4.2 Project KERNEL

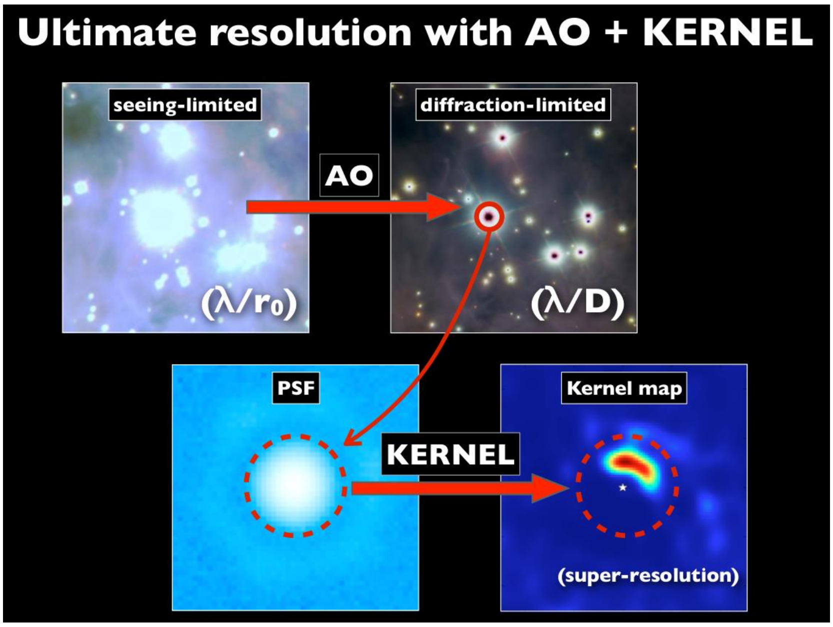

Figure 1: Combined with adaptive optics (AO), a kernel-phase data analysis makes it possible to further improve our understanding of astronomical images, and bypass the generally accepted limit of angular resolution, imposed by the diffraction. This is refered to as "super-resolution".

A Context and state of the art

Astronomy requires large telescopes to improve the sensitivity and the angular resolution of its observations. Of these qualities, angular resolution is the most difficult to maintain in the optical and near-infrared, since the atmosphere reduces it to that of a 10 cm aperture, regardless of the telescope size. This severe restriction has motivated, over the past 20 years, the massive development of a class of techniques generally refered to as Adaptive Optics (AO) : a combination of wavefront sensing and wavefront control techniques that actively compensates for the atmospheric aberrations and makes astronomical images closer to what the theory of diffraction suggests it should be.

Yet it turns out that even in near-ideal conditions, diffraction limited angular resolution by existing observing facilities is not sufficient in solving an important class of problems, that have to do with the identification of faint sources in the direct neighborhood of a bright object, or the discrimination of sources so close to each other that they are qualified of unresolved. The most prominent of such scenarios is the high-contrast imaging of **planets in orbit around nearby stars**, an objective that requires to overcome a double **challenge of contrast and angular resolution**. While with the development of the latest generation of so-called "extreme AO" (XAO) instruments has begun to uncover planets in the outermost regions of very young stars, the inner rocky planets of these systems and their more mature counterparts still elude observation.

Yet, taking full advantage of the resolving power of a large telescope was a goal achieved as early as 1873 by Edouard Stéphan, with a technique now known as masking interferometry. First limited by too small aperture sizes, the technique was revived roughly a century after Stéphan, after the advent of electronic detectors and the first use of an observable quantity inherited from radio-interferometry [1] known as the closure-phase [2]. The fundamental idea behind closure-phase is that although the information encoded in an interferogram may be corrupted by residual aberrations, a sub-set of observables exists that remains independent from these aberrations. On the 8-10 meter class telescopes, such closure-phase extracted from non-redundant masking (NRM) interferometry observations began to reveal otherwise invisible intricate structures of pinwheel nebula [3] or reveal faint companions around bright targets [4], triggering an unprecedented wave of renewed interest in the technique who's future only seemed to lie with long-baseline interferometry.

