simulation of the MORE measurements (distances between Earth and the spacecraft or Earth and Mercury).
- Last week : preparation of the final oral presentation.

#### EVALUATION

- Type of examinations: written (40%), project (60%).
- The written examination is a concise but detailed report on a chosen article.
- The student's performances will be evaluated based on the achievement of the project and on the code developed by the student to reach the goals(second half of the METEOR) .

#### Reference

- [Bepi-Colombo mission overview](#)
- [Testing GR with the Bepi-Colombo mission](#)

#### CONTACT

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# Formation and Evolution of Galaxies



**SUMMARY.**

This METEOR deals with extragalactic astronomy and presents our current knowledge on the formation and evolution of galaxies, both from the observational and theoretical points of view. The intrinsic and statistical properties of galaxies as well as their evolution in time are reviewed taking into account the most recent observational data sets. Detection and measurement issues, especially of (very) high-redshift objects, are addressed on this occasion. Key ideas on the hierarchical growth of structures within a  $\Lambda$ CDM cosmology are given and physical processes involved in the formation/evolution of galaxies are explained. All these topics prepare the student for state-of-the-art research in that domain.

By reproducing some results by his own during the practical part, the student will first gain practice in finding, downloading and manipulating data for the project he chose and second will learn basics in data/image analysis, error statistics, estimation theory and data modeling. The three proposed projects cover i) the determination of the galaxy morphology-density relationship, ii) the computation of the red-sequence of galaxies within clusters of galaxies, iii) the non-parametric shape estimators for distant galaxies.

**— OBJECTIVES —**

- Students will know about our current knowledge about the formation and evolution of galaxies within an evolving universe dominated by dark components, about the key observational facts, signatures, and the main physical processes at play. Student will be able to measure galaxy shapes in parametric and non parametric ways, estimate star formation rates, compute luminosity densities, derive optical depths and ionisation fractions, model absorption or emission lines, etc.
- Students will be able to understand the scientific content of papers dealing with this topic, identify the main questions and hypotheses, compare applied methods, check conclusions against results from other similar papers. Students will also be trained by practice in selecting, finding, downloading relevant data for their research using on-line databases and other electronic resources, as well as in data analysis, estimation theory and model fitting.

**— PREREQUISITES —**

- ✕ S2. Large-scale Universe

**✕ S2. Statistics**

**— THEORY —**

by E. SLEZAK

The study of galaxy formation and evolution is an active and rich research area in astrophysics. It aims to provide us with a clear understanding on how the properties of each individual galaxies result from their formation mechanisms and the various physical processes playing a role during their evolution. Many factors indeed contribute to the morphological, dynamical and chemical development of a galaxy during its hierarchical build-up from smaller entities and gas infall evidenced by theoretical simulations. This investigation implies first to characterize in great detail the intrinsic properties (luminosity, morphology, color, activity, etc.) of galaxies over a large range in lookback times in relation to their environment (field, group, cluster). One also need to measure over cosmic time the statistical properties of the galaxy population as a whole in order to link these formation and evolution processes to the underlying evolving cosmological density field and get answers to key questions. For instance, what is the global star-formation history of the Universe or the

relationship between the mass assembly of the galaxies, the interaction and merger rates, the build-up of the stellar content and the feedback processes (from stars to supermassive black hole growth) ?

In order to provide the background of the observations and physics required for understanding the formation and evolution of the galaxy populations in an Universe dominated by dark matter/energy, the syllabus covers the following topics : i) the galaxy properties, including morphologies, luminosities, spectra and dynamics with the fundamental correlations ; ii) the luminosity/size/colour/metallicity distributions of the galaxies and the nature of the environment dependence ; iii) galaxy interactions and mergers, with the related starbursts, structural transformations and kinematics signatures ; iv) the luminosity and mass assembly of galaxies, along with the methods used to identify high-redshift galaxies, the early stages of galaxy evolution and the mapping of the star-formation history ; v) the phenomenology of Lyman- $\alpha$  absorbers and the physics of the Lyman- $\alpha$  line ; vi) the phenomenology, physics and evolution of central black holes, active galaxy nuclei and quasars with their links to the evolution of galaxies.

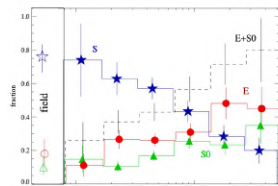
— APPLICATIONS —

by E.SLEZAK

Different applications can be chosen by the attendees.

Application 1

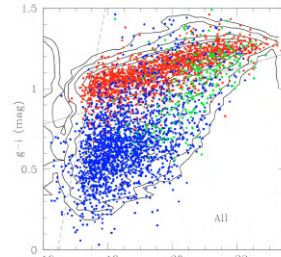
Galaxies have different morphologies, colours, luminosities, and masses. It appears that the mix of the different morphological types do depend on the local environment conditions, with spheroidal-like objects like elliptical galaxies mostly found in high-density regions while disky objects like spiral galaxies dominate the population in the field regions. This result, which can be quantified in different ways, is thought to be a consequence of different physical processes acting onto galaxies and shows that the evolution of these galaxies is at least partly due to interactions with neighbours, the intergalactic medium or both. In this applicative part, one will have to reproduce and study this result. To do so, one will first be provided with : i) more details on the physical processes at play in high density regions like mergers and ram-pressure stripping ; ii) a description of model fitting techniques and useful algorithms/software if necessary. Then, by making use of on-line databases, one will have to download data for different fields, either primary images or catalogues of galaxies depending on the skills of the attendee, and extract/obtain/compute the information required for the project accordingly, that is a proxy for the morphological type of each galaxy within the various fields and an estimate of the local number density of galaxies at each location. Finally, the dependence of the chosen proxy with the density of galaxies will be computed, discussed and compared to recent similar studies.



& Ebeling 2011)

Application 2 :

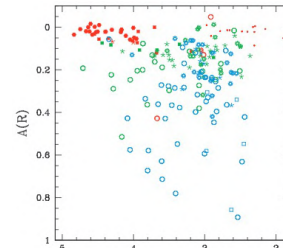
Galaxies with different morphological types have different colours and masses due to different merger histories and past/current star formation rates. This diversity is clearly exhibited in a colour-magnitude diagram which enables one to identify the so-called red sequence of passive elliptical galaxies, the blue cloud of spiral galaxies actively forming new stars, and the green valley of quenched spirals in between. Since elliptical galaxies are a tracer of overdense regions of galaxies, namely clusters of galaxies, such a red sequence is used to detect dynamically relaxed clusters of galaxies, characterize them and identify their galaxy members. In this applicative part, one will study the demographics of the galaxies for different fields with or without known (super)clusters of galaxies, at low and high redshifts. To do so, one will first be provided with more theoretical information about quenching mechanisms and AGN feedback processes. Then, colour-magnitude diagrams will be built for the different fields under study by downloading the relevant data using on-line databases. The transition between starforming galaxies and quiescent ones will be mapped and the red sequence(s) used to identify existing clusters with their galaxy members in the various fields. (Automatic) detection issues of this red sequence will be addressed at this step. Finally, a modeling of these red sequences will be performed and the variation of the slope parameter with the redshift discussed in terms of mass assembly and star formation efficiency.



(Gavazzi+2010)

Application 3 :

Galaxy structural analyses provide unique information about the formation processes that change galaxy structures over time. Parametric fitting using bulge/disk decomposition and a Sersic function to measure galaxy sizes and surface brightness profiles is extensively used for local galaxies. Non parametric methods, based for instance on the concentration, asymmetry and clumpiness (CAS) system, appear well-suited for analyzing the major features of more distant objects lacking spatial resolution and therefore for deriving galaxy evolution over cosmic time. Such an approach is currently tested to get reliable morphologies for the forthcoming Euclid mission. In this applicative part, one will classify realistic galaxies simulated for Euclid using a generative model and test the ability of the CAS system to discriminate among morphologies. To do so, one will first get a deeper insight into the assumptions, limitations and biases of the different methods used nowadays to quantify galaxy structural components and learn about generative adversarial (neural) networks. Questions related to noise issues, PSF blurring, reproducibility and parameter degeneracies will be addressed as well the benefit of using priors when modeling embedded physical components (eg. bulge, disk, bar, spiral arms). Then, one will implement the CAS measurements and perform the classification of a list of galaxies sampling the whole morphological range including peculiar (disturbed) cases. Finally, efficiency and completeness of this approach will be computed thanks to the truth table, and results discussed in terms of single/multiple components, bright/faint features, regular/irregular shapes.



