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

MAUCA

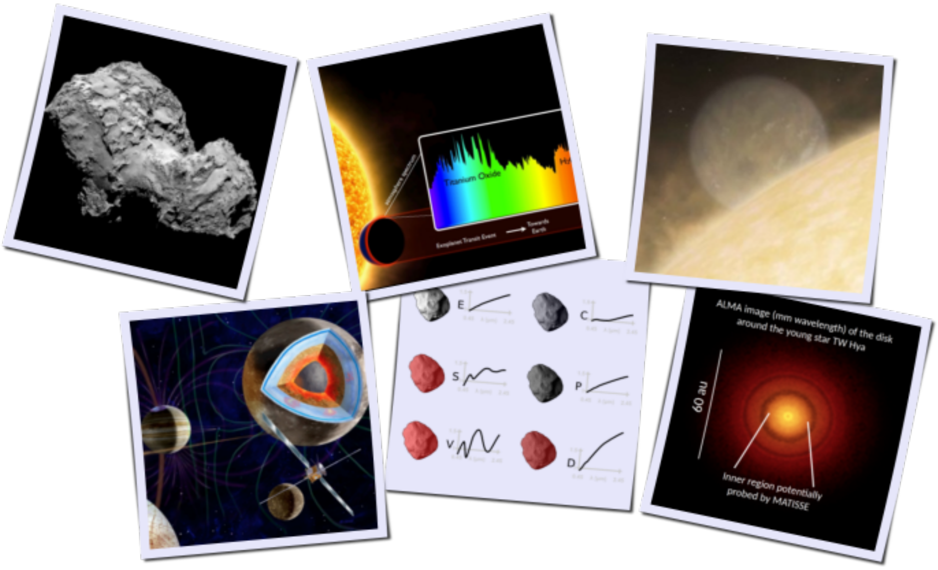
Leaflet of available METEORs

2025-2026

Contents

Chapter I

Planetary sciences



Contents

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 teached 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 teached; 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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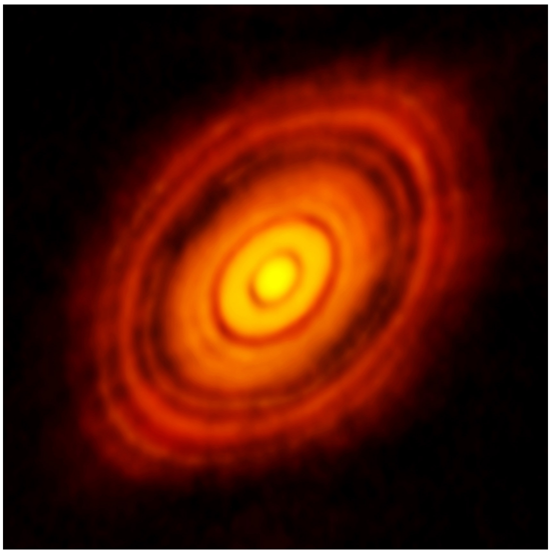
Planet-Disk-Interactions



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$_t$one 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.

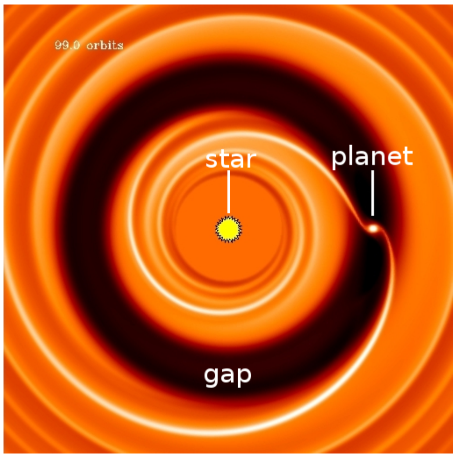
by E. Lega

Calssical 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 planets-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.

- **Personnal project:** Choose among the following possible personnal 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

- **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)

CONTACT

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Interior structures of solar system bodies: from Artemis to Juice

SUMMARY.
The interior structure of solar system bodies are key information for understanding the formation and evolution of these bodies. In this METERO, we are focusing on using radio science data and tidal deformation for deciphering the internal structure of planetary bodies such as Mars or Mercury but also icy satellites such as Ganymede in the Jupiter system. The choice of these bodies of interests is not just random but it correspond to main targets which will be visited by space missions in which Observatoire de la Côte d'Azur team is involved such as Insight for Mars, Artémis for the Moon, Bepi-Colombo for Mercury, Envision and Veritas for Venus and Juice for the Jupiter system.

```
$ make package
```

OBJECTIVES

The objectives of the METEOR is to learn how we understand the interior structures of planetary bodies (including natural satellites) only in using remote observations (no in-situ measurements). The student will learn the mechanisms behind the tides, how the tides deform bodies and how the body deformations induced by tides depend on its internal structure. The student will be introduced to spacecraft navigation and will understand how to use a spacecraft orbiting a body for determining its mass and shape and how these informations can be related to the tidal deformations. He will finally use numerical simulations for simulating how using radio tracking observations we can constraint the density, thickness and viscosity of the different layers of a planetary body.

PREREQUISITES

- ☒ S1. Data Sciences
- ☒ S1. Numerical methods
- ☒ S2. Dynamics & Planetology
- ☒ S2. Statistics
- ☒ S2. General mechanics

THEORY

by Anthony Mémin

In this METEOR, we will see the theoretical aspects related to the deformation of planetary body, including basic rheology laws and energy dissipation. These will tell us how the internal structure can induce different possible deformations. (Course A)

by Agnès Fienga

We will also see how to compute and constraint the orbit of a spacecraft using tracking data (doppler and range) and we will see how to determine the deformation of a planetary body using spacecraft orbitography. (Course B)

APPLICATIONS

by Anthony Mémin

In using the software ALMA3, the student will simulate different deformations induced by different possible internal structures, from a planetary satellite such as the moon, to earth-like planet such as Venus to icy satellite like Ganymede. (project A)

by Agnès Fienga

In using the software rebound, the student will simulate tracking data of a spacecraft orbiting a planetary body (Moon, Mercury, Venus, Ganymede) and he/she will simulate how well the tidal deformation of these bodies can be constrained from the tracking data. (project B) He/she will be then able to determine which orbital configuration can give stringent constraint on the different parameters of the internal structures (ie salinity of the Ganymede subsurface ocean). (project C)

MAIN PROGRESSION STEPS

The student can chose the objects of interest among Venus, Mercury and Ganymede and the associated missions (ENvision, BepiColombo and JUICE)

- **Part 1**: courses A/B and project A an B
- **Part 2**: project C

EVALUATION

- **Theory grade [30%]**
  This evaluation will be presentation of an article either one the Course A either on the Course B. The global understanding and the critical spirit will be evaluated.
- **Practice grade [30%]**
  - projects A and B (30%): thought-process and results
  - Project C (70%): initiative, progress, analysis
- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

BIBLIOGRAPHY & RESOURCES

- Review on JUICE mission
- BepiColombo and Mercury internal structure
- Example of icy satellites internal structure modelings
- Envision: From Earth to Venus

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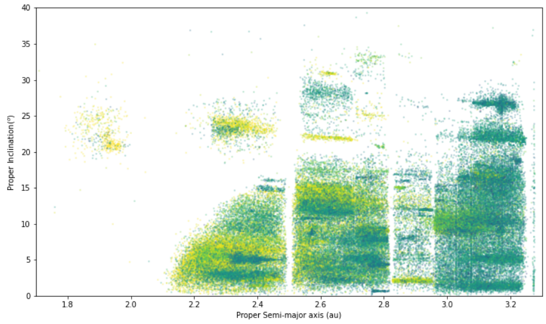
Distribution of asteroid compositions



The asteroid belt, color-coded by albedo

SUMMARY.

