Master 2 Research internship offer
Academic year 2024 – 2025

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Hosting research team: AIRI

Internship title: Direct detection and characterization of exoplanets: statistical learning, multi-epoch and multi-spectral data fusion

Summary of proposed work:

Context: The direct observation of the close environment of stars can reveal the presence of exoplanets and circumstellar disks, providing crucial information for a better understanding of planetary system formation, evolution, and diversity. Given the very small angular separation with respect to the host star and the huge contrast between the (bright) star and the (faint) exoplanets and disks, imaging the immediate vicinity of a star is extremely challenging. In addition to the use of extreme adaptive optics and a coronagraph, dedicated post-processing methods combining images recorded with the pupil tracking mode of the telescope are needed to efficiently suppress the nuisance component (speckles and noise) corrupting the signals of interest.

Beyond optimal post-processing of individual observations, fusing multiple observations of the same star taken over different epochs can significantly improve the detection sensitivity. The key challenge in this approach lies in accounting for both the nuisance statistics and the orbital motion of the exoplanet across epochs. To address this, the PACOME algorithm (for PACO Multi-Epoch; [1]) has been recently introduced. PACOME leverages statistical modeling of the nuisance component and its correlations at the local scale within a small pixel patch. This approach is inherited from the PACO algorithm, specifically designed for exoplanet detection from individual (mono-epoch) dataset of observations. The by-products of PACO from each epoch provide sufficient statistics that can be optimally combined using PACOME, while efficiently exploring the Keplerian motion of exoplanets. This multi-epoch strategy yields a combined detection score that is directly interpretable as a measure of detection confidence. In addition to improving sensitivity, PACOME enables the estimation of orbital parameters, along with their joint and marginal distributions. Although PACOME achieves state-of-the-art performance, there remains room for improvement, especially near the star. Here, the assumption of a local-scale statistical description of the nuisance component overlooks larger-scale spatial correlations, thus limiting the method's detection sensitivity.

In this context, data science developments are decisive to improve the detection sensitivity of exoplanets and the accuracy of the estimation of their orbit.

Research directions: This project will build on recent advancements in modeling the nuisance component that corrupts high-contrast total intensity observations. The focus will be on improving exoplanet detection and characterization. Possible research directions include:

1/ Modeling large-scale nuisance correlations: To address the limitations discussed, the goal is to integrate a more refined modeling of the nuisance component within multi-epoch detection algorithms. This can be achieved using the ASAP approach [2], which approximates the precision matrix (i.e., inverse of the covariance matrix) with a structured, sparse model that may better capture large-scale correlations compared to PACO.

2/ Joint spatio-spectral modeling of large-scale correlations: Building on point *1/*, the objective is to develop a joint spatio-spectral model of the nuisance that accounts for large-scale correlations across both spatial and spectral dimensions.

Data: The project will focus on developing / improving new processing algorithms using spectroscopic total intensity observations (i.e., spatio-temporal-spectral data recorded with an Integral Field Spectrograph) from the SPHERE instrument, currently operating on the Very Large Telescope (VLT). Several multi-epochs observations are available to both ground the performance of the proposed algorithm and to search for new exoplanets!

Once a proof of concept is established, simulations for HARMONI, one of the first-light instruments of the upcoming Extremely Large Telescope (ELT), may be considered. In this case, the algorithm will be adapted to account for HARMONI's specific features, particularly its higher spectral resolution. Achieving the required contrast with this instrument will require extended total exposure times on a single star, making a multi-epoch strategy indispensable.

Bibliography:

[1] Dallant+, "PACOME: Optimal multi-epoch combination of direct imaging observations for joint exoplanet detection and orbit estimation." *Astronomy & Astrophysics,* 679, A38, 2023, https://arxiv.org/pdf/2309.08679

[2] Thiébaut+, "Beyond FRiM, ASAP: a family of sparse approximation for covariance matrices and preconditioners." *Adaptive Optics Systems VIII*. Vol. 12185. SPIE, 2022, https://arxiv.org/pdf/2311.17721

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Potential for a follow-up as a PhD thesis: Yes