(Conselice+2015)

— MAIN PROGRESSION STEPS —

- **Tier 1:** i) theoretical courses : main properties and demographics of the galaxy population in the local Universe, key physical processes at play in galaxy evolution within the  $\Lambda$ CDM hierarchical model of structure formation (+ exercices) ; ii) start of the homework bibliographical study and of the practical projet.
- **Tier 2:** i) theoretical courses : structural parameters and evolution in time of sizes, evolution of the Hubble sequence, mergers, luminosity functions (+ exercices / presentation of a review paper) ; ii) homework is on-going, first results from the practical projet.

- **Tier 3:** i) theoretical courses : evolution of the cosmic star formation rate density, the Lyman- $\alpha$  universe and the reionisation epoch ; ii) bibliographical study (report due), final results and report for the practical project.
- **Last week:** preparation of the final oral defense.

— EVALUATION —

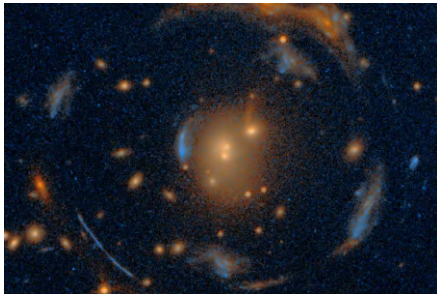
- **Theory grade [30%]**
  - exercices (40%): math. demonstrations, underlying physics, consequences
  - Presentation of a review paper (60%): context, questions, methods, results, etc.

- **Practice grade [30%]**
  - bibliographical study (50%): completeness of the survey, diversity of ressources, relationships with the theoretical/observational notions described in the meteor, etc.
  - Project (50%): initiative, progress, analysis
- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

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## Galaxy clusters as multiwavelength astrophysical laboratories



### SUMMARY.

Galaxy clusters are the largest gravitationally collapsed objects in the Universe, giving them a two-fold advantage in being both valuable cosmological probes as well as astrophysical laboratories. With current state-of-the-art surveys such as the Euclid mission, we are now able to detect and characterise more galaxy clusters than ever before. As the building blocks of the Universe, studying clusters allows us to understand how large scale structure has formed and evolved over cosmic time. One key advantage of clusters is their emission in multiple wavelengths, allowing us to understand their properties and how best to constrain them for cosmology. This METEOR will focus on extracting properties of known clusters to study the interplay between different wavelength observations, which is critical to use them for both cosmology and understanding the environments in which they grow and evolve.

### — OBJECTIVES —

- The student will gain a comprehensive theoretical and observational perspective on how clusters form based on our understanding of large scale structure. This will involve the necessary cosmological background. From the observational point of view, the student will learn the key observables from clusters, notably in optical, X-ray, millimetre, radio and gamma-ray wavelengths. They will also learn about observational inference, surveys, selection functions, statistical methods.
- The student will learn how to analyse observational datasets, such as cluster catalogues from different surveys. They will learn to run and write characterisation pipelines based on optical and SZ datasets.

### — PREREQUISITES —

- ✗ S1. General Astrophysics
- ✗ S2. Large-scale Universe
- ✗ S2. Gravity & relativity

### — THEORY —

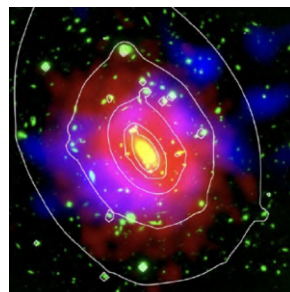
by SUNAYANA BHARGAVA & RÉMI ADAM

The theory component of this course will consist of two subsections. The first will introduce the cosmological framework to understand the context of galaxy cluster formation and evolution, such as understanding

the Friedmann equations, spherical top hat collapse model, structure formation and perturbation theory. The second part will focus on the composition of clusters and their observables in multiple wavelengths, as well as survey selection and statistics. We focus on the complementary views offered by optical observations of the galaxies and millimetre observations of the hot gas to study clusters.

### — APPLICATIONS —

Practical studies on cluster characterisation based on available public data. The main topics covered will be: (i) Analysis of nearby galaxy cluster catalogues and SZ datasets to study clusters ii) Plotting cluster galaxy density and SZ maps (ii) Comparison of cluster mass proxies and properties such as optical richness, red sequence, centring distributions and gas properties.



*Multiwavelength view of a cluster showing SZ (blue), X-ray (red) and lensing mass contours (white).*

### — MAIN PROGRESSION STEPS —

- Tier 1: courses A/B and exercices
- Tier 2: course C and project
- Tier 3: project

### — EVALUATION —

- Theory grade [30%]
  - Written exam (70%): theoretical question, base calculus from lectures
  - Presentation of an article (30%): critical spirit
- Practice grade [30%]
  - Exercices (30%): thought-process and results
  - Project (70%): initiative, progress, analysis
- Defense grade [40%]
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

### — BIBLIOGRAPHY & RESOURCES —

- G. W. Pratt et al. (2019), Space Sci Rev (2019) 215:25, <https://arxiv.org/abs/1902.10837>
- Cosmology, Nicola Vittorio (2018)

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# Star clusters: a looking glass into galaxy evolution



SUMMARY .

Prepare to unlock the secrets of galaxies! In this exciting METEOR, we will embark on a thrilling path that will lead us to young and fiery star clusters as well as their ancient predecessors that formed just a few hundreds million years after the Big Bang. Along this journey we will delve deep into the heart of stars clusters, from stellar populations to gas and dust. But we will not stop there! Armed with some of the most advanced spectro-photometric models and harnessing the exquisite power of Bayesian statistics, we will explore these fascinating celestial objects and move closer to understanding what they really tell us about the formation and evolution of galaxies across the universe.

— OBJECTIVES —

Over this METEOR, our grand objective is to learn what extragalactic star clusters teach us about the formation and evolution of galaxies. Combining lectures and practical work, by the end of the course we will be able to assemble photometric spectral energy distributions for clusters observed with HST and JWST, apply modern modeling (and optionally Machine Learning) techniques to derive ages, masses and dust extinctions, and critically assess the robustness of these measurements. A particular emphasis is placed on understanding and quantifying modeling uncertainties so that cluster demographics can be compared across different galactic environments within nearby galaxies.

— PREREQUISITES —

None! Come as you are!

— THEORY —

by JANICE LEE

Cluster-focused lectures: formation and early evolution of star clusters in galactic contexts; cluster initial mass function; environmental dependence of cluster formation efficiency; disruption processes and survivability; observational identification and classification of extragalactic clusters.

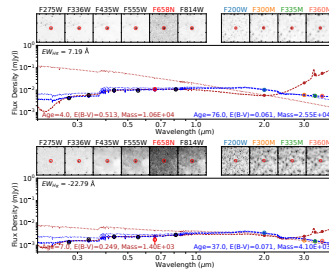
by MÉDÉRIC BOQUIEN

Modeling lectures: model ingredients (stellar population synthesis, nebular emission, extinction laws); fitting methods ( $\chi^2$ , Bayesian inference); model degeneracies and how to mitigate them; interpreting posterior distributions and reporting uncertainties.

— APPLICATIONS —

by MÉDÉRIC BOQUIEN & JANICE LEE

During this course, we will construct comprehensive panchromatic models and apply them to cutting-edge star clusters observations taken from the largest census to-date by the outstanding PHANGS HST and JWST Treasury surveys. Through the lens of Bayesian statistics, we will quantify the star clusters' physical properties. Subsequently, we will rigorously compare our findings with those of published studies, conducting a meticulous analysis to discern insights into the physical processes governing star cluster evolution and their consequence on galaxy formation and evolution.



Here we see a panchromatic star cluster model in action. It includes stars, ionized gas, and dust and is fitted to the multi-wavelength emission observed with both HST and JWST. Such models that we will build over the course of this METEOR will allow us to measure some of the fundamental physical properties of star clusters, such as their age and their stellar mass, which are essential for constraining galaxy

evolution models. Figure adapted from Henny et al. (2025).