Asteroids are the remnants of the original building blocks that formed the terrestrial planets. The early events of planetary migrations that occured in our Solar System left their prints in the distribution of asteroid orbits and compositions. While detailed compositions are determined from spectroscopy, multi-filter photometry from large surveys such as the SDSS or the LSST can be used to classify asteroids into compositional groups and study their distribution into orbital elements (see Figure on the left).

This METEOR combines theoretical knowledge with practical work (applicable to other research fields). It includes lectures on the composition of asteroids, their links with meteorites, their surface aging due to space weathering, and experimental work on the links between spectroscopy and photometry, and methods of classification

OBJECTIVES

- Acquire fundamental knowledge on asteroid compositions and their biased sampling by meteorites, space weathering, reflectance spectroscopy, and Solar System formation.
- Convert spectra into photometry. Classify large samples into coherent groups. Develop codes in python. Extract essential information from articles.

PREREQUISITES

☒ S1. Data Sciences

THEORY

by B. Carry, G. Libourel, P. Tanga

The theoretical part of the METEOR covers both fundamental knowledge on asteroids and on photometry/spectroscopy in astronomy.

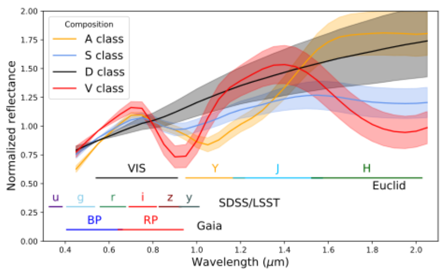
- Solar system formation. Accretion of planetesimals. Planetary migrations.
- Classification and composition of meteorites.
- Compositions, classification, distribution of asteroids.
- Surface aging by space weathering.
- Definition of the magnitude systems in astronomy. Convertion between spectra and magnitudes.
- Extraction of asteroid signal in sky surveys.
- Measurement of asteroid reflectance. Solar analogs.
- Clustering of data in high-dimension space wih machine learning.

APPLICATIONS

by B. Carry

Three projects are possible, reproducing all the steps used nowadays to conduct large scale study of asteroid compositions from sky surveys. You will

- retrieve the photometry from on-line repositories,
- compute reference colors from templates for comparison,
- reduce the dimensions of the sample while minimizing information loss,
- classify asteroid in groups from their observed properties,
- interpret their orbital distribution.



Examples of asteroid spectra

MAIN PROGRESSION STEPS

- **Tier 1**: Courses on photometry and Solar system, exercices on spectra.
- **Tier 2**: Courses on meteorites and machine learning. Start of the project.
- **Tier 3**: Project.

EVALUATION

- **Theory grade [30%]**
  - Written exam (70%): theoretical questions from lectures
  - Presentation of an article (30%): critical spirit, applied knowledge from lectures
- **Practice grade [30%]**
  - Exercice (30%): structure of the solution, precision of results.
  - Project (70%): initiative, autonomy, curiosity, results, critical analysis of results.
- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

BIBLIOGRAPHY & RESOURCES

- DeMeo & Carry 2014
- Mahlke et al. 2022
- Raymond et al. 2020
- https://scikit-learn.org

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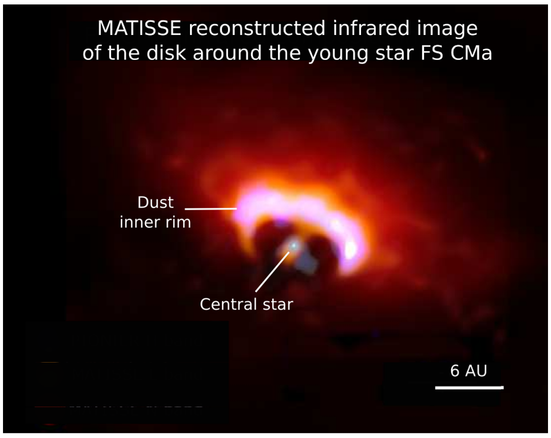
Observing the planet-forming region in protoplanetary disks



SUMMARY.

As of today, more than 4000 exoplanets have been discovered and show a great diversity. Understanding such a diversity requires direct observations of protoplanetary disks at a very high angular resolution in the infrared domain. MATISSE is a 2nd generation instrument for the Very Large Telescope Interferometer (VLTI) of the European Southern Observatory (ESO), built by a consortium of european institutes led by the J.-L. Lagrange Laboratory at OCA. By combining the light of 4 telescopes, this instrument is able to probe the dust and gas content in the innermost regions ($\sim$ 0.1-10 au) of protoplanetary disks, and thus characterize the planet building blocks. In this METEOR, we will explore the basics of optical interferometry and see how MATISSE works. We will then learn how to create disk models, using radiative transfer, and simulate disk observations with MATISSE.

OBJECTIVES

- Understanding optical interferometry and its applications.
- Developing knowledge and skills in radiative transfer, including the use of a radiative transfer code.
- Linking observations and constraints on the physics of disks.
- Developing a critical view on the feasibility of disk observations.

PREREQUISITES

☒ S1. Fourier Optics
☒ S2. Stellar physics
☒ S2. Dynamics & Planetology

THEORY

by A. Matter & B. Lopez

I) Optical interferometry
- Basics : temporal and spatial coherence, observables.
- the MATISSE instrument: Concept, sensitivity, accuracy, sources of noise.

II) Radiative transfer
- Basic equations of radiative transfer.
- Absorption and scattering processes by dust grains.

III) Observation of protoplanetary disks
- The inner disk regions: which wavelength and angular resolution ?
- Physical processes in disks and related spatial structures; effect on the observations.

APPLICATIONS

by A. Matter & B. Lopez

The project will consist of 3 steps:
1) after getting familiar with the radiative transfer code RADMC3D (and its python interface radmc3dPy), the students will produce a set of disk models including the corresponding brightness maps (synthetic images). This set of models will focus on one particular structure (e.g., gap, inner disk rim shape) or disk physical parameter that MATISSE may be able to detect or constrain in the inner disk regions.
2) From the synthetic model images, the students will then use the tool ASPRO2 to produce simulated MATISSE observations.
3) The simulated MATISSE data will then be examined to assess the feasibility of detection/characterization of the considered disk physical parameters.

MAIN PROGRESSION STEPS

For instance:

- Week 1-2: lectures on optical interferometry (+2 exercise sheets) and radiative transfer.
- Week 3: bibliographic study on MATISSE and disks + familiarization with RADMC3D.
- Week 4-6: feasibility study on disks observations (radiative transfer simulations + use of ASPRO2)
- Week 7: preparation of the final oral presentation.

EVALUATION

- Theory grade [30%]
  - Written exam (100%): homework assignment on optical interferometry and its applications.
- Practice grade [30%]
  The students will conduct a feasibility study based on radiative transfer disk simulations. The project will be evaluated on the level of initiative, progress and critical analysis of the results by each student. The final oral presentation will be based on that feasibility study.
- Defense grade [40%]
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

BIBLIOGRAPHY & RESOURCES

- The MATISSE instrument : Link
- RADMC3D website : Link
- radmc3dPy website : Link
- ASPRO2 website : Link

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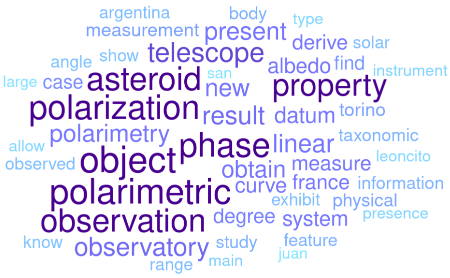
Asteroid Polarimetry: Observations and Data Analysis



SUMMARY.

