From statistical modeling to deep learning for exoplanet detection in direct imaging at high contrast

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Résumé

Detection of exoplanets by direct imaging is an active research topic in astronomy for the characterization of young and massive objects. The very high contrast between the host star and its companions makes the detection particularly challenging. In addition to the use of an extreme adaptive optics system and of a coronagraph to strongly attenuate the star light, dedicated processing methods combining multi-variate data recorded with the pupil tracking mode of the telescope are required. The different spatio-temporo-spectral behaviors of (i) the remaining stellar leakages and of (ii) the signal from the off-axis sources make it possible to unmix them and to detect exoplanets.

In previous works, we presented an algorithm (PACO (1)) capturing statistically the spatio-temporo-spectral correlations of the data with a weighted multi-variate Gaussian model whose parameters are estimated, in a data-driven fashion, at the scale of a patch of a few tens of pixels. This method is parameter-free and delivers reliable detection confidences with and an improved detection sensitivity with respect to the classical processing methods of the field (e.g., cADI (2), PCA (3), TLOCI (4)). However, there is a large room of improvement to push down the detection sensitivity due to the approximate fidelity of its model with respect to the observations. Very recently, we propose ((5)) to combine the previously mentioned statistics-based model with deep learning in a three steps algorithm. First, the data are centered and whitened locally using the PACO framework to improve the stationarity and the contrast in a pre-processing step. Second, a convolutional neural network is trained in a supervised fashion to detect the signature of synthetic sources in the pre-processed science data. Finally, the trained network is applied to the pre-processed observations and it delivers a detection map. The network is based on a U-Net architecture with a Res-Net18 backbone. It is trained from scratch with a customed data augmentation strategy allowing to generate a large training base from a single dataset. In this presentation, I will present the key methodological concepts of these two algorithms (based solely on a statistical modeling and based on a combination of a statistical modeling with a deep learning framework).

We apply our two methods on several datasets from the imager (IRDIS) and spectrograph (IFS) of the VLT/SPHERE instrument. Our results show that our methods lead to better detection sensivity than state-of-the-art comparative algorithms, with a typical improvement by about half to two magnitude(s). The deep learning stage is responsible for an improvement by about half a magnitude with respect to a modeling of the data with a statistical approach solely. Thanks to its unique detection capability and its control of the uncertainties

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(contrast, probability of detection and of false alarms, astro-photometry with reliable error bars), PACO is currently in the roadmap to re-analyze massively all the GTO observations ($>$ 300 datasets, $>$ 2 To data) of the VLT/SPHERE instrument. I will also briefly discuss the expected gains in that direction. On the methodological side, we are currently working on the control of the uncertainties of the deep learning stage and on an hybrid algorithm including a physics and/or statistics-based information directly inside the training loop to constrain the outputs of the network by these priors.

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(2) Marois et al., "Angular differential imaging: a powerful high-contrast imaging technique", The Astrophysical Journal, 641(1):556, 2006.

(3) Soummer et al., "Detection and characterization of exoplanets and disks using projections on Karhunen-Loève eigenimages." The Astrophysical Journal Letters, 755.2:L28, 2012.

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