Laboratory : Laboratoire d'Astrophysique de Marseille

Thesis supervisor : Hervé Le Coroller

Co-supervisor : Faucoz Orphee (CNES), Mathias Nowak (OBSPM)

Title of the thesis subject :

Direct detection of exoplanets near the ice-line with K-Stacker

Description of the thesis subject :

Detecting exoplanets through direct imaging is a considerable challenge, as they are 10^6 to 10^11 times fainter than their host stars. The majority of the 7,000 exoplanets discovered since 1995 have been detected indirectly via radial velocities and photometric transits.

In past years, instruments such as GPI [USA, Macintosh et al. 2014] and SPHERE [Europe/VLTconsortium; Beuzit et al. 2019] equipped with extreme AO and coronagraphs have achieved very high contrasts (10^6 at typically 500 mas). The main surveys carried out with these instruments (SPHERE/SHINE, GPI/Exoplanet Survey) provided valuable statistical constraints on the population of young giant planets. However, despite reaching their goals in terms of performance, they provided only a limited number of new detections (HIP65426 b and PDS70 b and c with SPHERE; 51 Eri b with GPI [Chauvin et al. 2017; Haffert et al. 2019; Macintosh et al. 2015]). Recent radial velocity surveys [e.g., Fernandes et al. 2019] and statistical studies of imaging surveys [SPHERE, Vigan et al. 2021] suggest that this limited number of detections is primarily due to the core population of giant planets being located near the ice line, between 2 and 5 AU, which is beyond the detection capabilities of SPHERE and GPI. To image these planets at small separations, a new generation of instruments and observatories will be commissioned in the coming years: SPHERE+ (2026) on the VLT-ESO followed by HARMONI, METIS, and MICADO on ESO's ELT (2027-2028). In space, the Roman Space Telescope (RST - 2027) and the Habitable World Observatory (HWO - 2040) will detect old exoplanets like those in our Solar System, in reflected light around nearby stars.

At small orbital separations (<5 AU), planets around the nearest stars exhibit significant orbital motion over the timescales required for their detection (i.e., integration times of several tens of hours to observe a Jupiter at a contrast of 10^-8 and an Earth-like planet at 10^-10, as probed by RST and HWO, respectively). From the ground, Males et al. 2013 were the first to highlight that orbital motion cannot be neglected during the typical exposure times (> 10 hours) required to detect Earth-like planets around nearby stars with the ELT. Moreover, event for companions at larger orbital periods that will not move significantly over the course of a single exposure, bad weather (e.g., turbulence degradation) or technical issues will force observations to be halted and resumed more than 24 hours later. An algorithm that accounts for orbital motion will therefore be essential to avoid losing these exposures, a major concern when considering the cost of a night of observation on the ELT. Finally, even if it is possible to detect young massive planets (at a contrast of 10^7) before they have had time to move along their orbit, it may be more advantageous to split the exposures, to observe only under excellent observing conditions to reach the higher contrast and to constrain the orbital parameters within an optimal exposure time.

Keplerian-Stacker [Le Coroller et al. 2015; 2020; 2022; Nowak et al 2018] **was the first algorithm capable** of addressing these challenges of **detecting planets moving along their orbits** in a series of observations, **even when they are not detectable (S/N < 2) at each individual epoch.** K-Stacker optimizes a likelihood function over N observations using a brute-force algorithm followed by a local gradient-descent re-optimization stage. Note that several teams around the world developed these last 2 years multi-epoch recombination algorithms inspired by K-Stacker [Octofitter: Thompson et al. 2023; PACOME: Dallant et al. 2023].

Nevertheless, the phase errors in the wavefront, inadequately corrected by adaptive optics near the coronagraphic mask, induce non-Gaussian speckle noise, which makes the detection of planets at the required contrast levels extremely challenging**.** K-Stacker enhances the contrast limit by effectively increasing the exposure time, even when planets move during the observation period. Nevertheless, **a new generation of reduction algorithms is needed. The objective of this Phd project is to develop new algorithms that will achieve the required contrasts using advanced statistical methods that account for the orbital motion of planets during observations.** The goal is to achieve a contrast exceeding 10^7 to enable the detection of exoplanets located near the coronagraphic mask (e.g., close to the ice line, within 5 AU at less than 30 PC) and to deliver robust detection probabilities with future instruments. To achieve this goal, several approaches are being considered:

- Integrate an MCMC framework (e.g., using *emcee*) to optimize the final computation of K-Stacker.

- Merge the MCMC algorithm developed by Beust, H. et al. 2016 (collaboration with LAM-OSUG) with K-Stacker to account for N-body orbital motions and complex orbits (e.g., $e > 0.9$).

- Develop a machine-learning-based version of K-Stacker from scratch.