Polarimetry is not the first observational technique coming to a Master student spirit. Moreover associated to the word asteroid it becomes more and more exotic. Nevertheless many information such as size, mineralogical type, surface physical structure can be obtained from the study through a polarimeter of Sun light reflected by an asteroid.
C2PU is involved since many years in such a research topic and has recently provide the largest data base on polarimetric data for asteroids (Bendjoya et al. 2022). Recently C2PU has began a new international collaboration (Finland, Gemany, Ireland and Italy) with a brand new polarimeter now installed (2023) at the Cassegrain focus of 1m telescope Omicron which performances open a major step forward in the characterization of fainter asteroids.
This METEOR will offer to the student(s) the opportunity to participate to campaigns of observation (if schedule @ C2PU permits), data reduction , data analysis and data mining to derive major physical information on asteroids.

OBJECTIVES

- link polarization of reflected light to asteroid physical parameters
- understand the functioning of a polarimeter and all of its components
- perform polarimetric observations on sky
- reduce polarimetric data
- derive Stokes parameters from raw images
- analyze data
- build the relevant so called Pr=f(phase angle) curves from which albedo, diameter, mineralogical features... can be derived
- cross-match polarimetric catalogs with other asteroid physical parameter catalogs and make statistical analysis for sub group of asteroids.

PREREQUISITES

The fundamental courses linked/coming in support to this METEOR are Electromgnetism (Licence lectures) and

✗ S1. Meteor C2PU

THEORY

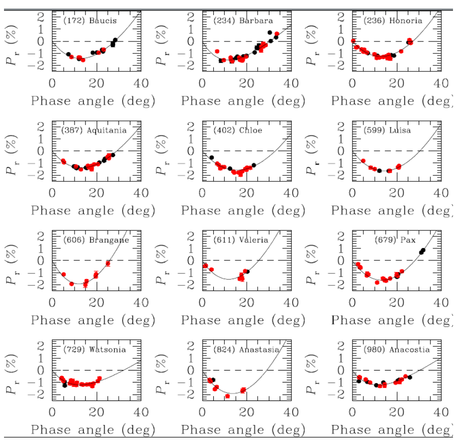
by Ph. Bendjoya

Polarization of reflected light, stokes parameters, physical parameters of asteroids, NEOs, dynamical families, asteroid mineralogy.

APPLICATIONS

by Ph.Bendjoya

After an introduction to polarimetry and polarimeter as well as their interest in asteroid studies, students will perform polarimetric observations at C2PU (if the polarimeter commissioning coincides with the METEOR or will use archive data from C2PU polarimetry), will reduce data, extract stokes parameters, build the $P_r = f(\alpha)$ curves,develop some scripts (Python) and will exploit different databases.



MAIN PROGRESSION STEPS

- First third period : theoretical courses (lectures, articles)
- Second third of the period : observation and reduction
- Third third of the period : exploitation of databases
- Last week : preparation of the final oral presentation.

EVALUATION

- `Theory grade [30%]`
  - Presentation of an article (30%): critical spirit
- `Practice grade [30%]`
  - Project (70%): initiative, progress, analysis
- `Defense grade [40%]`
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

BIBLIOGRAPHY & RESOURCES

Any reference or web page that students can read to have a better idea of the topic.

- Bendjoya et al. 2022

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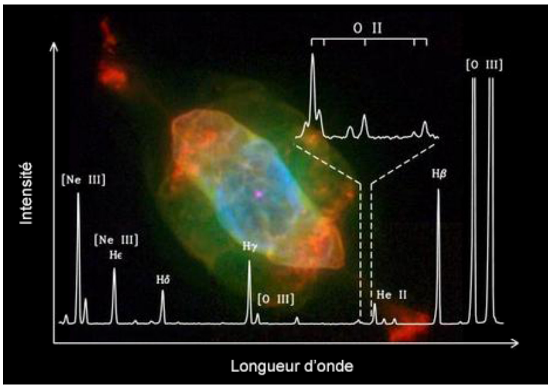
Chapter II

Stellar and galactic physics

Contents

Astrophysics of Gaseous and Dusty Nebulae



SUMMARY.
Gaesous 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

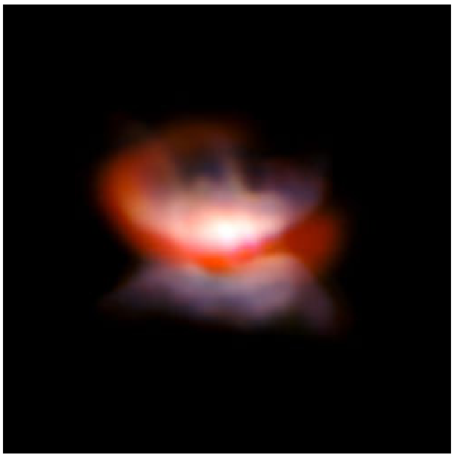
by Patrick de Laverny

All stars are formed from interstellar material and synthetize 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**: personnal 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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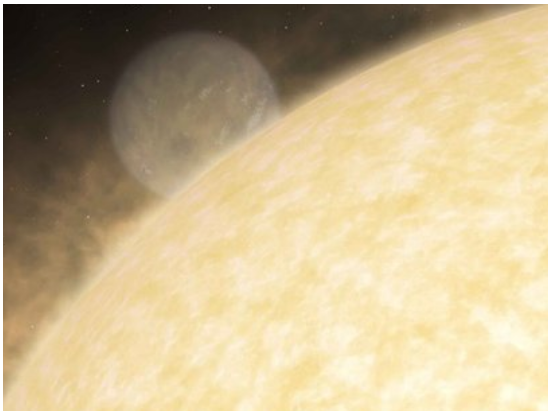
Atmospheres of stars and exoplanets



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

- *Undersand the thermal strucutre, 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 and Andrea Chiavassa

- 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

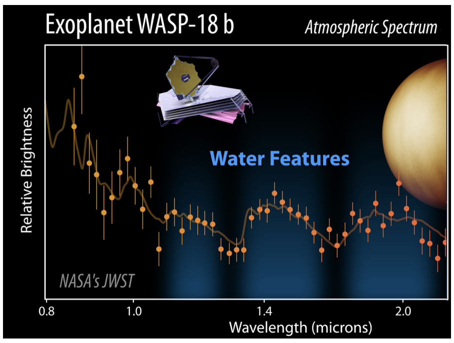
Then the students will pick a project with a focus on exoplanet or stellar spectra.

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 fro high-spectral observation from the HARPS spectrograph



by Andrea Chiavassa

Use a database of 1D and 3D stellar spectra, together with running actual simulations, to estimate the fundamental parameters of a few observed stellar spectra.

MAIN PROGRESSION STEPS

- **Tier 1:** Planetary atmospheres course, exercices and practical
- **Tier 2:** Stellar atmospheres course, exercices and practical
- **Tier 3:** project

EVALUATION

- **Theory grade [30%]**
  - Written exam on coursework (70%)
- **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
- Exemple of OPTIM3D code.

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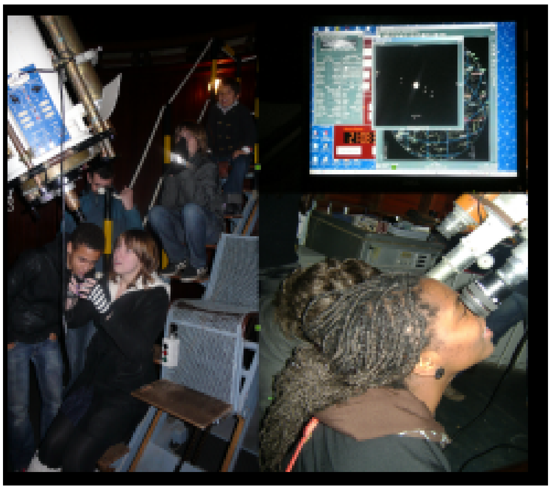
Stellar Pulsation and Evolution Polar and Space Missions



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 Velociy Curves.

