Thesis subject

Name of the laboratory: Laboratoire d'Astrophysique de Marseille

Thesis advisor: Hervé Le Coroller
Email and address: herve.lecoroller@lam.fr
Tel: 06 32 33 81 50 / 04 95 04 41 27
Co-advisor:

Subject's title: Keplerian-Stacker, toward an optimized instrument to detect earth-like planets with the E-ELT

Subject description:

Most of the 3500 exo-planets detected until now have been found using indirect methods such as radial velocity technique and photometric transit. Indeed, it is extremely difficult to detect the planet light that is drowned in the diffracted light of its host star. **A Jupiter and an Earth like planets are about $10^8 - 10^{10}$ fainter than their parent star in the visible.** Nevertheless, huge improvements have been done during the last decade with adaptive optics (to correct the phase errors induced by the atmosphere) and coronagraphic systems in order to attenuate the light of the star and to be able to detect directly the light of the planets. Since 2013, two new instruments SPHERE (Beuzit et al. 2008), and GPI (Macintosh et al. 2014), equipped with last technologies such as an extreme adaptive optics (XAO) system and an apodized coronagraph have started their scientific observations. For the first time these instruments are able to reach a contrast level of 10^{-6}, and are able to detect young Jupiter-like planets (we detect the thermal light produced by the planet in the near-infrared). But, even if these instruments have perfectly reached their objective in term of technical performance (high contrast at separation > 0.1 arcsec), after more than three years in operation, **the number of new exoplanets detected is extremely small (2, 3 …).** Taking into account the last statistics of the SPHERE/SHINE survey, the radial velocity surveys and planetary formation models, the planets could be closer to their star and more difficult to detect than expected.
Recently, we have proposed a new method of observation and reduction (Keplerian-Stacker) that could improve the detection limit of high contrast instruments such as SPHERE, up to a factor of 10. It consists in combining the images recorded during different nights, accounting for the orbital motion of the putative planet that we are looking for. Even if in each individual observation taken during one night, we do not detect anything, **we show that an optimization algorithm (K-Stacker) can align the planet images according to keplerian motions** (ex: 25 images taken over a long period of several months), increase the signal-to-noise ratio, **and detect the planet otherwise unreachable** (Le Coroller et al. OHP2015; Nowak, M. et al. 2017, A&A). This method can be used in combination with the "Angular Differential Imaging" techniques (Marois et al. 2006, ApJ) or any other high contrast data reduction method (TLOCI, PCA, etc.) to further improve the global detection limit. K-Stacker also directly provides orbital parameters of the detected planets, as a by-product of the optimization

algorithm. Finally, this method could also be used as part of a new scheme of observation, in which exposures would not be made sequentially in one night, but would be spread over multiple nights, in order to obtain better constraints on the orbit (in an equivalent total exposure time).

Proposed work:

1 - We have already tested K-Stacker (Python language) on simulated images of SPHERE (the IRDIS sub-system with atmospheric + instrumental phases errors) taken over several months with fake planets introduced at very low signal to noise ratio, down to ≃ 1 in the individual frames. We have proved that the K-Stacker algorithm (a brute-Force + local gradient to maximize the total signal to noise ratio) can re-combine these images and detect the planets hidden in individual images.
2 - We are currently **testing K-Stacker by introducing fake planets in real data** that have been reduced with the ADI technique (using NaCo and SPHERE VLT observations). The first tests are showing that we can detect the planets about with the same reliability than on simulated data when the total SNR of the re-centered images reaches 5. The student will have to pursue this work (introduction of fake planets before ADI reduction) and he will test K-Stacker on more data and images reduced by different methods: TLOCI, PCA, etc.
3 - A theoretical works (+ simulations) will have to be done by the student to **calibrate this technique in order to extract, the photometry and astrometry of the detected planets.**
4 - SPHERE has been working for three years. At the end of this Phd, we will have about 6 years of data. **Several interesting stars are followed** to study their disk, or a planet already known. So, **we are confident to detect new planets** around these objects (K-Stacker will increase the contrast by a factor 3-5 on these targets with 3-5 observations by year during 5 years). It will be also possible to test it on public archives (Keck, etc.). Only a few new candidates (ex: 1-2 new planets detected in the survey of more than 700 stars) will bring very important constraints for the statistic of the survey and will help to better understand the planet formation mechanisms. **It will also be possible to propose a program of observation with this method on SPHERE.** Beyond K-Stacker, **the student will have the possibility to be involved in the largest imaging survey ever (SHINE)** for the exo-planets search (and their characterization) with SPHERE. He will participate to the observations (at VLT/Chili) and data reduction.
5 - Adjustment of K-Stacker on the E-ELT and future techniques: As part of this work, the goal is also to validate the interest of this method in particular **to detect exo-earths with the European-Extremely Large Telescope:** K-Stacker could be the solution to reach the required contrast at the end of all the chain: XAO, coronagraph, ADI/SDI reduction with the E-ELT. More generally, we will study new techniques (image processing and instrumental) that could help to detect and characterize (spectrum, orbital parameters) exo-earths.
In particular, we would like to study a nulling recombination with the E-ELT (Le Coroller, HDR 2015). This work is more prospective and instrumental, but the goal is quite similar: increasing the contrast limit to be able to detect earths like planet, and eventually to search for bio-signatures. We want to use the property that a planet plus his star form a very simple image (only one spatial frequency is required to separate the planet from his parent star). By putting all the energy of the 40 m telescope in this spatial frequency (all the energy to pilot 2-4 actuators

by spectral canal at the end of the chain) we think that we can have a very accurate sensor, and a very efficient nuller, able to detect earth like planets (10^{-9} in the visible). During the PhD, the student will have the possibility to take the leadership of projects around these topics (instrumental or observations with K-Stacker)…

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