Drawing from the notions used in the field of astronomical interferometry, a framework created by the PI of this project now makes it possible to extract generalized self-calibrating observables called **kernel-phases** from conventional astronomical images [5]. Bypassing the non-redundancy requirement of the aperture makes the technique significantly more **sensitive** than a mask that typically discards between 70 and 90 % of the light collected. This powerful method results in an effective boost in angular resolution by a factor of ~2 to 3, a regime refered to as **super-resolution** (cf. Figure 1). A complementary application of the method makes it adapted to wavefront sensing purposes, with powerful properties in comparison with more conventionally used approaches [6].

B Current activity

APPLICATIONS TO ASTROPHYSICS :

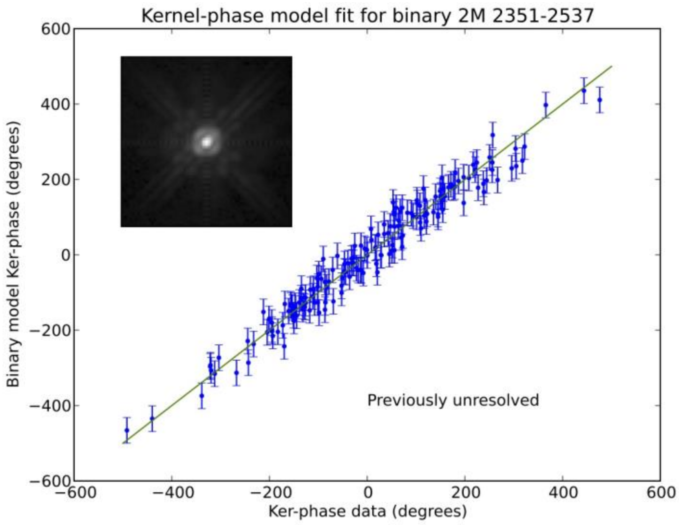

Figure 2: Example of clear yet previously unknown binary detection in a single HST/NICMOS1 image of the L-dwarf 2M 2351-2357. The companion, although invisible in the image is unambiguously retrieved by the kernel-phase analysis of the same original image.

The method was first applied for the reduction of NICMOS (HST) archival data: in the original concept paper, [5] recovers a companion known from PSF fitting procedures of the same data, but with superior relative astrometry, in excellent agreement with orbital parameters characterized from ground based observations.

Applying the data reduction pipeline called PYSCO, developed by the PI for HST/NICMOS data processing to a homogeneous survey of nearby brown-dwarfs, Pope et al (2013) doubled the number of known brown-dwarf binaries (cf. Figure 2), and systematically improved relative astrometric constraints found in the litterature for the previously known binaries.
The approach was also proven to be usable on ground based AO data: using observations of the bright star Ras Alhague (α Oph) performed at the Palomar Hale Telescope, it managed to

recover the companion, that is apparently invisible from visual inspection of images. Pope et al (2016), further enhanced the analysis and benchmarks the kernel-phase detection against NRM-interferometry data acquired using the same instrument, confirming that with sufficient AO correction, the non-redundant mask is no longer required to extract high-quality self-calibrating observables.

APPLICATIONS FOR WAVEFRONT CONTROL :