OBJECTIVES

- *This Meteor provides students with the knowledge and research ability for a career in Astronomy towards an improving the research developement 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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PLAnetary DYnamics and Stellar Evolution PLADYSE

SUMMARY.

Stellar evolution for star with mass between 1 an 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.

`$ make package`

OBJECTIVES

Students will be able to

- model gravitational forces in N body problem
- model non-gravitational forces in N body problems
- use MESA code for stellar evolution
- couple gravitational code and MESA 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 & G. Niccolini

Restricted three body problem. !
N body problem (N small).
Non gravitational forces : friction, wake , mass loss, Yarkovsky...
numerical ODE integration,
MESA code use

APPLICATIONS

by Ph. Bendjoya & G. Niccolini

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,
Numerciaml 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)
- https://github.com/maxmahlke/rocks

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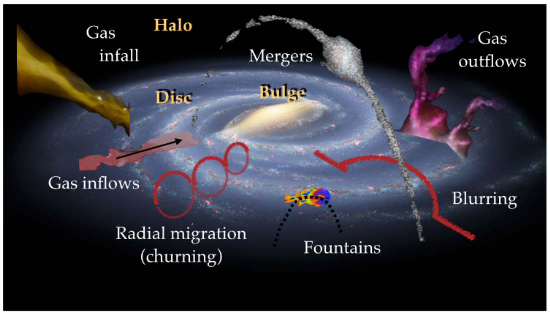
Galactic Archaeology and the Gaia mission



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

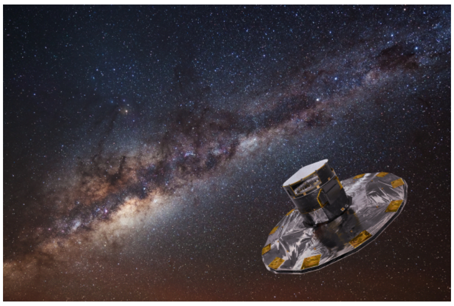
Galactic Archaeology aims to reconstruct the history of the Milky Way by analyzing stars, just as the history of life was deduced by examining rocks. Stars record their past in their ages, chemical compositions and kinematics and can thus provide unprecedented constraints on the early phases of galaxy 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 exercices
- **Tier 3:** personnal 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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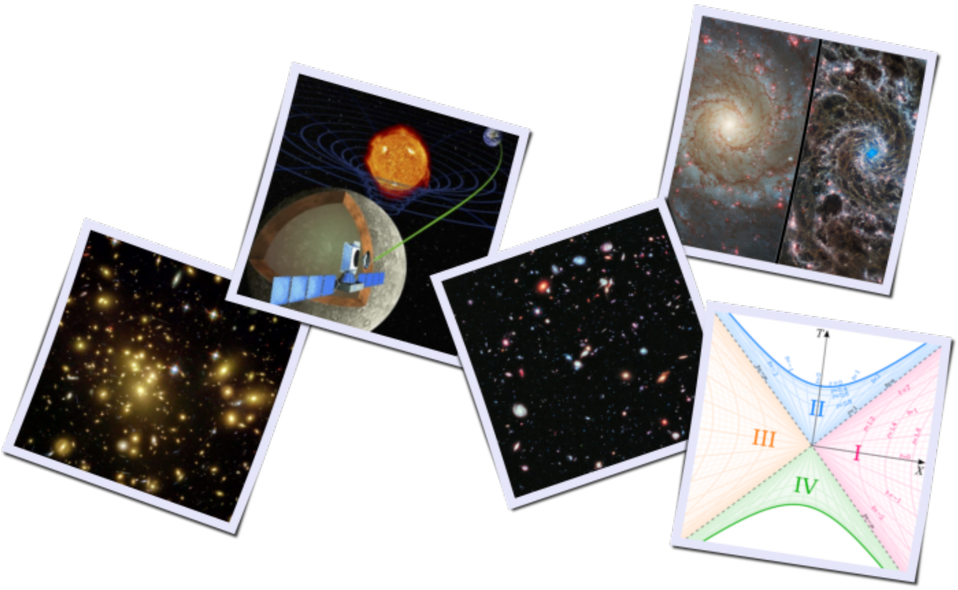
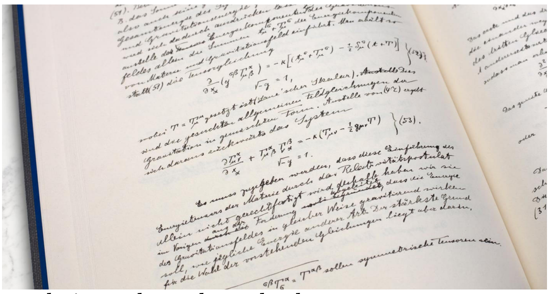
Chapter III

Extragalactic, cosmology & relativity



Contents

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 payed to exact GR solutions.

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 calculous, Riemannian geometry, ...).

THEORY

by Bertrand Chauvineau

- **Mathematics**

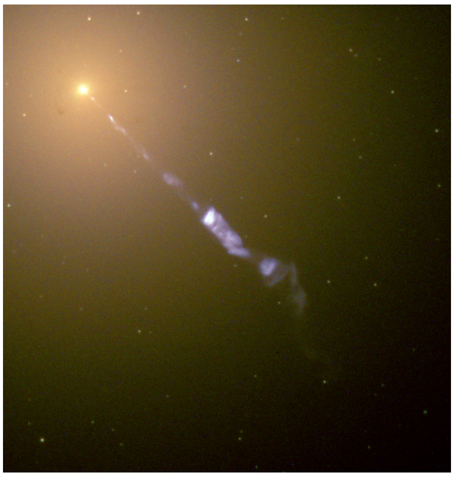
Tensor calculous
Riemannian geometries: metrics, geodesic curves, covariant derivatives, curvature.
Advanced topics (Killing vectors, ...).

- **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 (& 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.



APPLICATIONS

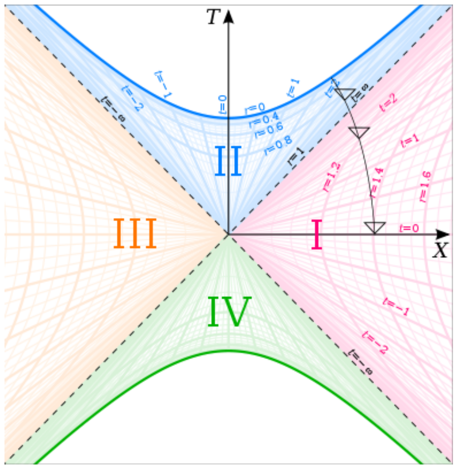
by Bertrand Chauvineau

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.

MAIN PROGRESSION STEPS

- Whole period 18 theoretical courses and exercises (about 60h, planified on 3/4 sessions a week).
  Reading of some review and/or pedagogical papers.

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



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

— 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. Tourrenc, "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 calculous. (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 exercises, with corrections.

A. Barrau, J. Grain, "Relativité Générale" (Dunod, 2016).
> mainly compilations of exercises, with corrections.

— CONTACT

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Chapter IV

Signal processing & numerical methods

Contents

Detection of Exoplanets

SUMMARY.
This METEOR provides a training to detection methods for exoplanets. General tools and concepts are studied and applied, from the viewpoint of statistical detection theory and of astronomical instruments. The studied exoplanet detection techniques are direct imaging, radial velocities and transits. Applications data are from ground-based instruments like SPHERE and space missions like KEPLER, JWST or Plato.