— MAIN PROGRESSION STEPS —

The first two weeks of the course will be dedicated to providing a comprehensive theoretical overview of panchromatic galaxy modeling, coupled with an introduction to the range of projects available, which will be selected by the end of the second week. The following weeks will be focused on the project implementation and presentations of complementary topics around galaxy cluster modeling. The course will culminate on the preparation of the oral presentations during the final week.

— EVALUATION —

The first component of the evaluation will comprise five short oral presentations that will complement theoretical lectures, revolving around the main physical components of galaxies and Bayesian techniques (30%). The second part of the evaluation will be based on the written document that will dig into one of the topics seen during the class (30%). Final oral presentation (40%).

— BIBLIOGRAPHY & RESOURCES —

- Boquien et al. (2019)
- Lee et al. (2022)
- Lee et al. (2023)
- Henny et al. (2025)

— CONTACT —

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# Chapter IV

## Signal processing & numerical methods



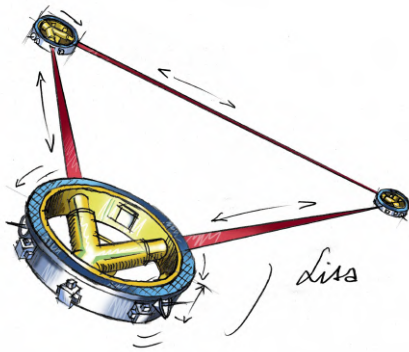
### Contents

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1	LISA data analysis . . . . .	27
2	High Performance Computing for Fluids . . . . .	28
3	Machine Learning for Stellar SEDs . . . . .	29
4	RFI masking recast as a supervised segmentation problem . . . . .	30

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# LISA data analysis



**SUMMARY.**

This METEOR will be dedicated to data analysis for the Laser Interferometer Space Antenna (LISA) – a space-based gravitational-wave detector that is planned to be launched in the mid-2030s.

We will study methods for LISA data analysis, focusing on techniques for signal detection and Bayesian parameter estimation. We will explore approaches ranging from classical Markov chain Monte Carlo (MCMC) methods to modern machine-learning techniques.

The theoretical part of the course will include a brief introduction to the construction of gravitational-wave waveforms for LISA as solutions to the field equations of general relativity. It will also cover probability theory and signal processing, as well as provide an overview of machine-learning techniques, including common neural-network architectures and modern generative modelling approaches.

The practical part will involve implementing the algorithms required for LISA data analysis.

**— OBJECTIVES —**

- The student will learn the basics of solving the equations of general relativity and gain an understanding of Bayesian parameter estimation.
- The student will acquire skills in implementing parameter estimation using MCMC methods and generative modelling (sometimes called simulation-based inference).

**— PREREQUISITES —**

- ✗ S1. Data Sciences
- ✗ S1. Numerical methods
- ✗ S2. Gravity & relativity
- ✗ S2. Statistics

**— THEORY —**

by NATALIA KORSAKOVA

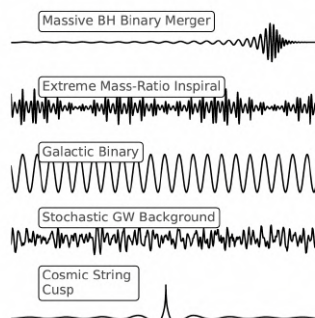
We will learn to derive gravitational waveforms as solutions to the Einstein field equations. We will study different approaches to solving Bayes' theorem and understand the similarities and differences between these methods.

**— APPLICATIONS —**

by NATALIA KORSAKOVA

We will implement some of the basic detection and parameter estimation algorithms and understand the challenges involved in LISA data analysis. In the project, we will attempt to

tackle some of the unsolved problems in LISA data analysis.



Typical gravitational wave signals that will be observed by LISA.

- Week 4: lectures on generative modelling and project
- Weeks 5-7: project

**— EVALUATION —**

- Theory grade [30%]
  - Oral exam (70%): theoretical question, base calculus from lectures
  - Presentation of an article (30%): critical spirit
- Practice grade [30%]
  - Project: initiative, progress, analysis, thought-process
- Defense grade [40%]
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

**— MAIN PROGRESSION STEPS —**

- Week 1: lectures on the introduction to gravitational waves and practical demonstrations
- Week 2: lectures on probability theory and exercises
- Week 3: lectures on machine learning and project starts

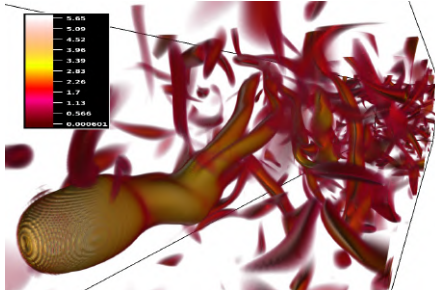
**— BIBLIOGRAPHY & RESOURCES —**

- Schutz, A first course in general relativity
- Bishop, Deep learning
- LISA red book

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## High Performance Computing for Fluids



### SUMMARY.

Numerical simulations are an indispensable tool in studying astrophysical problems. The development of new algorithms and the increasing computational power of supercomputers consisting nowadays of millions of computing units allow for realistic simulations of complex environments. This meteor provides the fundamental know-how that is behind these demanding simulations. The students will learn to code numerical schemes for compressible fluids such as the interstellar medium. For this, a modern algorithm called Discontinuous Galerkin (DG) will be introduced. The students turn theory into practice and implement short but challenging applications.

### — OBJECTIVES —

- Studying numerical schemes employed in modern codes to simulate gases include finite difference (FD), finite volume (FV), discontinuous Galerkin (DG) methods. **The students will understand the main differences between numerical methods.**
- C++ is a computing language that is not only used in scientific computing but also in many other performance critical applications. It allows user friendly abstractions while keeping optimal performance. **The students will learn modern C++ through practice.**
- Today's supercomputers are massive parallel. They contain fast-interconnected nodes equipped with several multi-core CPUs and accelerators such as graphics processing units (GPU). **The students will learn how to use supercomputers** by adapting their algorithms for parallel computing.

### — PREREQUISITES —

- ✗ S1. Numerical methods

### — THEORY —

by HOLGER HOMANN

Numerical methods have to be fast and precise. The students will understand why the order of convergence matters. Why high-order (complicated) methods (such as discontinuous Galerkin) are faster than low-order (simple) methods. The students will understand critical ingredients of numerical schemes such as conservation, Riemann problems and dissipation.

Fast codes run on fast hardware. The students will learn the architectural differences of modern computing hardware. What does object-oriented and data-oriented design mean? How can we reconcile both to get the optimal code?

### — APPLICATIONS —

by HOLGER HOMANN

Astrophysical problems often involve smooth flow and regions where the formation and dynamics of shocks is important. The students will understand main properties by studying two one-dimensional model problems: the Burgers equation and the isothermal gas equations.

The students will themselves implement from scratch a modern numerical scheme for such equations. A focus can either be on the modern algorithms (such as discontinuous Galerkin) or on modern hardware (such as graphic cards (GPUs)).



Today's supercomputer consist of a mixture of CPUs and GPUs

### — MAIN PROGRESSION STEPS —

- Recalling finite difference and finite volume methods
- Introduction to discontinuous Galerkin methods

- Introduction to Riemann solvers
- Study of relevance of DG schemes for astrophysical applications (study of paper).
- Introduction of C++ for scientific computing
- Project: Students choose a scientific coding project among

- High-order discontinuous Galerkin methods
- Comparison of Riemann solvers
- Compressible gas simulations
- Parallelization for supercomputers

### — EVALUATION —

- Theory grade [30%]
  - Oral exam : theoretical questions on numerical methods and programming, base calculus from lectures
- Practice grade [30%]
  - Coding project: initiative, progress, quality of code, autonomy
- Defense grade [40%]
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

### — BIBLIOGRAPHY & RESOURCES —

- Nair-Lauritzen-Levy(2011)
- Colella-Puckett(1994)
- Schaal-etal.(2015)

### — CONTACT —

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# Machine Learning for Stellar SEDs



**SUMMARY.**

Current space missions, benefiting from technological progresses, have raised the amount of collected data to unprecedented levels, and have highlighted a critical need for the development of new tools capable of processing and analysing big data from space. Artificial Intelligence (AI) is a powerful tool that is becoming more common across a wide range of fields, including astronomy and Earth observations. In this module, the student will use AI techniques for the analysis of stellar SEDs (spectral energy distribution) from the Gaia All Sky Parameters for Stars (GASPS) service. This module is provided by ACRI-ST, an SME of the space sector that provides engineering and data services for space missions.