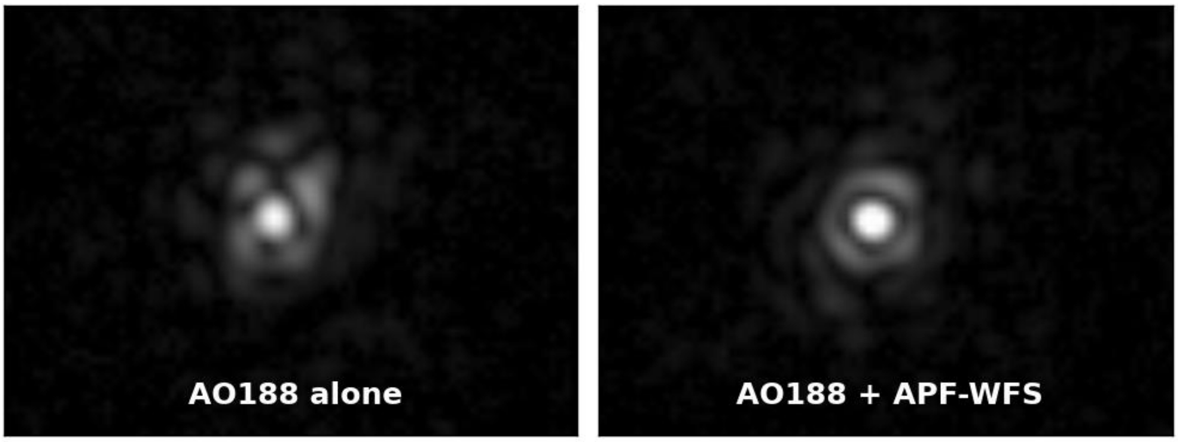

Figure 3: Left: AO closed-loop on-sky PSF acquired by the SCExAO instrument after a telescope repointing. Right: on-sky PSF acquired after running the focal-plane based wavefront control loop relying on the KERNEL framework.

The same framework can also be used for wavefront sensing purposes. The method was deployed on the SCExAO instrument hosted at the Subaru Telescope, for which the proposal PI served as Project Scientist, until his hiring at OCA, September 2013. The Asymmetric Pupil Fourier Wavefront Sensor (APF-WFS) has been successfully deployed during on-sky observations (cf. Figure 3), to drive the instrument main deformable mirror (DM) to a position that optimizes image quality. Because it uses the scientific image for wavefront sensing purposes, APF-WFS is proving to be a powerful feature of the instrument that makes it possible to compensate for the important problem of the non-common path (NCP) error (otherwise invisible to an upstream AO sensor). While seemingly trivial, this NCP-error problem cannot be overlooked, as it is at the origin of the contrast detection limits experienced with exoplanet imaging surveys done with classical AO. This problem has motivated the development of dedicated calibration procedures (phase-diversity) or hardware in extreme AO instruments like SPHERE.

C Future steps

KERNEL is a project that aims at enabling every optical and near-infrared telescope to reach its ultimate angular resolution potential, that goes beyond the diffraction limit, at full sensitivity, using the Fourier-phase framework invented by its PI. KERNEL adopts an interferometric point of view of image formation to permit the extraction of self-calibrating observables called kernel-phases, that are robust against residual optical aberrations. The project has applications ranging from the re-interpretation of archival science data to the development of wavefront control strategies for the giant segmented aperture of large telescopes.

These ambitious objectives will be achieved thanks to:

- a streamlined general use and accessible data reduction process
- a coordinated effort to revisit existing archival AO (or assimilated) data
- an enhanced robustness of the framework that will open new use cases
- further development of applications to high-contrast, wide-field and complex sources
- the development of prescriptions for wavefront control strategies on existing and future observing facilities both on the ground and in space

These require the combined development of:

- an **upgraded Fourier-phase extraction/processing software**
- an **experimental setup** that will validate the concepts, strategies and prescriptions.

The project is organized into a set of five work-packages (WP) that all rely on these two elements and that will lead to four distinct PhD projects. These tools will be maintained and expanded upon over the five-year period covered by the ERC funding :

