ED-352 thesis subject

Thesis advisor: Thierry Fusco Email: thierry.fusco@lam.fr HDR: yes	**Co-advisor**: Romain Fétick Email: romain.fetick@lam.fr HDR: no

Laboratory: Laboratoire d'Astrophysique de Marseille (LAM)

Subject's title: A new WFS concept for Extreme AO systems dedicated to direct extrasolar planet imaging on VLT and ELT. From theory to on-sky validation

Subject description:
Adaptive optics [AO] equips the majority of optical instruments for astronomical observation from the ground. Nevertheless, the increase in the size of telescopes with the forthcoming advent of the Extremely Large Telescope [1] [ELT] combined with the ever-increasing demand for ultimate performance in terms of correction of disturbances (whether generated by atmospheric turbulence or by the telescope itself), efficiency and operational robustness, constantly renews the scientific and technical challenges associated with AO. This calls for innovative upstream research, in particular in the field of wavefront analysis and control.

One of the most exciting promises of this new generation telescope is probably the detection of rocky exoplanets around sun-like stars. Although still limited to gas giants because of the "small" diameter of current existing telescopes, the next generation of 39-m ELT equipped with exquisite AO systems will allow for the discovery, the direct imaging and the spectral characterization of planets down to Earth-like masses. Detecting the presence of water, or even complex molecules in an exoplanet would revolutionise our view of the Universe and offer strong evidence for life on other planets. Imaging exoplanets with an ELT is however extremely challenging, and technological breakthroughs are still required. One of the key milestones toward imaging exoplanets is to significantly improve the AO performance. For exoplanet imaging it translates to "extreme" adaptive optics for extreme wavefront control, combining high actuator count deformable mirrors, fast real-time control algorithms, and the use of very high resolution, extremely sensitive and accurate (nanometric precision) Wave-Front Sensors [WFS]. Exoplanet detectability could be improved (x10) with faster (x2-3), more sensitive (1-2mag) and specifically optimised (against noise and aliasing) Wave-Front Sensors.

The very goal of the thesis is to pave the way toward the development the optimisation and the operational exploitation of such devices

Among the recent innovations in WaveFront Sensing for AO, the Fourier Filtering Wave-Front Sensors (FFWFS) are of particular interest [5]. Indeed, they can potentially offer the highest sensitivity while being simple to implement. Nevertheless, to achieve the ultimate

performance of such sensors in terms of sensitivity and accuracy, FFWFS must operate in their peak performance regime (no modulation) and be coupled with Super-Resolution processes recently proposed in the WFS field [6,7]. This will allow access to a wider range of spatial frequencies and thus significantly increase the WFS spatial resolution. If the theoretical performance of these sensors is now well established [8,9], there are still very few operational systems integrating FFWFS and none of them is reaching their full potential. There is thus a strong need in terms of development, lab tests and on sky validation of non-modulated super-resolved FFWFS. This will allow better understanding of its performance and limitations in complex and representative environments and preparing the 3rd generation of instrumentation on the VLT (2025-2030) and the 2nd generation on ELT (2030-2040).

In this context, LAM and ONERA have jointly developed a unique AO-facility in Europe combining laboratory (LOOPS [10]) and on-sky (Papyrus [11]) benches to test new ideas and new components developed for the next generation of AO systems. The LOOPS bench has been used intensively in the LAM premises for more than 5 years now and has demonstrated its ability to trigger and support the development of brand new concepts. In addition to LOOPS, the Papyrus bench has just been released after two and a half years of design, integration and testing. It saw its first astronomical photons at Observatoire de Haute Provence [OHP] in June 2022 (see Figure 1 and PAPYRUS Press Release).

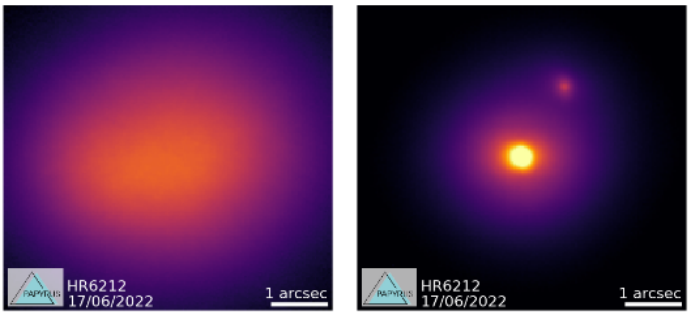

Figure 1: Double Star HR6212, observed the 17th of June 2022 at OHP, without (left) and with (right) AO correction using the PAPYRUS bench. Image in the visible at 635 nm.