— OBJECTIVES —

The student will analyse spectral energy distribution of stars in the GASPS survey using AI. In particular, the student will learn:

- AI techniques and understand their advantages and limitations.
- Run an XGBoost machine learning model and familiar with the GASPS service.

— PREREQUISITES —

- ✗ S1. Data Sciences
- ✗ S1. Numerical methods
- ✗ S2. Statistics

It is recommended to have good coding skills in python. Familiarity with machine learning is also beneficial.

— THEORY —

by JERONIMO BERNARD-SALAS

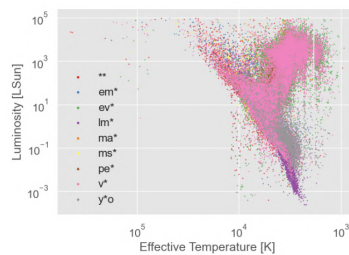
The module will cover an introduction to machine learning, the Gaia mission, and GASPS which includes data from different missions like Gaia, WISE, 2MASS etc...

— APPLICATIONS —

by NICK COX

The student will analyse GASPS results in the context of supervised machine learning models. The project covers different steps in a data science

workflow, from data retrieval, machine learning inference, and data analysis and interpretation.



An HR-diagram from stars of the GASPS service.

— MAIN PROGRESSION STEPS —

This module is divided in three main stages as described below:

- **Week 1:** Introduction to machine learning, Gaia and GASPS.
- **Week 2-5:** Model deployment.
- **Week 6-7:** Model Inference, project report and presentation.

— EVALUATION —

- **Theory grade [30%]**
  - Written Report (70%): bibliography, thematic and technical description

- Project Presentation (30%): questions

- **Practice grade [30%]**
  - Progress meetings (30%): progress
  - Project report and presentation (70%): initiative, analysis, results

- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

— BIBLIOGRAPHY & RESOURCES —

The links below provide information on basic machine learning and on the methodology at the core of the module.

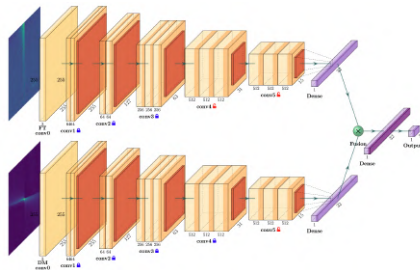
- Machine learning in python
- Machine learning and data mining for astronomy
- Machine learning based stellar classification with highly sparse photometry data.

Image credits: Title (NASA, ESA, Hubble Legacy Archive, Utkarsh Mishra). HR diagram: S.E. Cody et al. (Open Research Europe, 2024)

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# RFI masking recast as a supervised segmentation problem



**SUMMARY.**

Radio Frequency Interference (RFI) remains one of the main limitations in modern radio astronomy, severely affecting the detection of faint astrophysical signals such as Fast Radio Bursts (FRBs) or pulsars. This project proposes to explore and develop machine learning approaches for automatic RFI detection and masking in high-dimensional radio telescope data.

Students will investigate state-of-the-art deep learning techniques.

— OBJECTIVES —

- Understand the astrophysical context of transient radio sources: Fast Radio Bursts (FRBs) and Pulsars.
- Gain a solid understanding of Radio Frequency Interference (RFI): its origins, its impact on radio telescope data, and why automated masking is critical at modern facilities such as NenuFAR.
- Frame RFI mitigation as a supervised pixel-wise segmentation problem and understand how deep learning methods can address it.
- Develop hands-on proficiency in building, training, and evaluating segmentation neural networks using modern tools (PyTorch Lightning, MLFlow).
- Critically assess model performance on real observational data and understand the gap between benchmarks and deployment.

— PREREQUISITES —

- ✗ S1. Data Sciences
- ✗ S2. Statistics

— THEORY —

by SARA EL BOUCH

This module begins with a concise review of machine learning fundamentals (supervised vs. unsupervised learning, loss functions, gradient descent, overfitting and regularization) before introducing deep learning: convolutional neural networks (CNNs), residual connections, and encoder-decoder architectures. Particular attention is paid to the **segmentation task**, assigning

a label to every pixel of an input, as the core methodology for RFI masking.

The astrophysical motivation is woven throughout: students are introduced to the time-frequency representation of radio telescope data (dynamic spectra), the morphology of RFI signals, and the characteristics of genuine astrophysical pulses such as dispersed FRB and pulsar signals. This dual perspective provides the conceptual grounding needed to design and interpret segmentation models responsibly.

— APPLICATIONS —

by SARA EL BOUCH

- **Practical work 1: Tooling:** Hands-on introduction to PyTorch Lightning (training loops, callbacks, checkpointing) and MLFlow (experiment tracking, metric logging, model registry). Students train a simple classifier on a toy dataset to build confidence with the workflow.
- **Practical work 2: Segmentation baseline:** Implementation of a U-Net-style encoder-decoder from scratch. Students explore architectural choices (depth, skip connections) and experiment with different loss functions on a labelled RFI dataset.
- **Project: RFI masking on NenuFAR data:** Students apply and refine their segmentation pipeline on real dynamic spectra from the NenuFAR low-frequency array. The project includes data preprocessing (normalisation, augmentation), training on labelled observations, and qualitative and quantitative evaluation of masks. Students are expected to document their experimental choices, analyse failure cases, and propose improvements.

— MAIN PROGRESSION STEPS —

- **Tier 1: Foundations of ML/AI and radio astronomy context:** Lectures on supervised learning, CNNs, and the physics of FRBs/Pulsars. Introduction to dynamic spectra and RFI phenomenology.
- **Tier 2: Segmentation theory and tooling:** Deep dive into encoder-decoder architectures, loss functions, and evaluation metrics. Practical works 1 and 2.
- **Tier 3: RFI masking project on real data:** End-to-end project on NenuFAR observations, from raw HDF5 data loading to mask generation and critical analysis.

— EVALUATION —

- **Theory grade [30%]**
  - Written exam (70%): Covers ML/AI fundamentals, CNN architectures, segmentation losses, and evaluation metrics.
  - Article presentation (30%): Students select and present a research paper on RFI mitigation or related ML for radio astronomy (e.g., FETCH, AOFlogger, or a recent deep learning approach). Graded on clarity, critical analysis, and ability to connect the paper to course material.
- **Practice grade [30%]**
  - Practical works (30%): Assessed on correctness of implementation, quality of experimental protocol, and written answers to guided questions.
  - Project (70%): Graded on initiative and originality of design choices, rigour of evaluation on

