Thesis subject

Laboratory : Laboratoire Astrophysique Marseille

Thesis supervisor : Hervé Le Coroller

Co-supervisor : Orphee Faucoz (CNES)

Title of the thesis subject : Revolutionizing Exoplanet Detection with Keplerian-Stacker algorithms

Description of the thesis subject:

Most of the 7,500 exoplanets discovered to date have been identified through indirect methods such as radial velocity, transit photometry, and astrometry. While these techniques have been highly successful, they provide limited information about the physical and atmospheric properties of exoplanets. Direct imaging remains constrained by the contrast limitations of current ground-based instruments like SPHERE and GPI (contrast of ~10^6 at 500 mas). As a result, only a handful of exoplanets, primarily young, massive gas giants, have been directly imaged, with those located near the snow line (< 10 AU) remaining undetectable. Future space telescopes, including the Roman Space Telescope (RST) and the Habitable Worlds Observatory (HWO), will push the boundaries of direct imaging by enabling observations closer to the snow line. However, characterizing low-mass exoplanets akin to those in our solar system with RST and HWO will require very long exposure times (> 10 hours), during which orbital motion significantly degrades the signal-to-noise ratio (S/N).

The Keplerian-Stacker project proposes a paradigm shift in high-contrast imaging by transforming orbital motion from a challenge into an asset. Instead of relying on single-epoch detections, this approach leverages the Keplerian motion of exoplanets (K-Stacker: Le Coroller et al. 2015, 2022, 2025; OCTOFITTER: Thompson et al. 2023) to combine multi-epoch and multi-technique observations (direct imaging, radial velocities, astrometry). By simultaneously fitting the flux and orbital parameters of planets across the entire observational dataset, these algorithms can detect exoplanets with S/N < 2 that would otherwise be lost in noise when analyzed independently. This method not only reduces the total observation time required for large surveys but also maximizes scientific return by enabling the detection and characterization (atmosphere, orbit) of fainter, previously inaccessible targets.

This project will focus on three key objectives:

1. Development of Multi-Epoch Algorithms: One goal of this phd is to advance K-Stacker by integrating orbital dynamics, multi-technique data fusion, and high-dispersion spectroscopy. First, we will jointly infer planet flux and orbital parameters within a unified MCMC framework, explicitly modeling phase-dependent reflected light variations, a novel approach for atmosphere and surface characterization. Second, we will develop new likelihood functions to combine high-contrast imaging (HCI), astrometry (e.g., GAIA), and radial velocity (RV) measurements using tools like Kepmodel, enabling a coherent analysis of all observational data. Finally, we will adapt K-Stacker (KS) for the first time to high-dispersion spectroscopy cross-correlation techniques (Snellen et al. 2015) and incorporate an N-body orbital fitting module (Beust et al. 2003, 2016), pushing detection thresholds beyond current multi-epoch algorithm limits.

2. Machine Learning for Orbital Motion Detection: The student will design and train machine learning models to identify orbital signatures, complementing classical K-Stacker algorithms (see 1.) to improve detection sensitivity, especially for low-mass planets.
3. Modular Software Infrastructure (MSI): The student will develop an end-to-end reduction (RAW->ASDI->KS) infrastructure enabling the validation of algorithms developed in 1. and 2., the assessment of optimal multi-epoch observation surveys strategies, and the full reduction of real observational data. We'll develop the MSI on LAM's computing cluster to automate large dataset reduction and generate detection statistics (e.g., ROC curves).
The Keplerian-Stacker project will directly support the scientific goals of the Roman Space Telescope by enabling the detection of Jupiter-like exoplanets around nearby stars by Phd completion (e.g., NASA White paper to observe eps eri b with RST). Furthermore, it will lay the groundwork for HWO observations, with the aim of characterizing dozens of exoplanets near the snow line, many of which would remain undetectable without these algorithms. Ground-based observations will also utilize K-Stacker to process high-contrast imaging datasets obtained for example with HARMONI and PCS-ELT. By bridging the gap between indirect and direct detection methods, this work will contribute to the search for biosignatures, a cornerstone objective of HWO, and advance our understanding of planetary system architectures.

References :

Le Coroller, H. 2025, JATIS,"White paper on Keplerian…algorithms: unlocking HWO…", Submitted
Thompson, W. et al. 2023, AJ, "..Orbit Modeling to Detect Exoplanets", 166, id. 164
Le Coroller, H. 2022, AA, "Efficiently combining alphaCenA multi-epoch HCI data", 667, id.A142
Beust, H. et al. 2016, AA, "Orbital fitting of imaged… PZ Telescopii B", 587, idA89
Le Coroller, H. et al. 2015, "a new way of detecting … exoplanets …", ESS meeting #3, id.112.06.
Snellen, I. et al. 2015, AA, "..high-dispersion spectroscopy with high contrast..", 576, A59
Beust, H. et al. 2003, AA, "Sympletic integration of hierarchical stellar systems", 400, 1129

Profil du candidat *

Strong expertise in image processing methods and advanced statistical techniques, particularly Markov Chain Monte Carlo. Knowledge of Machine Learning is highly desirable. The ideal candidate also holds a Master's degree in Astrophysics.

Cofinanceur(s) envisagé(s) *

1/2 bourse de thèse CNES (demande en cours)