OBJECTIVES

- One main objective of this METEOR is to train the students to learn in autonomy, to identify what can help them to progress, to identify and correct their errors, to define a project related to a problem of their interest and to solve it.
- The students will learn various skills in detection. They will learn to set-up statistical models, to follow systematic approaches to build statistical tests, to characterize the tests' performances in terms of significance level and of detection power.
- The students will learn a set of dedicated numerical techniques to implement these tests and will improve their coding skills (Python).
- The students will get a fair background about state-of-the-art and forthcoming techniques for detecting exoplanets from ground and from space.

PREREQUISITES

☒ S1. Data Sciences
☒ S2. Statistics

THEORY

by David Mary

With more than 5400 exoplanets known to date, exoplanet detection is an extremely active field of research. Two methods, Radial Velocities (RV) and transits, have brought together more than 90% of these discoveries. This METEOR will focus on these two methods, but detection by direct imaging will also be studied. Students will learn the principles of these techniques and how detection algorithms work for such data. Exoplanet detection techniques based on RV, transit or image data rely on a statistical model of the data. This model encapsulates information on the signature that one wishes to detect (*e.g.*, quasiperiodic signals for RV, U-shaped signatures for transits, star/companions' PSF in images) and the perturbations that affect the data (*e.g.*, photon noise, instrumental noise from the detectors, from the stellar atmosphere, speckles,...). These perturbations always involve random phenomena. This is the reason why the data model on which the detection test is built is always a *statistical* model, which involves parameters related both to the noise and to the planetary signature.
In this framework, current detection algorithms can advantageously be understood and analyzed in the general framework of statistical detection theory. Most transit detection algorithms fall in the category of Matched-Filter detection, and most RV detection methods are based on periodogram analyses. Detection theory provides Astronomers with an arsenal of systematic methods and concepts to analyze and quantify their performances, and of new concepts like the False Discovery Rate in multiple testing. For these reasons, the theoretical part of this METEOR will heavily build on statistics and numerical methods.

Students will investigate a series of statistical tools that they will be able to use in many other contexts during their career – these general tools are in fact routinely used in other domains of Astrophysics, and even also in other fields like climatology, genetics, econometrics or telecoms. It should be clear that the heart of this theoretical part is truly statistical (this is why this METEOR is not, for instance, in the Planetology theme of MAUCA), even if the studied exoplanet detection techniques will build on (astro)physical models.

The theoretical part is divided in 6 chapters:

- Chapter 1: General introduction
- Chapters 2 and 3: Tools in detection (LR, GLR)
- Chapter 4: Regular sampling : Fourier analysis and the periodogram
- Chapter 5: Detection tests in regularly sampled time series
- Chapter 6: Detection tests in irregularly sampled time series

APPLICATIONS

by David Mary

- With the help of the supervisor, students will define a small research project according to their personal interest. Following the students' interests, the detection techniques learned in the theoretical part will be applied in this project to real data such as JWST and SPHERE for imaging, HARPS for RV and Kepler for transits.
- The METEOR provides an intensive training to Python for the numerical exercises of the Theoretical part and during the project.

MAIN PROGRESSION STEPS

- During the whole duration of the METEOR, each student has a personal channel on Discord allowing easy connection with the supervisor outside the scheduled meeting slots. A general channel serves also as a forum for general infos/questions/hints.

- First half of the period (possibly more): the students learn theory. They are requested to work on the lecture notes on their own, with regular discussions planned with the supervisors to answer their questions. They do the theoretical and numerical exercises proposed in the lecture notes document and they post them on the fly on their personal channel. As in the Statistical Methods lecture, each chapter has its own 'Friendly Quiz' and 'Noted Quiz'.
- During the first two weeks, the students identify a topic of the lecture they are mostly interest in and define the topics of their project: choose a technique (RV, transit or imaging) and define the problem to be studied for the selected technique.The supervisor helps the student to ensure that the project's objectives are relevant and reachable.
- Rest of the period : the students work on their research project.
- Last week : last results and preparation of the final oral presentation.

EVALUATION

- Average mark of 4 quizs, one mark for the numerical Homework in Python + exercises, one mark for the final written exams (2h) on the theoretical part. The average of the three marks provides the mark "Theory" (30% of the total mark).
- The mark for the "Project part" is the average of 6 marks (autonomy; interaction; initiative; efficiency; progression (final project status); critical thinking. (40%)
- Final evaluation during the global oral presentation (40%).

BIBLIOGRAPHY & RESOURCES

- On-line lecture notes, slides,, homeworks, criteria evaluation grid, data, solution codes.
- A PhD thesis with a good introduction on exoplanet detection by RV
- M. Perryman, *The exoplanet handbook*, Cambridge Univ. Press, 2011.
- T.H. Li , *Time series with mixed spectra*, CRC Press, 2013.
- S.M. Kay, *Detection Theory*, Prentice Hall, 2009
- Encyclopedia of exoplanetary systems

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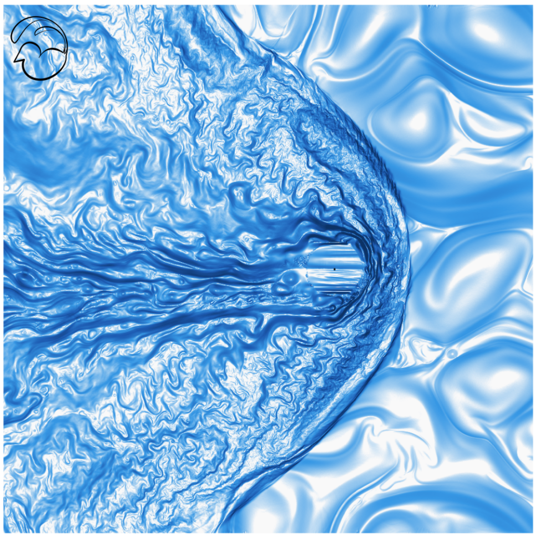
Astrophysical & space plasma



SUMMARY.

The vast majority of astrophysical visible matter is composed of plasmas, a state of matter with complex (i.e. non-linear and out-of-thermodynamic equilibrium) dynamics combining both small scale, individual particle interactions and large scale collective effects. The equations for plasmas are non linear and do not always have analytical solutions. The study of plasmas thus often requires numerical simulations for which a plethora of techniques and codes exist. In this METEOR, the student(s) will first learn theory to describe and understand space and astrophysical plasmas. The student(s) will then implement a numerical code to describe the dynamics of fundamental astrophysical and space plasma processes. This code will be optimized to introduce high performance computing basics (e.g. parallelization, GPU porting) and/or be used to study energy conversion processes in front of space plasma shocks.

OBJECTIVES

- Learn relevant theory to model astrophysical plasma phenomena and understand how to choose the relevant model for a given scientific question (**Eulerian, PIC, Hybrid PIC...**).
- Write, from scratch, a Vlasov-Poisson solver. Various numerical schemes will be taught, and the student will choose an appropriate spatial and temporal scheme.
- Understand high performance computing (HPC) code and architecture with the goal of preparing the student to work on large HPC machines.