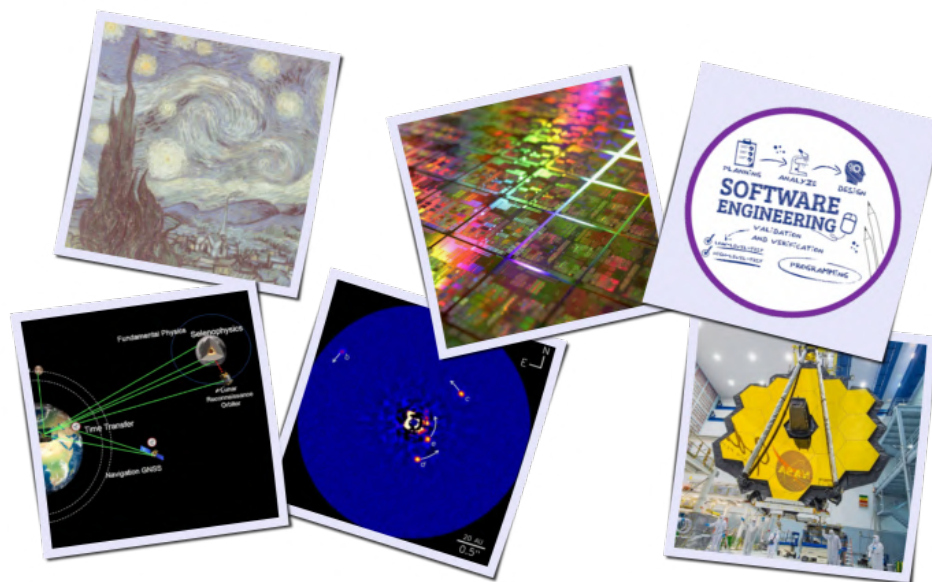
MAUCA – METEOR in Signal

RFI masking recast as a supervised segmentation problem

- NenuFAR data, quality of analysis (including failure cases), and clarity of the written report.
- Defense grade [40%]
  - Oral and slides quality
  - Context
  - Project
  - Answers to questions
- BIBLIOGRAPHY & RESOURCES —————
- FETCh Deep learning classifier for FRB candidates
- Goodfellow, Bengio & Courville, *Deep Learning* (MIT Press), Chapters on CNNs and regularisation.
- Ronneberger et al. (2015), *U-Net: Convolutional Networks for Biomedical Image Segmentation*, MICCAI.
- Offringa et al. (2012), *A morphological algorithm for improved RFI de-tection* AOFlagger reference.
- NenuFAR documentation and open data portal.
- PyTorch Lightning and MLFlow official documentation.
- CONTACT —————
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# Chapter V

## Astronomical optics & instrumentation



### Contents

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1	Stellar amplitude interferometry . . . . .	33
2	Photonics for high angular resolution astronomy . . . . .	34
3	Co-phasing Segmented Optics . . . . .	36
4	Imaging Exoplanets . . . . .	38
5	Ground to Space Laser Links for Space applications . . . . .	40
6	Astronomical Adaptive Optics . . . . .	41
7	Graviational Wave Detector . . . . .	42

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## Stellar amplitude interferometry



The four Unitary Telescopes of the Very Large Telescope in the Desert of Atacama, Chile.

This course introduces students to amplitude stellar interferometry and to the main issues involved in meeting the requirements needed to achieve major advances in astrophysics with this technique.

Observing with a stellar interferometer provides access to high angular resolution. We will show how visibility measurements, derived from interferometric data, can be used to determine parameters related to the scientific targets as angular diameters or binary separations.

Because interferometric observable quantities are influenced by the Earth atmosphere and instrument's response, we will identify the main effects that impact the associated transfer function, the aim being to acquire the most stable and reliable sets of data possible.

The spectro-interferometer MATISSE, operating at the Very Large Telescope Observatory in the Atacama Desert in Chile, will serve as a central example throughout the course. The ultimate objective is to perform processing, calibration, and modelling of MATISSE data.

The courses consist of lectures presented on blackboard. Slide presentations will also be used to show relevant images and plots. The good understanding by the students of the addressed topics will be evaluated through their ability to solve analytical and numerical exercises. Laboratory works will also be conducted. Numerical work will be carried out using examples of data analysis from the MATISSE instrument. Active learning is mainly expected through in-class exercises, numerical modelling and simulation projects.

\$ make package

— OBJECTIVES —

- **Knowledge and understanding.** Students will learn the techniques of amplitude stellar interferometry, will apply diffraction theory to define the appropriate formalism, will learn the effects of the Earth atmosphere and of instrumental defects.
- **Applying knowledge.** Students will solve analytical exercises, run numerical simulations, conduct lab measurements, use MATISSE data to perform data calibration and modelling with such an instrument.

— PREREQUISITES —

- ✗ S1. Fourier Optics

— THEORY —

by SYLVIE ROBBE-DUBOIS

After a short historical overview and introduction, we will address the question of why a stellar interferometer is needed. The diffraction theory introduced in the Fourier Optics course will be used to define the intensity measured by an interferometer, as well as the degree of mutual coherence. Considering an interferometer as a spatial filter, we will show how to estimate the observable quantity, the squared visibility, which provides information about the source morphology.

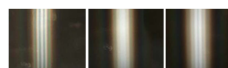
Factors that degrade the visibility will be studied, including terrestrial atmospheric turbulence and instrumental effects, leading to the error budget of the MATISSE instrument.

— APPLICATIONS —

by SYLVIE ROBBE-DUBOIS

Analytical exercises based on case studies will be proposed as direct applications of the course. Simulation exercises will also help for the preparation of the project. The labwork will help to understand the effect of the source morphology on the observable quantity, the squared visibility.

Concerning the project, two topics are offered, both related to data analysis from the MATISSE spectro-interferometer: model fitting of different types of sources (such as limb darkening, binary system, and star with envelope) based on visibility analysis; and the study of instrumental effects on the data, including residual effects from adaptive optics.



Simulated interferograms with varying contrast.

— MAIN PROGRESSION STEPS —

- 15h-20h: courses, analytical and numerical exercises

- 4h: labwork
- 15h-20h: project

— EVALUATION —

- **Written tests [20%]:** Quiz-type: definitions and base calculus from lectures. Accuracy, relevance, completeness, conciseness.
- **Written lab report [20%]:** Understanding, methodology, accuracy and relevance of the data collection, data analysis and interpretation of results.
- **Project [20%]** Progress, analysis, initiative
- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

— BIBLIOGRAPHY & RESOURCES —

- Millour F., New Astron.Rev. 52:177-185, (2008)
- Lopez B. et al., A&A, vol 659 (2022)

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# Photonics for high angular resolution astronomy



**SUMMARY.**

The wide availability of adaptive optics (AO) and other telescope beam stabilization techniques now make it possible to design complex instruments like **interferometric recombiners** and **spectrographs** out of ultracompact **integrated optics**. At the VLTI, several generations of instruments (PIONIER, GRAVITY and now ASGARD) are taking advantage of this technology, to great effect. At Lagrange, our group is using a laboratory setup to test and characterize devices that can, through thermo-optical effects, actively control the electric field of light of astrophysical origin without any moving parts. Next generation active spectro-interferometers are on the horizon and offer very unique opportunities for exciting astrophysical use cases like the direct detection and characterization of extrasolar planets.

— OBJECTIVES —

Students will be introduced to the wonderful whimsical world of photonics, a very active modern sub-field of optics concerned with the emission, transport and manipulation of light at microscopic scales. Applied as its name suggests, to astronomy, **astrophotonics**, makes it possible to design instruments that would otherwise be incredibly complex to build. With now ubiquitous access to AO and general beam stabilization techniques (or the possibility of space-borne observatories), we can take advantage of **single-mode photonics**, that is at the core of an upcoming wave of instruments. The students will gain practical exposure to two use cases that take advantage of this new modality: high-angular resolution astronomy - that we will explore through the lens of optical interferometry - and spectroscopy.

The students will see (and experience first hand) that the current R&D challenges lie (at least in the visible and near-infrared) at the interface between the telescope beams and the integrated optics - the so-called injection stage - and in the design of circuitry that can efficiently cover a wide spectral range.

The context of the recent and still ongoing commissioning of the VLTI/ASGARD instrument suite is a great opportunity to explore the potential of a prospective integrated optics high-contrast imaging recombining called SEIDR that would implement our latest findings.

— PREREQUISITES —

- ✗ S1. Fourier Optics
- ✗ S1. Numerical methods
- ✗ S2. Imaging through turbulence

— THEORY —

by F. MARTINACHE & N. CVETOJEVIC  
The theoretical part of this METEOR will cover:

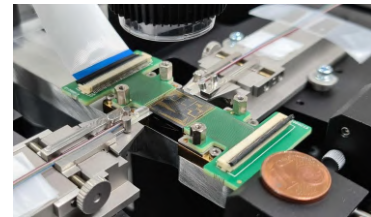
- an introduction to the field of astrophotonics, including lectures on the fundamental light guiding principles, a description of the manufacturing processes for fibers and integrated optics chips, and a review of active astronomical instruments that rely on photonics.
- an introduction to the field of optical interferometry, starting with a review of the properties of spatial and temporal coherence of light, the properties of interference fringes, the imaging capability of interferometers and high-contrast imaging use cases.
- an in-depth look at the design of several types interferometric recombiners using integrated optics: the ABCD recombining, as well as high-contrast recombiners.

