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RECONCILING CORONAGRAPHY AND KERNEL-PHASE FOR DIRECT DETECTION OF EXOPLANETS

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Abstract. The kernel-phase and coronagraphy are considered profoundly incompatible. We present three approaches aimed at combining the two methods despite their incompatibility:

*We applied kernel-phase in a more benign case of transfer function destruction: saturated images. Using an advanced interpolation technique, we mended archival images and were able to apply kernel-phase analysis and detect a stellar companion around Gl 494 well beyond the reach of classical methods.

*One technique used with coronagraphy, Angular Differential Imaging, is used to self-calibrate observations using the field rotation. We have designed a kernel-phase version of this algorithm and are currently evaluating its on-sky performance.

*The "shaped pupil" apodizing masks, only change the shape of the telescope's aperture in order to obtain a more favorable PSF and do not destroy the Transfer Function. We designed one specifically to work with kernel at the SCExAO instrument, and to evaluate the performance boost.

Keywords: High angular resolution, high contrast, image processing, kernel-phase

1 Introduction

Even for the most nearby systems, the direct detection of exoplanets at Solar-system scales requires very high contrast sensitivity ($c \leq 10^{-6}$) at small angular separations ($\rho \leq 1$ arcsec).

Suppressing the diffraction of the central bright star, coronagraphs theoretically address the contrast problem. They are however highly vulnerable to the unavoidable residual wavefront errors left by adaptive optics. Alternatively, the kernel-phase approach that generalizes the idea of closure-phase, is built around robustness to small wavefront errors (Martinache 2010): its high-contrast detection is limited by the photon noise.

Unfortunately, this approach cannot be applied to the processing of coronagraphic observations because coronagraphs destroy the transfer function usually provided by imaging instruments. This work explores synergies that can be developed despite this limitation between kernel-phase and coronagraphy through the use of apodization masks, extended image dynamic range enabled by partial saturation, and borrowed post-processing techniques like ADI.

2 Blind saturation recovery

In coronagraphy, the transfer function of the instrument is destroyed, making Fourier domain techniques irrelevant. We experimented with a less dramatic case of transfer function invalidation: the case of saturated images.

In conditions where the Point Spread Function was sufficiently stable (Hubble Space Telescope), we were able to reconstruct saturated images to detect (Fig.1) and characterize a companion to Gl494 (Laugier et al. 2019) on archival images dating from 1997, years before its first direct measurement in 2000 by Beuzit et al. (2004). This new measurement at older epoch improves the constraints on orbital and physical properties of these red dwarf stars.

3 Angular Differential Kernel (ADK)

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Angular Differential Imaging (Marois et al. 2006) and its variants are used extensively in coronagraphy. We are currently experimenting with an algebraic projection based on the same principles of field rotation to calibrate the static instrumental biases on the scientific target itself, while retaining the statistical properties of the analysis. SCExAO observations of the binary star 3 Ser show good performance despite the poor observing conditions (Low Wind Effect) mitigated here by frame selection.

The resulting maps shown in Fig.2 show a calibration performance on par with the classical method, without the need to find and oserve a calibrator.

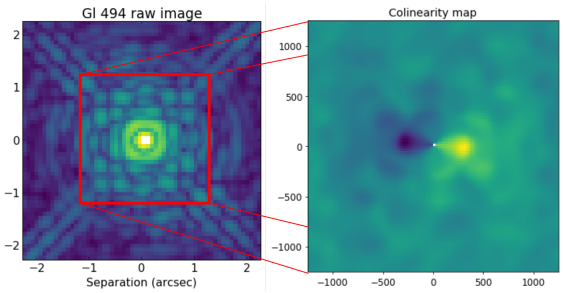

Fig. 1. Image of Gl 494 with saturation in 4 pixels shown in white (left), and a matched filter map revealing the companion at $\approx 55\times$ and separation of $\approx 1.3\lambda/D$.

4 Apodization mask for improved contrast

Binary (shaped pupil) masks (Carlotti et al. 2011) simply modify the transfer functions and are therefore compatible with kernel-phase analysis. We designed a mask with a geometry suited to the kernel-phase analysis and installed it as part of the SCExAO instrument at the Subaru telescope (Fig.3). The mask provides somewhat uniform 10^{-4} contrast in the the PSF over an annular region contained between 3 and 7 λ/D. The relative simplicity of the geometry of the mask makes it easy to build the discrete representation for the extraction of kernel-phase. A prototype was laser-cut and installed in the pupil mask wheel of SCExAO for on-sky experimentation. Preliminary tests suggest that the detection limits of kernel-phase are indeed boosted by the apodizer.

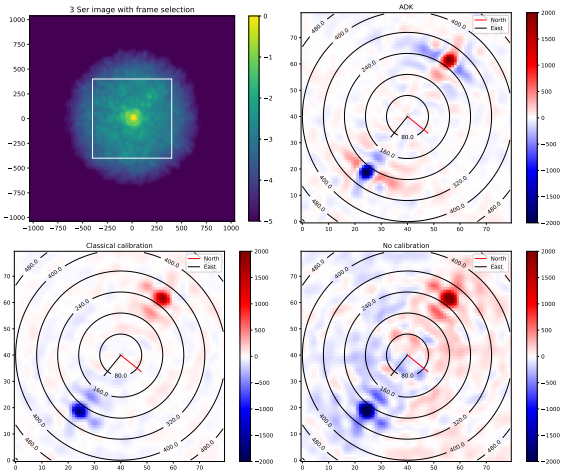

Fig. 2. On-sky image of 3 Ser with the Region of Interest (upper left), kernel colinearity maps of the ADK signal (upper right), classical calibration (lower left) and raw signal (lower right) showing the x62 contrast companion as a red spot.

References

Beuzit, J.-L., Ségransan, D., Forveille, T., et al. 2004, Astronomy & Astrophysics, 425, 997

Carlotti, A., Vanderbei, R., & Kasdin, N. J. 2011, Optics Express, 19, 26796

Laugier, R., Martinache, F., Ceau, A., et al. 2019, Astronomy & Astrophysics, 164, 1

Marois, C., Lafreniere, D., Doyon, R., Macintosh, B., & Nadeau, D. 2006, The Astrophysical Journal, 641, 556

Martinache, F. 2010, The Astrophysical Journal, 724, 464

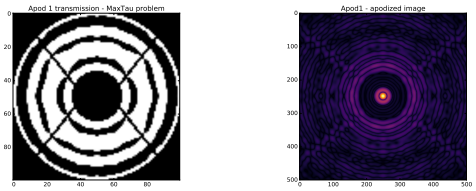

Fig. 3. The binary pupil mask designed with M. N'Diaye's implementation of the Carlotti's algorithm for the Subaru SCExAO pupil (left), the apodized PSF (right). The mask was optimized for a moderate contrast boost and simple shapes.