- **WP1** is all about the scientific exploitation of the pipeline, in a systematic exploration effort of all available archival data acquired in modes compatible with the default kernel-phase analysis. The amount of data covered by this WP is very large and will therefore involve all members of the KERNEL project.
- **WP2** is about going further the original requirements of the default analysis : sufficient image sampling, non-saturation and low-aberration. The latter being the most challenging, but also the most rewarding, as it will going to open new observing vistas, particularly at shorter wavelength with an even enhanced angular resolution. The solution lies with the formulation of spectral or polarimetric differential observables whose exact formulation will be the object of a first PhD project.
- **WP3** will cover the development of a specific high-contrast imaging operating mode, to make it possible to combine the powers of interferometry with that of coronagraphy. The approach relies on the adaptation of a calibration technique used in the context of coronagraphy, that creates off-axis references that can serve as interferometric references. Testing this technique in the lab and on sky on the SCExAO instrument [7] will be the object of another PhD project.
- **WP4** will go beyond the elementary point source detection scenario, and explore the wider landscape of general interferometric image reconstruction. Unlike long baseline optical interferometry with only a few baselines, the KERNEL observing mode acquires a very large number of observables that make it possible to use elegant direct solutions for image reconstruction, that will benefit from the work covered in the other WPs. The formulation of adapted image reconstruction methods and their exploitation will be the object of the third PhD thesis project of KERNEL.
- **WP5** will complete these « science » applications with a focus on the wavefront sensing potential of the Fourier-analysis. A fourth and final PhD project will be dedicated to the study of the multi-reference use-case which will make it possible, from the analysis of a single focal-plane image to perform a complete 3D (tomographic) caracterisation of the atmosphere, required for any type of wide-field AO imaging, that will be also implemented on-sky, this time using the CIAO platform (cf. Theme 4.4).

References

[1] Jennison, A phase sensitive interferometer technique for the measurement of the Fourier transforms of spatial brightness distributions of small angular extent, Jennison (1958), MNRAS, **118**, 276

[2] Baldwin et al, Closure phase in high-resolution optical imaging (1986), Nature, **320**, 595

[3] Tuthill et al., A dusty pinwheel nebula around the massive star WR104 (1999), Nature, **398**, 487.

[4] Pravdo, Shaklan, Wiktorowicz, Kulkarni, Lloyd, Martinache, Tuthill, Ireland, Masses of Astrometrically Discovered and Imaged Binaries: G78-28AB and GJ 231.1BC (2006), ApJ, **649**, 389

[5] Martinache, Kernel-phase for Fizeau interferometry (2010), ApJ, **724**, 464

[6] Martinache, The Asymmetric Pupil Fourier Wavefront Sensor (2013), PASP, **125**, 422

[7] Jovanovic et al, The Subaru Coronagraphic Extreme Adaptive Optics System : Enabling high-contrast imaging on Solar-system scales (2015), PASP, **127**, 890

D International collaborations

While designed to be self-consistent, the project takes advantage of an important network of collaboration with two foreign research groups :

- the team supporting the maintenance and upgrade of the SCExAO instrument at the Subaru Telescope (Hawaii, USA), lead by Prof. O. Guyon. This collaboration ensures access to an advanced experimentation platform on an 8-meter wold class telescope.
- the research group centered around Prof. P. Tuthill of the University of Sydney (NSW, Australia), the current guru of NRM interferometry. This collaboration is at the origin of the co-supervision of students on the frontier between masking and full aperture interferometry.

E List of people involved in the project

- Frantz Martinache (PI) will be spending 70% of his time to this project (5 years).
- One post-doc position is fully funded for the same five year period.
- Four PhD students will be fully funded for three years each over the course of the project.

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F Most significant publications of the team

- « Kernel-phase in Fizeau Interferometry », **Martinache F.**, (2010), ApJ, **724**, 464.
- « The Asymmetric Pupil Fourier Wavefront Sensor », **Martinache F.**, (2013), PASP, 125, 422.
- « Dancing in the Dark: New Brown Dwarf Binaries from Kernel-Phase Interferometry », Pope B., **Martinache F.**, Tuthill P., (2013), ApJ, **767**, 110.
- « The Palomar kernel-phase experiment: testing kernel phase interferometry for ground-based astronomical observations », Pope B., Tuthill P., Hinkley S., Ireland M., Greenbaum A., Latyshev A., Monnier J., **Martinache F.**, (2016), MNRAS, **455**, 1647.
- « A demonstration of wavefront sensing and mirror phasing from the image domain », Pope B., Cvetojevic N., Cheetham A., **Martinache F.**, Norris B., Tuthill P. (2014), MNRAS, **440**, 125.

Short CV of participants

F Martinache, Maître de Conférences (Assistant Professor) at OCA. Expert of high angular resolution imaging instrumentation : interferometry, adaptive optics and coronagraphy. Chair of Excellency awarded by CNRS. Lead of the KERNEL project, funded by the ERC. 37 referred publications.