This theoretical section will conclude with a discussion of the potential future of fully photonic space borne telescope designs.

— APPLICATIONS —

by F. MARTINACHE  
The students choosing this METEOR will be able to take advantage of the PHOTONICS characterization test-bench

hosted at the Lagrange laboratory (see Figure below) as well as the availability of early commissioning data acquired by the ASGARD/HEIMDALLR fringe tracker at the focus of the VLTI.



PHOTONICS integrated device in lab

With practical expertise gained in the characterization of the spectral behavior of (a possibly active) near-infrared 4-input beam recombining, the students will be able to examine the fringe-tracking performance of ASGARD/HEIMDALLR at VLTI, to model and predict the high-contrast imaging potential of a new envisioned module called ASGARD/SEIDR (meaning “black-magic”).

— MAIN PROGRESSION STEPS —

- **Tier 1:** First half of the period : introduction and initial lab tour followed by a series of 6 lectures on photonics and interferometry (bibliography review presentation after week #2 and a written exam after the end of week #4)
- **Tier 2:** lab sessions, data-analysis and modeling toward the completion of student projects.

- **Final week:** preparation and rehearsal of the final oral presentation.

Depending on lab and staff availability, the students will have the opportunity to gain expertise in some operation aspects of the PHOTONICS test-bench. Whether working in the lab, modeling or analysing actual data, the students will be requested to keep a physical and/or virtual lab book to keep track of their experiments and the progress of their understanding. The content of the lab book will be used as part of the student project evaluation.

— **EVALUATION** —

- **Theory grade [30%]**

- Reading assignments, critical review of selected papers (30%)
- Written exam: critical essay as well as answers to questions (70%)

- **Practice grade [30%]**

- Lab work / lab book practices (30%)
- Data analysis and/or modeling work (30%)
- Written project report (40%)

- **Defense grade [40%]**

- Oral and slides quality
- Context
- Project / Personal work
- Answers to questions

— **BIBLIOGRAPHY & RESOURCES** —

- Taras et al (2024)
- Martinache & Ireland (2018)
- Benisty et al (2009)
- F. Martinache lectures (YT, 2005)
- F. Martinache - kernel-nulling (YT, 2020)
- PHOTONICS project webpage

The PHOTONICS test-bench is financed by the ANR program PEPR Origins (ANR-22-EXOR-0005).

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## Cophasing Segmented Optics



**SUMMARY.**

Increasing the telescope diameter from a few meter class telescopes towards tens of meters and beyond imposes segmentation in order to keep the telescope mechanically and optically feasible and minimize failure risks. Large-segmented telescope projects from the ground or in space incorporate a number of components or subsystems that are technically challenging and have barely ever been operated on a routine basis at an astronomical telescope. Deploying segmented optics on large-scale structures turns active and adaptive optics into co-phasing optics for aligning multiple optical paths in real-time operation. Cophasing optics that correct for the misalignment of individual segments of the primary segmented mirror is a key optical process to reach exquisite image quality and stability: to bring the segmented telescope’s maximum performance close to the ideal single mirror case.

— OBJECTIVES —

Students following this METEOR are expected to acquire knowledge in both theoretical and practical cophasing optics and telescope optics with segmented telescopes, including laboratory experimentation, numerical modeling, and system dimensioning. They will focus on international projects and benefit from intensive training by research. Cophasing is the process of controlling the individual segments in a segmented mirror so that the segments form a surface nearly as good as if the segmented mirror was made in a single unit (monolithic mirror). Cophasing implies active control of three degrees of freedom of each individual segment mirror with high precision: translation along the optical axis (piston) and rotation about two axes perpendicular to the optical axis (tip-tilt). Segments suffer from gravitation force, wind blowing, and thermal and pressure changes.

If the precise alignment of each segment is not achieved, the resolution of the telescope degrades and could be the same as if the telescope had a diameter equal to the size of a single segment. Cophasing optics strives to achieve a segment’s alignment so that the telescope gets a resolution commensurable with that of a monolithic telescope of the same diameter of the segmented surface. Depending on the astrophysical objective, cophasing must reach a precision better than  $\lambda/30$  rms to a precision better than  $\lambda/10$  rms (exoplanet imaging).

— PREREQUISITES —

- ✗ S1. Fourier Optics
- ✗ S1. Numerical methods
- ✗ S2. Imaging through turbulence

— THEORY —

by P. MARTINEZ

The theoretical part of this METEOR will provide insights into

- telescope optics: understanding the relationship between the telescope optical structure and image diffraction characteristics,
- a global introduction to segmented telescope projects, architectures, and impact on the image quality,
- segmented telescopes needs and requirements,
- the state-of-the-art of co-phasing systems, including fundamental limitations and systems technological maturity,
- specialized courses for co-phasing loop control, systems dimensioning and numerical modeling,
- laboratory illustrations with the SPEED testbed.

Specific care for the dichotomy occurring between space and ground-based observatories will be discussed. In particular, a specific study of the NASA/JWST co-phasing process will be proposed in a dedicated chapter.

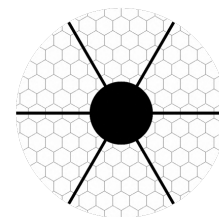
Because of the unique circumstances of the stable space environment, co-phasing architecture on JWST is different from large active telescopes on the ground, where the

dominant factor requiring rapid correction for active and adaptive telescopes on Earth is gravity-induced deformations. Space disturbances change much more slowly than the durations of typical changes on the ground.

— APPLICATIONS —

by P. MARTINEZ

The application part of this METEOR will provide specialized courses including laboratory practice with the SPEED testbed, numerical modeling with generic and peculiar co-phasing systems, and performance evaluation. These courses will cover the area of telescope architectures, co-phasing optics and sensors.



*The SPEED testbed offers a telescope simulator with a primary mirror made of 163 segments*

In particular, this module will benefit from numerical modeling training to simulate part or a whole system and will take advantage of privileged access to the SPEED instrumental facility (Segmented Pupil Experiment for Exoplanet Detection) at the Lagrange laboratory. The SPEED project is

MAUCA – METEOR in Instrumentation

Cophasing Segmented Optics

an optical platform for testing systems and subsystems for high-contrast imaging (exoplanet imaging) with segmented telescopes. The project is supported by various partners (Lagrange, OCA, UNS, CNES, ESO, Airbus Defense and Space, Thales Alenia Space, PACA, EU) and collaborations: LESIA (Paris), Subaru Telescope (Hawaii) and LAM (Marseille).

— MAIN PROGRESSION STEPS —

- First half of the period : theoretical courses (exam at middle or end term, tbc).
- Second half of the period : student projects, final report at end term.
- Last week: preparation of the final oral presentation and term project report.

The METEOR program is based on various pedagogic structures:

- Focus lectures that are opening lectures on a single and specific topic (e.g., the SPEED testbed co-phasing sensors, the ESO-ELT, the JWST),
- Computer practicum that are numerical practical work (e.g., mag-

nitude & phase, 2D Fourier transform, Zernike, PSF & MTF, diffraction in segmented telescopes, piston errors, interaction and control matrix),

- Labs hands-on that are practical work in lab environment (e.g., co-phasing sensors and correction, diffraction in segmented telescopes),
- Reading assignments that are active learning based on scientific articles,
- and Mini-project, consisting of the analysis of a research article or answering an open question, students are asked to understand and reproduce the results of the article or the scientific properties raised by the question. Students can tackle the problem using either theoretical knowledge, numerical modeling or lab experiment.

— EVALUATION —

- **Theory grade [30%]**
  - reading assignments (written/oral questions, presentation may be asked);

- homework assignments (oral presentation may be asked);
- a final exam (conceptual essay and/or questions and quantitative problems).