PREREQUISITES

☒ S1. Data Sciences
☒ S1. Numerical methods
☒ S2. General mechanics

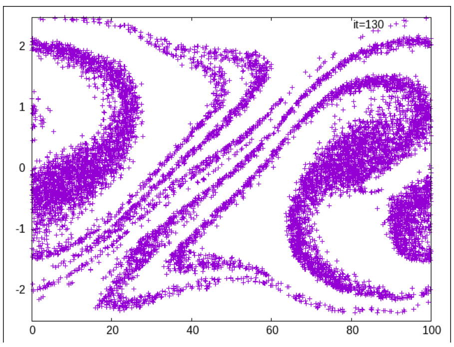
THEORY

by F. Sporykhin

Small and large scale interactions within space and astrophysical plasma arise from the self-consistent interaction between the electromagnetic field and charged particles that compose the plasma. At small scales, particles of opposing charges serve as a shield and lessen the single-charged particle electric potential in a phenomenon known as Debye shielding. At scales larger than the Debye length that characterized such screening, only large-scale interactions controlled by collective behavior occur in a plasma. Starting with the Poisson equation, the student will derive the (linear) Debye screening theory as well as single charged particle motion dictated by the Lorentz force, which results in cyclotron motion and drifts. This section will allow the student to understand what happens to individual charged particles within a plasma.

by P. Henri

Plasma waves and instabilities. The energy transport in astrophysical and space plasmas is significantly controlled by wave propagation. Such waves are often trigger by unstable configuration, source of free energy, that drive plasma instabilities. The student will study an archetype of space plasma waves (Langmuir waves) and of plasma instability driving such waves (bump-on-tail, two-stream instabilities).



Phase space representation (velocity w.r.t. space) of a PIC simulation of a two-stream instability.

APPLICATIONS

by P. Henri, F. Sporykhin

- **Common Project**: Write a 1D-1D Vlasov-Poisson solver capable of simulating the non-linear, out-of-thermodynamic equilibrium evolution of a distribution of charged particles. This can be done in the student's language of choice (e.g. C++, Fortran, Python). The solver must be then validated with a well studied case such as a two-stream instability or Landau Damping.
- **Personal Project**: depending on the progress of the common project, we then propose the following to the student(s):
  - Parallelising the solver on a GPU using, for example, (**CUDA, Kokkos, OpenMP, SYCL...**). The student may also be taught how to access large HPC centres to run on high end hardware.
  - Apply the developed code to model the nonlinear evolution of accelerated charge particles in front of an astrophysical or a space plasma shock. Perform a spectral analysis together with a phase space analysis of the simulation output. This will allow the student to familiarise themselves further with the data analysis

needed for astrophysical and space plasma simulations.
  - Expanding the code to a second dimension. This allows to study the symmetry breaking in the transverse direction of space plasma kinetic instabilities associated to accelerated charged particles.

MAIN PROGRESSION STEPS

- Week 1 and 2: Theory lectures and bibliographical work
- Week 3: Oral exam on the theory and a start on writing the code
- Weeks 4 and 5: Coding and debugging
- Weeks 6: Validation
- Weeks 7: Debugging and preparation for the defence

EVALUATION

- Theory grade [30%]
  - Oral exam (70%): theoretical questions
  - Curiosity and engagement (30%)
- Practice grade [30%]
  - Code quality (50%)
  - Validation report of the code (50%)
- Defense grade [40%]
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

BIBLIOGRAPHY & RESOURCES

- Chapter 2 of Computer Simulation Using Particles. Hockney, R.W; Eastwood, J.W (ask for djvu file)
- Chapter 2 of Plasma Physics via Computer Simulation. Birdsall, C.K; Langdon, A.B (ask for djvu file)
- https://gitlab.com/etienne.behar/menura

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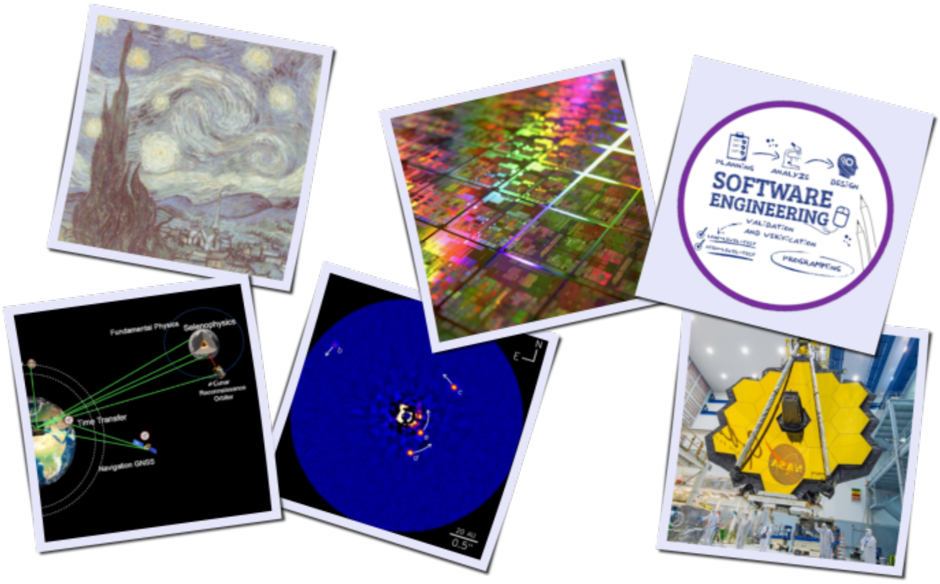
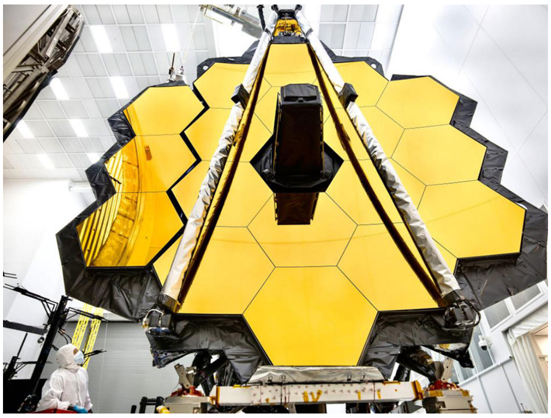
Chapter V

Astronomical optics & instrumentation



Contents

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.

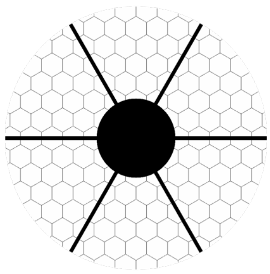
Specific care for the dichotomy occurring between space and ground-based observatories will be discussed. In particular, a specific study of the NASA/JWST co-phasing process will be proposed in a dedicated chapter.

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 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., magnitude & 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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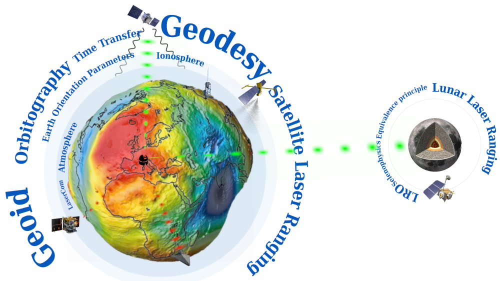
Ground to Space Laser Links for Space Applications



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

MAIN PROGRESSION STEPS

- Week 1: MéO telescope visit - Introduction to Space Geodesy - Laser Ranging
- Week 2: Laser and Gaussian Optics - exercices
- Week 3: Laser through the atmosphere - project
- 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%): exercice 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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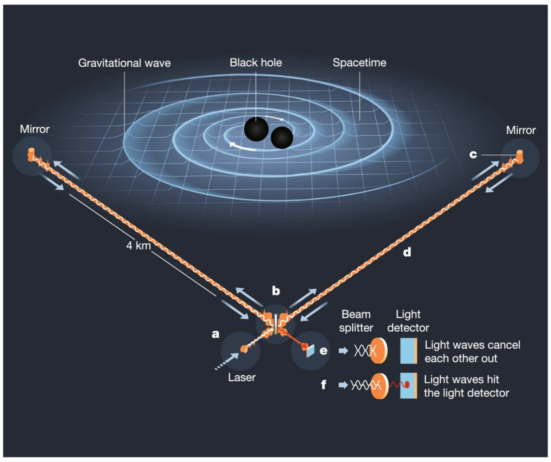
How to set up a Gravitational Wave Detector



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

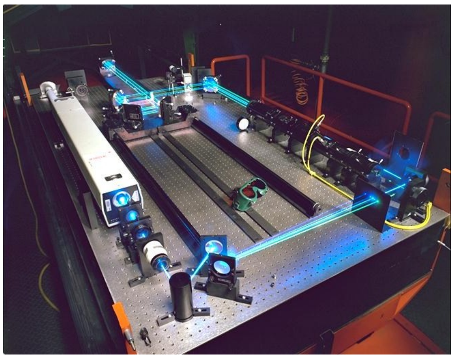
THEORY

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

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.einsteintelescope-emr.eu/en/

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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).

