Thesis subject

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Subject's title: K-Stacker, an algorithm to hack the orbital parameters of planets hidden in the speckle residuals of high contrasts images, and to detect super-earth like planets with the Extremely Large Telescope

Subject description:

Most of the 4800 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. The latest instruments such as SPHERE, and GPI (Beuzit et al. 2019, A&A, 631; Macintosh et al. 2014) equipped with last technologies (extreme adaptive optics system and apodized coronagraph) have been able to reach a contrast level of 10^{-6}, that allow to detect and characterize 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 objectives in term of technical performance (high contrast at separation > 0.1 arcsec) and number of publications (> 100 for SPHERE with planets characterization, sometime in interaction with their disk…ex: HIP65426 et PDS70 b et c; 51 Eri with GPI; Chauvin et al. 2017, Keppler et al. 2018, Haffert et al. 2019, etc.), after more than six years in operation, the number of new exoplanets detected is small. These high-contrast imaging surveys have shown a low occurrence rate of giant planets beyond 30 au (0.6 %; see Bowler 2016). Today, the Gemini Planet Imager Exoplanet Survey (GPIES) and the SPHERE High-contrast ImagiNg survey for Exoplanets (SHINE) indicate that this scarcity extends down to 10 au (Nielsen et al. 2019; Vigan et al. 2020), suggesting that the bulk of the giant planet population is typically located between 1 au and 10 au. A prime goal of the future surveys will be to bridge the gap with indirect techniques (transits, radial velocity) by imaging young Jupiters down to the snowline at about 3–5 au

In this context, 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. 2020, A&A, 639; Nowak, M. et al. 2018, A&A, 615, 12). This method can be used in combination with the "Angular Differential Imaging" techniques (Marois et al. 2006) or any other high contrast data reduction method (ex: TLOCI, PCA - ASDI) 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. Moreover, future observations to search for new Earth-like planets around the nearest stars with instruments in the visible (ex: SPHERE+ / Zimpol) or with the European – Extremely Large Telescope (E-ELT - ESO telescope of 39 m) will absolutely require to use algorithms such as K-Stacker, because the Point Spread Function will be $5 - 15$ times smaller, and orbital motion will cause the planets to move by several PSF diameters between epochs of observations.

Proposed work:

We have already built and tested a first K-Stacker algorithm (in Python, which runs of the LAM computer cluster). An extensive amount of work went into testing the algorithm on simulated date to make sure that it was capable of recombining images properly (Nowak, M. et al. 2018, A&A, 615, 12), and to re-detect known planets such as beta pic b in real datasets, to demonstrate that the algorithm also works with real-world data (Le Coroller et al. 2020, A&A, 639). Recently, we also have confirmed the probable presence of a 4 – 7 earth radius planets located in the habitable zone of AlphaCen A star (Le Coroller, et al. 2021, in preparation) using NEAR / VISIR observations.

Despite these successes, the current version of the algorithm still suffers from a number of limitations, inherited from an initial development as a prototype/demonstration algorithm. The next step in the project is thus to rework the algorithm, solve these last few issues so as to be able to fully start the scientific exploitation of the algorithm.
A number of improvements are already being implemented, and some observations are currently being acquired (alpha Cen with SPHERE/ZIMPOL, see point 1 below). Therefore, we expect the selected candidate to quickly get up-to-speed with the algorithm, and take the lead on those projects.
The PhD project is expected to be a mixture of data analysis with the algorithm, development and improvement of the existing code, and of more prospective work on other aspects related to K-Stacker (use on different types of data, use on future telescopes, etc.)
The exact content of the PhD work will depend on the profile and personal tastes of the selected candidate, but several key elements and options are outlined below.

1 – A search for alpha Cen A b in SPHERE-ZIMPOL data:
An observing program is currently on-going on SPHERE/ZIMPOL, to search for the planet candidate around alpha Cen A (K. Wagner et al. Nature Com., 12, 922). The program is extensive, with more than 50 hours of observing time schedules on the target. The combination of a program spread over several months and the small size of the instrumental point-spread function (in the visible) makes it unlikely that the candidate will be detected by any simple co-addition of the observations. In this context, K-Stacker will be a very important tool to analyze this dataset, and is an integral part of the on-going proposal. However, in its current implementation, the algorithm is too slow, and it would take months to analyze that data. One of the first goals of this Phd, will be to improve the computation time of K-Stacker (re-write the algorithm to use pre-calculated grids of the Keplerian solutions, work with images convolved by the reduced PSF, optimize the way K-Stacker launch the computations on several cores, etc.). The reduction of the computation time will allow a full analysis of the alpha Cen A data, with the potential of revealing new planets around this close-by star.

2 – A K-Stacker/Andromeda re-analysis of the SPHERE survey:
The current version of K-Stacker was designed to work with calibrated observations, in units of flux. For this, its uses a formalism base on the Signal-to-Noise calculations, which shows a number of limitations. Recent development in high-contrast imaging data-reduction have led to a new generation of algorithms, which have largely departed from this flux/SNR-based formalism, to and turned to a likelihood-based technics (see, for example, the ANDROMEDA algorithm, Cantalloube, F. et al. 2015 A&A, 582). These algorithms provide a much better estimate of the detection probability, with uncertainties much closer to a Gaussian distribution. As a consequence, K-Stacker is expected to be much more efficient on these types of reduced data. An objective of the PhD project will be to adapt the algorithm to work with ANDROMEDA reduced data. If successful, then the whole SPHERE/SHINE survey could be re-analyzed with this combination of ANDROMEDA/K-Stacker, potentially revealing new candidates around some targets which have been observed several times during the survey. If planet candidates are found, the PhD student is expected to submit follow-up observing proposals with either VLT/SPHERE or VLTI/GRAVITY to characterize them.
This part of the project will be an opportunity for the selected candidate to interact and play a role within the SPHERE direct imaging community.