- Build an infrastructure capable of injecting a large number of synthetic planets (spanning various orbits and fluxes) to produce robust detection statistics (e.g., rates of true/false positives and negatives).

- Process data from future observatories (ELT instruments, RST, HWO).

The aim of the Machine Learning/Deep Learning techniques is to develop an alternative approach to the classical PCA-ADI (classical High contrast imaging methods) and K-Stacker methods. The goal will be to search for planets directly in the raw data, as they move along their orbits during the observation, potentially bypassing ADI processing. We will check whether the neural network has converged towards a solution corresponding to a Keplerian orbit (inverse approach). We plan to use a UNet-type algorithm [Huang, H., et al. 2020; Ronneberger, O., et al. 2015; Zhou, Z., et al. 2018], potentially combined with a denoising method [Buchholz, T.-O., et al. 2020], or an unsupervised deep learning model such as

‘Recorrupted-to-Recorrupted’ for image denoising. The “Laboratoire d’Astrophysique de Marseille” (LAM) has strong expertise in Machine Learning, thanks to its team at the “Centre de Données Astrophysiques de Marseille” (CeSAM), and has already applied UNet to detect transits in simulated data from the PLATO space telescope [Vivien, H.G. et al. 2024], a mathematical problem closely related to what we aim to achieve, with the added complexity of orbital motion (i.e., detecting a planet peak instead of a transit, in non-Gaussian noise).

The student will be integrated into the LAM, within a team specialized in high-contrast imaging. He will be supervised by H. Le Coroller, who is responsible for multi-epoch recombination algorithms (CO-I) for the NASA HWO project, and will collaborate with E. Choquet’s team, leading the ERC-Escape project, which will provide simulated RST images. The student will also interact with other experts, such as A. Vigan, RST’s French representative for CNES at LAM. In the context of the Roman Space Telescope (RST), the student will have the opportunity to collaborate with CNES, which brings its expertise—through its collaboration with Orphee Faucoz, on Machine Learning and Deep Learning techniques. Additionally, the student will benefit from the support of the Machine Learning “Centre de données Astrophysiques de Marseille” (CeSAM). The Laboratoire d’Astrophysique de Marseille (LAM) will provide access to a computing cluster managed by CeSAM, along with technical support for intensive computational tasks.

References :

Beuzit, J.L., et al. 2019, A&A, “SPHERE : the exoplanet imager for the V.L.T”, 631, idA155 [link]
Beust, H. et al. 2016, A&A, “Orbital fitting of imaged… PZ Telescopii B”, 587, idA89 [link]
Buchholz, T.-O., et al. 2020, « DenoiSeg: Joint Denoising and Segmentation », arXiv: 2005.02987
Chauvin, G. et al. 2017 , A&A, “Discovery of a warm, … planet around HIP65426”, 605,id.L9 [link]
Dallant, J. et al. 2023, A&A, “PACOME: Optimal multi-epoch combination…”, 679, 38 [link]
Fernandes, R.B. et al. 2019, ApJ,” .. the Giant Planet Occurrence Rate”, 874, 81 [link]
Haffert, S.Y. et al. 2019, Nature Astro., “Two accreting protoplanets … PDS70”, 3, 749 [link]
Huang, H., et al. 2020, arXiv e-prints, arXiv:2004.08790
Le Coroller, H. et al. 2015, “a new way of detecting … exoplanets …”, ESS meeting #3, id.112.06. [link]
Le Coroller, H. 2020, A&A, “K-Stacker: an algorithm to hack the orbital parameters..”, 639, id.A113 [link]
Le Coroller, H. 2022, A&A, “Efficiently combining α CenA multi-epoch HCI data”, 667, id.A142 [link]
Macintosh, B. et al. 2014, Proc. Natl. Acad. Sci., “First light of Gemini Planet Imager”, 111, 12661 [link]
Macintosh, B. et al. 2015, Science, “Discovery and spectroscopy of .. 51 Eri b …”, 350, 6256 [link]
Males, J.R. 2013, ApJ, “Direct Imaging in the H.Z. and the problem of Orbital motion”, 771, 10 [link]
Nowak, M. et al. 2018, A&A, “K-Stacker: Keplerian image recombination…”, 615, A144 [link]
Ronneberger, O., et al. 2015, arXiv e-prints, arXiv:1505.04597
Thompson, W. et al. 2023, AJ, ”..Orbit Modeling to Detect Exoplanets”, 166, id. 164 [link]
Vigan et al. 2021, A&A, “The SPHERE infrared survey for exoplanets (SHINE)”, 651, A72 [link]
Vivien, H.G. et al. 2024, Exoplanets5, submitted
Zhou, Z., et al. 2018, arXiv e-prints, arXiv:1807.10165