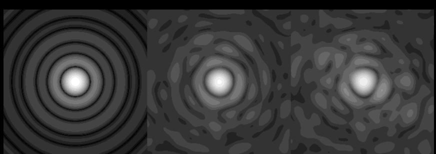
PREREQUISITES

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

THEORY

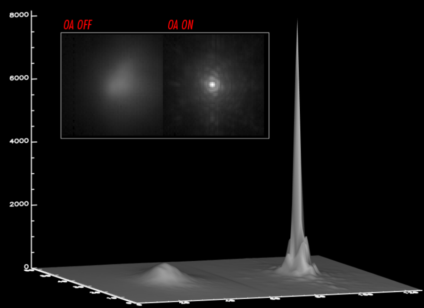
by Marcel Carbillet & Olivier Lai

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

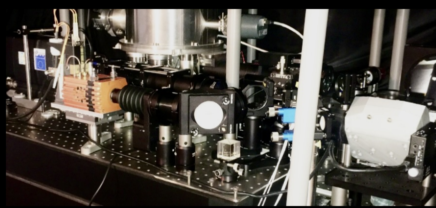
by Olivier Lai & Marcel Carbillet



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).

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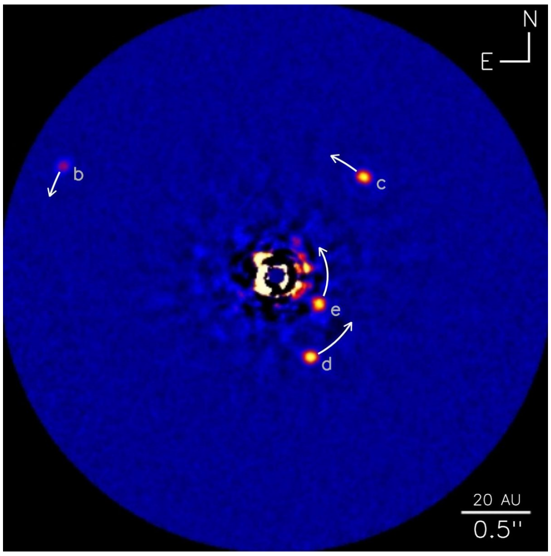
Imaging Exoplanets



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

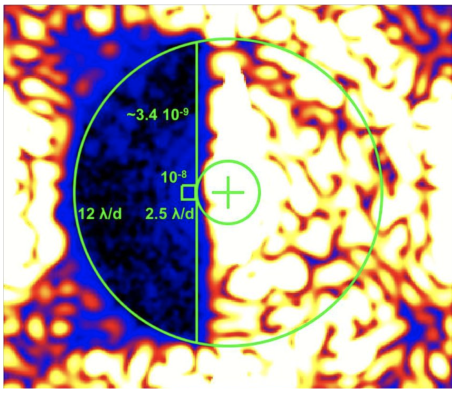
by P. Martinez

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

MAIN PROGRESSION STEPS

he 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

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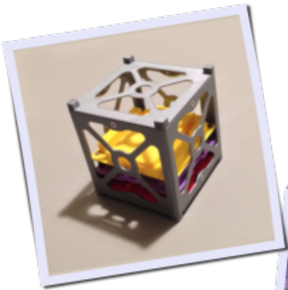
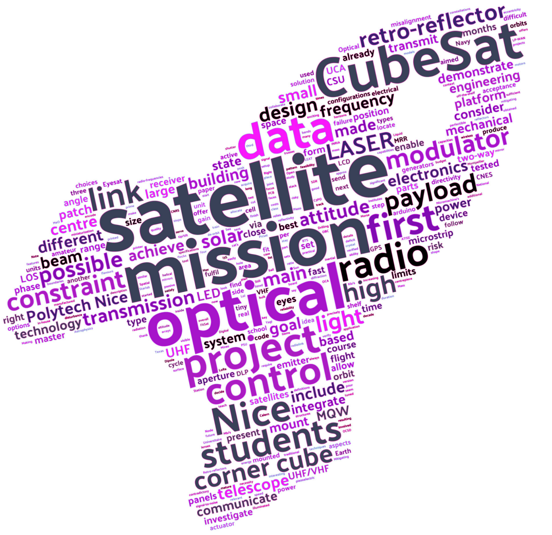
Chapter VI

Space & industry



Contents

Smallsats



SUMMARY.
Have you ever thought of building an artificial satellite yourself? It is now more than 60 years that the first artificial satellite, Sputnik, was set into orbit around the Earth. This satellite served as an inspiration for generations of researchers and engineers to develop the technologies of aeronautics and space, which are nowadays very commonly found in everyday life (telecommunications, localisation, computers, digital cameras, materials, etc.). The recent development of the so-called 'NewSpace' offers opportunities to set new frontiers in space exploration.
This METEOR aims at giving a glimpse of spacecraft physics and bringing space technologies notions to the hands of students in the form of short courses, and a direct contribution to the Nice Cube project, the nanosatellite project of Université Côte d'Azur, which will demonstrate a laser link between the ground and the satellite.

OBJECTIVES

Today, it is possible to test and validate scientific ideas and new technologies in space on small timescales (typically 5 years). This can be done aboard tiny satellites called "CubeSat". These are standardized satellite plat- forms made of cubes of 10 cm side and 1 W of available electrical power (1U format). Several cubes can be combined (2U, 3U, etc.). Such a platform enables motivated students to learn on a hands-on project the technologies, project management, and all the space- related competences. In this METEOR, the student will first follow lectures on space technologies. They will learn how to read a scientific or technical article, and then they will work on a hands-on project related to the mission in development in Nice, called Nice Cube.

What you will acquire:

- you will be aware of nanosatellites space missions particularities and know where to find relevant information on a space mission development.
- You will know how to read a scientific or technical article and extract its main information to raise your understanding level of a topic.
- You will have a first experience on a real mission, Nice Cube.
- You will acquire basic knowledge of the physics of space- crafts (positioning, orbits, orientation).
- You will also learn the essentials of space project management, that you will practice on one focused aspect of space missions.

PREREQUISITES

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

THEORY

by F. Millour

Introduction to optical communications. Using light to transmit a message has been done for ages. The same principle is nowadays used to improve inter-satellite communications. Principles of free space optics, light propagation in different media, issues and solution for free space optical communications will be reviewed in this course.

by G. Metris

Orbital dynamics notions - impact on orbits choice. The Keplerian model for a setallite's orbit is not a valid approximation in the complex Earth environment. The main orbit perturbations will be reviewed, and their impact on the orbital dynamics. We will deduce from that the criteria to use in order to choose a best-suited orbit for a satellite mission.

by L. Dell'Elce

Satellite Attitude Determination and Control System (ADCS). This course is an introduction to the fundamental concepts that are necessary to design an attitude control system, which aims at orienting the satellite in a pre-defined position. After a brief glance at the most-commonly used hardware for ADCS, a mathematical approach on the control problem will be developed.