PAPYRUS is now in the final phase of validation and characterization in its reference configuration (modulated Pyramid FFWFS associated with a conventional wave-front reconstructor). It will be ready, from early 2023, to host new hardware and software components to further increase its performance and its operability. The thesis objectives are:

1- Proposing, from the earliest concept to the final realisation, of a non-modulated super-resolved FFWFS to be integrated and tested on the LOOPS bench and then the PAPYRUS bench. The activities will include some theoretical developments, the full simulation of the WFS included in the AO loop, the optical design of specific aspects of the WFS, in particular the interfaces between LOOPS and PAPYRUS.
2- On-sky comparison of the new optimised FFWFS and the reference Papyrus configuration (classical modulated Pyramid) and demonstration of the expected gain in performance and robustness

3- Early proposition and simulation of a ELT version of the WFS in the frame of the Planetary Camera and Spectrograph [PCS] preliminary studies.

The student will build on the developments already carried out in the context of SPHERE-SAXO [2,4] development for the VLT and the dimensioning phases of the ELT projects (in particular the HARMONI [12] instrument and its AO suite). Both of them have allowed a fine description and a complete understanding of the problem of extreme AO correction for extrasolar planet direct imaging. Improving the solutions already proposed for the VLT and ELT instruments, or proposing alternative concepts, will be of importance for all future astronomical instruments.

Bibliography:

[1] Tamai et al 2018 “The ESO's ELT construction status”, SPIE Proc. Vol 10700; 1070014 (2018)
[2] Beuzit et al 2019 ”SPHERE: the exoplanet imager for the Very Large Telescope”, A&A, 631, A155
[3] A Bohn et al 2020 “Two Directly Imaged, Wide-orbit Giant Planets around the Young, Solar Analog TYC 8998-760-1”, ApJL 898 L16, https://iopscience.iop.org/article/10.3847/2041-8213/aba27e/pdf
[4] T Fusco et al 2014 “Final performance and lesson-learned of SAXO”, SPIE Proc. Vol 9148
[5] Fauvarque 2017 “Optimisation des analyseurs de front d'onde à filtrage de Fourier”, PhD Thesis
[6] S Oberti et al 2022 “Super-resolution wavefront reconstruction“, A&A, to be published
[7] C Correia et al 2022 “Super-resolution wavefront reconstruction in AO with pyramid sensors”, SPIE 2022 (Montreal), to be published
[8] V Chambouleyron 2021 “Optimisation de l'analyse de surface d'onde par filtrage de Fourier“, PhD Thesis, https://www.theses.fr/s213980
[9] V Chambouleyron et al 2022 “Optimizing Fourier-Filtering WFS”, SPIE 2022 (Montreal), to be published
[10] P Janin-Potiron et al “AO with programmable Fourier wavefront sensors”, JATIS, 5(3), 039001 (2019)
[11] E Muslimov et al 2021 ”Current status of PAPYRUS” SPIE Proc. Vol 11876
[12] N Thatte et al 2021 “HARMONI: the ELT's First-Light NIR and Visible IFS”, ESO Messenger No. 182
[13] M Houllé et al 2021 “Direct imaging and spectroscopy of exoplanets with ELT”, A&A 652, A67 (2021)

Justification of the scientific importance of the subject and/or its strategic interest:

The proposed developments will naturally be used for the High Contrast mode of the HARMONI project [13] but can be extended to the future Planet Finder system AO that will see the light of day in the next two decades: SPHERE+, and RISTRETTO projects on the VLT, ANDES and PCS on the ELT to quote only the principal ones.

Description of the work environment (resources, collaborations…) of the thesis:

The student will have access to all the means of the CELTIC centre (joint laboratory LAM/ONERA for Adaptive Optics) and of the ANR WOLF (https://anr-wolf.com/) with in particular the laboratory bench LOOPS and the PAPYRUS AO system installed on the 1.52m telescope of the OHP.

Thierry Fusco has a strong experience in PhD supervision with highly productive students who completely renewed the way of performing wavefront sensing for astronomy. The LAM is now a worldwide leader on the WFS topic due to this experience.

Romain Fétick defended his PhD in 2020 at LAM and is highly involved in the supervision of the current thesis of Alexis Lau that will end in one year from now.