- **Practice grade [30%]**
  - hands-on experience with the hardware and software components will be made possible;
  - computer practicum that are numerical practical work;
  - project: initiative, progress, analysis, final report.
- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

— BIBLIOGRAPHY & RESOURCES —

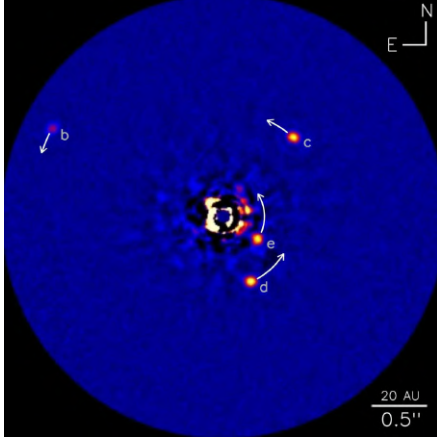
- NASA JWST Facebook page
- European-ELT project
- SPEED project website

— CONTACT —

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# Imaging Exoplanets



**SUMMARY.**

Understanding the formation, evolution and diversity of extrasolar planets is one of the challenges of modern astrophysics. Numerous discoveries have revealed the complex nature of more than 5000 exoplanets, whose analysis of the chemistry of the atmospheres is crucial to determine the conditions for the appearance of life. The observation of exo-Earths is a considerable technological challenge due to the significant difference in flux between the host star and its planet, located at a short angular separation (typically  $10^{10}$  at least of a second of arc, in the visible and near-infrared domains). Direct imaging and study, particularly of exo-Earths, exoplanets similar to Earth, requires the development of instrumental concepts where active and passive optics play an important role. This METEOR gives a broad overview of the subsystems that are part of a coronagraphic instrument for imaging exoplanetary systems.

— OBJECTIVES —

Planets beyond our solar system are a hot topic of modern astronomy through the development of the most up-to-date instruments since 1995, the date of the first detection (51 Pegasi-b). Known exoplanets, numbering in the thousands, have been detected using mainly indirect methods, but direct imaging enlarges the discoveries paradigm. Exoplanet direct imaging is a snapshot of the planet(s) around a central star. However, they are much fainter than their parent star and separated by small angles, so conventional imaging systems are inadequate. This METEOR provides a global introduction to the outstanding exoplanet search problem, in particular, it presents the dedicated technological and instrumental requirements for direct imaging.

A high-contrast imaging instrument for observing exoplanets must

- suppress the bright star's image and diffraction pattern,
- suppress the star's scattered light from imperfections in the telescope.

We expect students taking this METEOR to understand how exoplanets can be imaged by controlling diffraction with coronagraphy and scattered light with deformable mirrors. Students following this METEOR are expected to acquire knowledge in both theoretical and practical aspects related to exoplanet imaging, including

laboratory experimentation, numerical modeling, and system dimensioning.

— PREREQUISITES —

- ✗ S1. Fourier Optics
- ✗ S1. Numerical methods
- ✗ S2. Imaging through turbulence

— THEORY —

by P. MARTINEZ

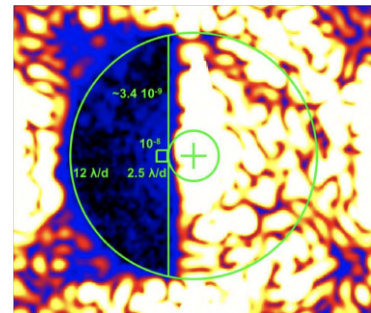
In this part of the METEOR, we discuss the theory behind stellar diffraction patterns and the impact of wavefront aberrations on the performance of high-contrast imaging instruments. In particular, we show how they induce stellar speckles in the scientific image. Using coronagraphy we show how it is possible to control unwanted radiation to some extent. We present instrumental and signal processing techniques used for on-sky minimization of the speckle pattern (sensing, controlling and suppressing speckles). The theory of wavefront control and shaping is presented and the importance of active and passive optical elements such as deformable mirrors and coronagraphs are studied. Finally, a posteriori calibration of the speckles in order to improve the performance of coronagraphs is presented. This part includes lectures, exercises, discussions of examples, and literature research.

— APPLICATIONS —

by P. MARTINEZ

The application part of this METEOR will provide specialized courses including laboratory practice with the

SPEED testbed, numerical modeling, and performance evaluation. These courses will cover the area of telescope architectures, co-phasing optics and sensors, diffraction suppression systems (coronagraphy) and wavefront control (deformable mirrors). In particular, this module will benefit from numerical modeling training to simulate part of an instrument for exoplanet detection and will take advantage of privileged access to the SPEED instrumental facility (Segmented Pupil Experiment for Exoplanet Detection) at the Lagrange laboratory.



Dark hole generated on the high contrast imaging testbed (HCIT) at JPL using wavefront control

The SPEED project is an optical platform for testing systems and subsystems for high-contrast imaging (exoplanet detection) with segmented telescopes. The project is supported by various partners (Lagrange, OCA, UNS, CNES, ESO, Air-

bus Defense and Space, Thales Alenia Space, PACA, EU) and collaborations: LESIA (Paris), Subaru Telescope (Hawaii) and LAM (Marseille).

#### — MAIN PROGRESSION STEPS —

The METEOR program is structured in 7 modules:

- the challenges of exoplanet imaging,
- diffraction in a telescope,
- telescope and wavefront errors,
- wavefront sensing and control,
- deformable mirrors: control and suppress speckles,
- coronagraphy: control unwanted radiation,
- and basics of data post-processing & observing strategies,

with the following progression steps:

- **First half of the period** : theoretical courses, numerical practical works (exam at middle or end term, tbc).
- **Second half of the period** : Labs hands-on and practical works, student project, final report at end term.
- **Last week** : preparation of the final oral presentation and term project report.

The METEOR program is based on various pedagogic structures:

- Focus lectures that are opening lectures on a single and specific topic (e.g., ESO/SPHERE instrument, NASA/JWST, high-contrast lab. settings),
- Computer practicum that are numerical practical work (e.g., magnitude & phase, 2D Fourier transform, Zernike, PSF & MTF, diffraction in segmented telescopes, whose telescope is this?, from wavefront errors to speckles, coronagraphy, deformable mirror),
- Labs hands-on (upon availability and mini-project selection) that are practical work in lab environment (e.g., wavefront sensors, coronagraphy, deformable mirror),
- Reading assignments that are active learning based on scientific articles,
- and Mini-project (e.g., wavefront sensor to correct for non-common path aberrations, wavefront sensor to co-phase a segmented aperture, speckle temporal stability in high-contrast coronagraphic images, speckle symmetry with high-contrast coronagraphs, coronagraphy, high-dynamic-range using a deformable mirror: dark-hole generation).

#### — EVALUATION —

- **Theory grade [30%]**
  - reading assignments (written/oral questions, presentation may be asked);
  - homework assignments (oral presentation may be asked);
  - a final exam (conceptual essay and/or questions and quantitative problems).
- **Practice grade [30%]**
  - hands-on experience with the hardware and software components will be made possible;
  - computer practicum that are numerical practical work;
  - project: initiative, progress, analysis, final report.
- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

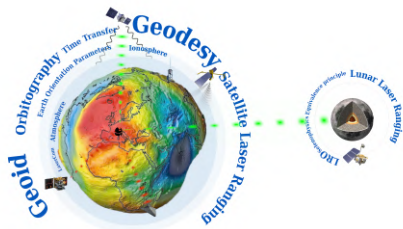
#### — BIBLIOGRAPHY & RESOURCES —

- Exoplanets explained
- Exoplanets.eu
- SPEED project website

#### — CONTACT —

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# Ground to Space Laser Links for Space Applications



**SUMMARY.**

Have you ever dreamed of shooting lasers into space for science? The aim of this METEOR is to provide a comprehensive introduction to techniques for establishing laser links between the ground and space targets. After an introduction to the scientific context surrounding laser links to space (Space Geodesy, Lunar Science, Fundamental Physics), we'll look in detail at the satellite laser ranging technique. The course will detail the ground and space technologies and physics required to establish highly precise distance measurements (mm) between the ground and a space target hundreds of thousands of km away. We will also look at the emerging topics of classical and quantum laser communications and space debris tracking. A part of this METEOR will be carried out at the Calern observatory for projects involving sky-based experimentation.

