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

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- 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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