3 – Exploring the population of moons around asteroids in the Solar System:
The search for moons around asteroids in the Solar System shares similar issues with the search for planets around near-by stars (the separation between the moon and the asteroid is small, the contrast is significant, and the moon is in Keplerian orbit around the asteroid), but also has its specificities (the objects involved are not point-like sources, their rotation induce flux variations, the distance of the asteroid change between the epochs, etc.). K-Stacker has recently been identified has a potentially very useful tool to help in this search for asteroid moons. A number of changes are required to adapt the algorithm to search for asteroid moons. If the selected candidate is interested in this idea, he could take the lead in this project, adapt the algorithm, and look for moons around asteroids, in the frame of a collaboration with Pierre Vernazza (PI of a 152h large program with SPHERE, dedicated to the search for asteroid). This work will allow to study the mass, density and formation origins of these asteroids and moons.

4 – Improving the algorithm:
A number of possible improvements for the K-Stacker algorithm have already been identified, and the selected candidate is expected to work on some of those.

a – machine learning:
Our experience with K-Stacker has shown us that the false positives in the recombined images can usually be recognized by an experienced user. This empirical observation has never been precisely quantified or investigated, but suggests that shape of the recombined PSF can be used to identify true planet candidates and false positives. If this is truly the case, then a machine-learning algorithm (probably in the form of a convolutional neural network, which have already been proven useful for the detection of high-contrast targets, see Gomez Gonzalez et al., 2018) could be trained on simulated or real datasets, to automatically recognize true candidates in the grid of K-Stacker results.
b – future instruments:
The upcoming ELTs, and the future generation of high-contrast instruments, will certainly benefit from an algorithm like K-Stacker. The small size of the PSF on 40 m class telescopes and the higher apparent motion of the planets at the smaller separations probed by these instruments, will pose a challenge for the combination of observations even on short timescales (see Males et al. 2013, ApJ, 771, 10). To adapt the algorithm to future instruments, a study needs to be conducted in which fake planets will be injected in simulated images (taking into account the XAO performances, coronagraph, etc.) of future instruments (SPHERE+, ELT - HARMONI, METIS, etc.) to predict the performances of K-Stacker and

its capability to detect earth like planets with the E-ELT. The goal is to prepare future observing proposal with K-Stacker on these instruments (targets, time / number of nights required, etc.).

c – astrometry with K-Stacker:

The usual procedure used to characterize the orbit of a planet observed with high-contrast imaging is to observe the planet repeatedly, extract the astrometric position at each epoch, and use an MCMC algorithm to estimate the best orbital solution given the astrometric measurements and their error bars. K-Stacker works in a different way, as the orbital parameters are estimated directly from the images. This means that K-Stacker bypasses the step in which each image is reduced to a single astrometric measurement, plus error bars. Since the algorithm is keeping more information and propagating the error bars directly from the images to the posterior distributions, the K-Stacker orbital parameters may prove to be better that the parameters derived in the usual way. A detailed study is warranted to compare the orbital parameters found by K-stacker with the 'classical' solutions of the more classical MCMCs methods and determine whether or not K-Stacker can provide more robust orbital parameters than the algorithms working on the positions that may be biased at very low signal to noise.

5 – Using K-Stacker in combination with high-resolution cross-correlation observations:

Another possible use case of K-Stacker is to search for warm Jupiters around nearby stars using high-resolution spectroscopic data in the near infrared (CRIRES at the VLT). Through the use of cross-correlation methods, high-resolution spectroscopic data have been successfully used to detect hot-Jupiters, in very close-in (<0.1 AU) orbits around a number of stars, including using infrared spectra. However, in the case of warm Jupiters, several important differences can complicate the observations and analysis. For example, the detections of hot Jupiters are often supported by radial velocity observations which constrain the orbit and phases of the planet. When targeting young stars, such radial velocity data may not be available (because of the lack of spectral lines in the near infrared), or unusable (due to stellar activity). If the orbit of the potential planets are totally unknown, a blind search may be necessary, which would be possible to perform using the existing machinery provided by K-Stacker (grid search on orbital parameters, distributed on the LAM computer cluster). This is a more prospective idea, which can be explored.

Beyond K-Stacker, the student will have the possibility to be involved in the largest imaging survey ever (on SPHERE+) for the exo-planets search and their characterization. More generally, we will study new techniques [image processing and instrumental] that could help to detect and characterize exo-earths. In particular, we would like to study a nulling recombination with the E-ELT (Le Coroller, HDR 2015: http://lecoroller.obs-hp.fr/uploads/htmlHerve/HDR_LeCoroller_PLUS_Annexes.pdf). 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. The goal is to propose a very accurate sensor, and a very efficient nuller, able to detect earth like planets at contrast of 10^{-9} in the visible/IR.

During the PhD, the student will have the possibility to take the leadership of projects around these topics (instrumental and/or observations with K-Stacker).

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