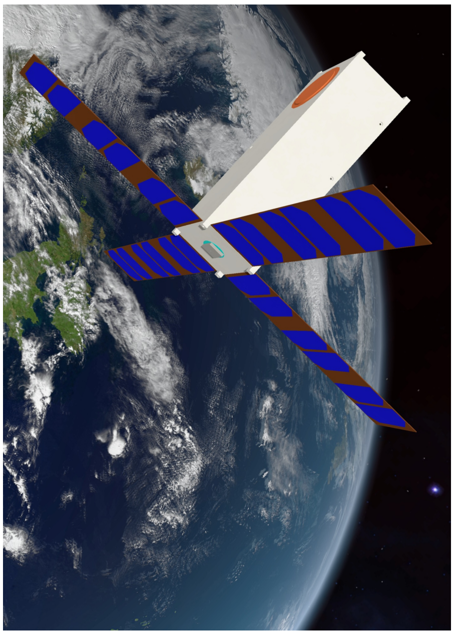
by L. Rolland

Global Navigation Satellite Systems (GNSS). GNSS such as GPS, GLONASS, Galileo are key components of modern terrestrial space missions. This course first reviews the basics con- cepts of GNSS precise positioning. A more practical session covers the main steps of the GNSS processing chain: from data acquisition with a GNSS de- vice to the final position. We finally dis- cuss the limitations of GNSS navigation in terms of precision and accuracy.

APPLICATIONS

by F. Millour, L. Dell'Elce, L. Rolland, G. Metris

The students will work on a short project during 1 month (4 weeks). This assignment will be directly related to the Nice Cube mission being developed at Université Côte d'Azur. These mini-projects contain a theoretical part and a practical part, and depend on the needs of the Nice Cube project. Example projects titles are: "Space mechanics", "Optical communications", "Precise Orbit positioning with GPS/GNSS", "On-board image compression and data transfer".



The Nice Cube nanosatellite project as envisionned in 2025.

MAIN PROGRESSION STEPS

For instance:

- **Week 1-2**: theoretical courses (5 topics) and bibliographic study with presentation of a paper.
- **Week 3-6**: mini-project related to the Nice Cube mission.
- **Week 7**: preparation of the final oral presentation.

EVALUATION

The evaluation of the nanosatellite METEOR is distributed as follows:

- **Theory grade [30%]**
  - Written exercise (50%): two articles summaries
  - Presentation of two articles (50%): critical spirit
- **Practice grade [30%]**
  - mid-course report on the mini-project (50%).
  - end report on the mini-project (50%).
  - The behavior during the mini-project (oral reporting of the weekly work, attitude, motivation) will be positively evaluated.
- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

BIBLIOGRAPHY & RESOURCES

- Article on the Nice Cube project
- CSU website

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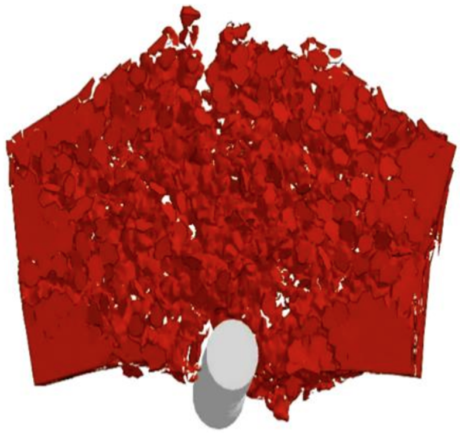
Holistic approach of (Rock Fragmentation) Digital simulation



SUMMARY.

Digital simulation is becoming an essential tool for engineering complex industrial projects due to its rapid implementation and low cost, when compared with in situ experiments. Paradoxically, it is little used in the blasting industry, despite its origin dating back to the Manhattan project. Although the Manhattan project, aiming at modelling the nuclear detonation process, dates back to the Second World War, we had to wait until the mid 1990s for research workers to become interested in the potential of digital simulation to predict the interaction between rock and explosives. To begin with, digital simulations attempted to model the interaction of well-known phenomena or materials (the effect of a shell on armour plating, a bomb on buildings, air on an aircraft's wing, etc.), so the deterministic approach naturally dominated. When it is a question of dealing with blasting issues, the unknown features of the rock led to a fundamental difference in the approach among the pioneers in the field. Katsabanis & Liu, Favreau, Preece and Chung, Dare-Bryan, Wade & Randall chose to capitalise on the assets of deterministic approaches from closely related industries. In Europe, Bernard explored another avenue, based on his University research carried out at the beginning of the 1990s, and developed a so-called holistic simulation and forecasting model, capitalising on deterministic theories. Considering that the time to resolve deterministic equations is de-correlated from the industrial time, he proposed a pragmatic approach making a summary of the deterministic principles, enabling perfectly identified, and well-known causations to function together (e.g. Newton's physics), in order to meet the present challenges and needs of the sector, here and now.

OBJECTIVES

by Thierry Bernard

Digital simulation (or digital experiments) offers a computer reproduction of a complex physical phenomenon, whose evolution we wish to study. Hence, digital simulation has enabled us to reap the benefits of the trial and error process, whilst integrating progress made in terms of the knowledge of the physical phenomena, thanks to the increase in calculation capabilities of computers. The phenomena could not have been studied using traditional experimental techniques.

Provided that we have an accurate knowledge of the structure and characteristics of the elements that we want to have interacting, the chief challenge with simulation is to imitate reality as closely as possible, by accurately reproducing each of its mechanisms.

Exhaustively simulating the sequence of all the causes and effects induced by blasting is a challenge that the most sophisticated models have been unable to meet, despite the increasing computing power available for civilians and industry. Far from hiding the unfinished nature of their simulation, the developers of these software programmes emphasize the impossibility of accurately reproducing natural mechanisms, in particular due to their complexity.

An accurate and complete reproduction of the natural mechanisms coming into play would not only suppose taking into account the physical and chemical characteristics of the explosive, the drilling pattern of the blast, the position of the holes in space, and of course the initiation sequence, but also a very wide knowledge of the geology and the geo-mechanical properties of each of the elementary particles of rock, which is unattainable in the present state of science and techniques. Besides, astrophysics has encountered the same limits. The complexity of cosmic phenomena has led astrophysicists to use digital simulation for fifty years. The majority of the astrophysical phenomena today are governed by a corpus of physical laws with no analytical solution. Therefore, digital calculations are used to provide an approximate expression for the solution but the physical mechanisms that come to play become too expensive in terms of computing time, leading to the necessity of finding new approaches. Now, we know since Newton that the laws of physics that govern the heavens and the Earth are the same.

The holistic approach to the phenomena involved in blasting enables us to avoid the deterministic stumbling block, by accepting the principle that we are simulating the effect of a known product, the explosive, on an environment that is only partly and imperfectly known, rock. It is of interest to note that the debate raging in the world of the digital simulation of blasts has already taken place within fundamental physics and that decisive objections contradict some of the basic principles of the deterministic theories.

— PREREQUISITES

— APPLICATIONS

by Thierry Bernard

The students will first learn about the process of holistic approach of digital simulation based on an example of rock fragmentation by explosive.

After getting familiar with the process, they will build a model that will simulate the impact of an asteroid on Earth. The model will include trajectography in the earth atmosphere, then the student will select either to model the impact on solid ground or water and will select to model either the impact of the seismic waves, or the cratering effect for ground impact or tsunami effect for water impact. The final goal is to obtain damage zone for people and structures depending on the initial conditions of the asteroid. Use of G.A.I. will be used for coding.

— EVALUATION

- **Theory grade [30%]**
- **Practice grade [30%]** Theory and practice will be evaluated through the continuous assesment with regular short exams or presentations.
- **Defense grade [40%]**
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

— BIBLIOGRAPHY & RESOURCES

-
- Machine learning and data mining for astronomy
- Fusformer for super-resolution and data fusion

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