**OBJECTIVES**

Understand the general instrumentation and physical concepts needed to perform free space laser links (laser ranging, optical communication,...) between Earth and an orbiting target. Be able to design an experiment for laser ranging or optical communication

- **Knowledge:** Lasers, telescope, detectors, space target,...
- **Skills:** Optical calculation, data analysis, extract information from ground to space laser experiment (target shape, attitude, link budget,...)
- **Project:** Define and run your own project, including observation, data acquisition and processing

**PREREQUISITES**

- ✗ S1. Fourier Optics
- ✗ S1. Numerical methods
- ✗ S2. Imaging through turbulence

**THEORY**

by JULIEN CHABÉ

- Introduction to Space Geodesy
- Principle of Satellite Laser Ranging and Time transfer
- Time and distance Metrology
- Laser propagation through the atmosphere
- Laser Communication and Quantum keys distribution to Space

**APPLICATIONS**

by JULIEN CHABÉ

- Evaluation of budget links for laser experiments
- Error budget in laser ranging experiment
- Observations with the MéO telescope (Moon, geodetic satellite, space debris)
- Data processing and analysis



The MéO telescope in action

- Week 4: Metrology of time and Time Transfer to Space - project
- Weeks 5-7: project

**EVALUATION**

- **Theory grade [30%]**
  - Written exam (50%): theoretical questions
  - Case study (50%): exercise based calculation
- **Practice grade [30%]**
  - Project (60%): thought-process and results
  - Project report (40%): presentation of your results
- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

**BIBLIOGRAPHY & RESOURCES**

During the METEOR free accomodation to the Calern observatory is provided by OCA.

- Degnan, J. Millimeter Accuracy Satellite Laser Ranging: A Review
- Learn to make a better Lunar Laser Ranging Experiment than this
- Join us here

**CONTACT**

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Astronomical Optics and Instrumentation

METEOR Astronomical Adaptive Optics (AAO)

SUMMARY.

Modern optical telescopes deploy adaptive optics (AO) systems in order to reach the expected angular resolution in spite of atmospheric turbulence. In that sense, this METEOR has fundamental connections with all major facilities (8-m class telescopes, ELT projects). After the necessary theoretical basics, numerical studies will be performed in the framework of the instrument AOC (AO at C2PU/Calern). Then, different custom-made applications will be discussed, concerning either the present optimisation of AOC or much more advanced perspectives, via numerical modelling and possibly on-sky observations.



OBJECTIVES

The expected expertise/skills acquired during this METEOR are: knowledge of the theoretical and practical basics of astronomical AO, including laboratory experimentation, dimensioning of an AO system, post-AO imaging, and numerical detailed modelling of the main types of AO systems for astronomy (standard AO, extreme AO, wide-field AO).

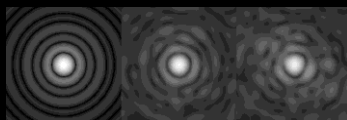
PREREQUISITES

(1) Fourier optics ; (2) Imaging through turbulence ; (3) Numerical methods.

THEORY

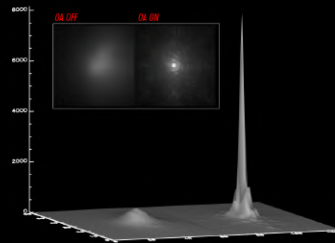
by MARCEL CARBILLET & OLIVIER LAI

The scope is to provide a global introduction to AO for astronomy, practice with AO systems dimensioning and numerical modelling, including wavefront sensing, wavefront correction, loop control, detector characteristics, performance evaluation, etc.



APPLICATIONS

by OLIVIER LAI & MARCEL CARBILLET



The application part of this METEOR will first focus on detailed numerical modelling and performance evaluation of a standard AO system, namely the AOC system in its stellar mode. EXTreme AO (XAO), with application to exoplanets detection, and Ground-Layer AO (GLAO), for wide-field astronomy will also be tackled. Custom-made applications will then be determined with the student(s), in function also of the individual interests, and will imply numerical modelling and hopefully on-sky observations..

MAIN PROGRESSION STEPS

First part: theoretical courses. Second part: applications. Last week : preparation of the oral presentation.



EVALUATION

Theoretical part: a report on the dimensioning and numerical modelling of a generic AO system. Application part: a report on the custom-made application chosen.

BIBLIOGRAPHY & RESSOURCES

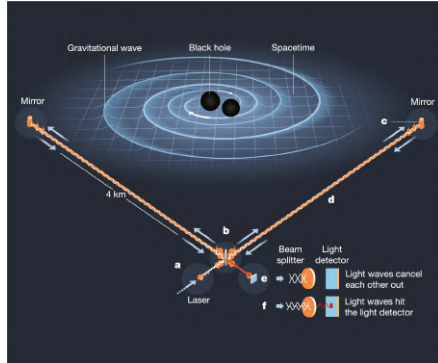
Material for this METEOR. Numerical modeling tool used (CAOS).

CONTACT

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# How to set up a Gravitational Wave Detector



**SUMMARY.**

Gravitational Wave Detectors are a powerful and unique tool to study the mysteries of our Universe. Unlike optical telescopes, they are able to directly detect merger between two black holes, black hole and neutron stars, among other sources. They work as Michelson interferometers which use lasers to convert small length changes caused by a gravitational wave to power changes which we can measure with a photodetector. Currently these detectors are able to measure length changes more than a thousand times smaller than the diameter of a proton. To achieve this incredible sensitivity they had to come up with complex designs and innovative techniques to overcome quantum noise, thermal noise, seismic noise, laser noise, among others. In this course you will learn the challenges of Gravitational Wave Detectors and will have the opportunity to set up a small Michelson interferometer and measure its sensitivity curve and the displacement of one of its mirrors. Hence, you will learn in theory and practice the basic experimental techniques to set up a Gravitational Wave Detector! The theory and experimental part of the course will be given at the Côte d’Azur Observatory (Mount Gros site), and you will interact with researchers that are active in the LIGO-Virgo-KAGRA collaboration, and work on the group which built the lasers for the Virgo detector.

— OBJECTIVES —

- Understand the theory of how a Gravitational Wave Detector works, and what are the noise sources that limit their sensitivity, especially laser noise
- Gain general knowledge of optics experimental techniques, interferometer alignment, control loops
- Learn how to measure the sensitivity of interferometers, and how to perform laser power stabilization

— PREREQUISITES —

- ✗ S1. Fourier Optics
- ✗ S1. Signal & Image processing
- ✗ S2. Gravitation & Cosmology
- ✗ S2. Quantum mechanics
- ✗ S2. Atmospheric turbulence, image formation & adaptive optics

— THEORY —

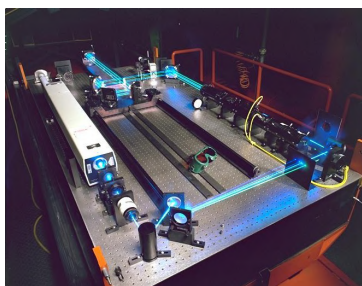
by MARGHERITA TURCONI AND MARINA NERY

- Introduction to gravitational waves
- Basic principles and sensitivities of Gravitational Wave Detectors
- Noise sources in Gravitational Wave Detectors: quantum noise, thermal noise, seismic noise, laser noise

- Laser stabilization techniques
- Einstein Telescope and future plans for Gravitational Wave Detectors

— APPLICATIONS —

by MARGHERITA TURCONI AND MARINA NERY



Picture source:

[https://en.wikipedia.org/wiki/Optical\\_table](https://en.wikipedia.org/wiki/Optical_table)

After an introduction to lab practice, students projects will include, for example, some of the following activities:

- Characterization of a laser beam
- Set up and align a Michelson interferometer

- Implement a control loop to stabilize and operate the interferometer at the mid fringe
- Measure the interferometer displacement sensitivity curve
- Identify and analyze noise sources
- Stabilize the power of the laser at the input of the interferometer

— MAIN PROGRESSION STEPS —

- Theory courses and exercises: 3 weeks
- Lab work and analysis: 4 weeks

— EVALUATION —

Theoretical part 30%: exercises that will be handed gradually during the theoretical course. Application part 30%: a full report of the experiment covering measurements and its analysis. Final defense 40%.

— BIBLIOGRAPHY & RESOURCES —

- <https://www.ligo.caltech.edu/>
- <https://www.einsteintelelescope-emr.eu/en/>

— CONTACT —

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