Direct Imaging of Exoplanets: Science & Techniques
Proceedings IAU Colloquium No. 200, 2005
C. Aime and F. Vakili, eds.

doi:10.1017/S174392130600980X

An off-axis four-quadrant phase-mask coronagraph: concept and first results

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Abstract. We have recently deployed a four-quadrant phase-mask coronagraph behind an unobscured, circular, off-axis section of the Palomar 200-inch telescope. To obtain very good wavefront correction across the 1.5 m subaperture, our relay optics reimage the sub-aperture onto the adaptive optics system's deformable mirror. This approach combines the advantages of low diffraction from obscuring elements, due to the off-axis aperture, with high wavefront correction, due to the magnification of the pupil, and high stellar rejection, due to the phase mask coronagraph. Our initial on-sky results include Strehl ratios exceeding 90%, peak stellar rejections of >100:1, and an improvement in contrast of 235:1 on a binary of separation $2\lambda/D$.

Keywords. coronagraphy.

1. Introduction

The goal of direct exoplanet detection requires the development of high-contrast imaging techniques such as coronagraphy. To detect faint planets in close proximity to bright stars, observations at a small inner working distance (IWD) and high contrast ratio are needed. Coronagraphic techniques show great promise in this regard, but coronagraphic observations on real telescopes tend to be limited by a number of factors such as a large IWD and wavefront errors which scatter large amounts of light. To image close to bright stars, three things are needed: a coronagraph to improve the intrinsic planet/star contrast ratio, a very good adaptive optics (AO) system to reduce scatter, and a means of reducing diffracted light from beam obscurations such as the secondary mirror. Our approach addresses and mitigates all three of these factors.

One obvious approach to better wavefront correction is to increase the number of elements in the AO system's deformable mirror (DM). However, another approach, which can be implemented quickly and cheaply, but which has not heretofore been pursued, is to reimage a smaller section of the primary mirror onto the DM, thereby reducng the effective spacing of the DM elements. Specifically, if the targeted subaperture is an unobscured quadrant of the primary mirror (between the spider support legs) in a Cassegrain telescope, a well-corrected, unobscured, off-axis telescope is generated, thus completely eliminating diffraction from vignetting elements, while also reducing scatter because of the closer actuator spacing. Note that while producing improved performance across a subaperture, no additional demands are placed on an already extant AO system. With e.g., the existing Palomar AO system (Troy *et al.* 2000), wavefront accuracies of under 100 nm and Strehl ratios >0.9 in the K band (2.2 μm) are expected.

In fact, at least one recent coronagraphic approach is ideally suited to an unvignetted, off-axis telescope configuration – the four-quadrant phase-mask (FQPM) coronagraph (Rouan it *et al.* 2000, Boccaletti *et al.* 2004)), which introduces phase shifts of π radians in two diametrically opposed quadrants of the focal plane (Fig. 1). Because there

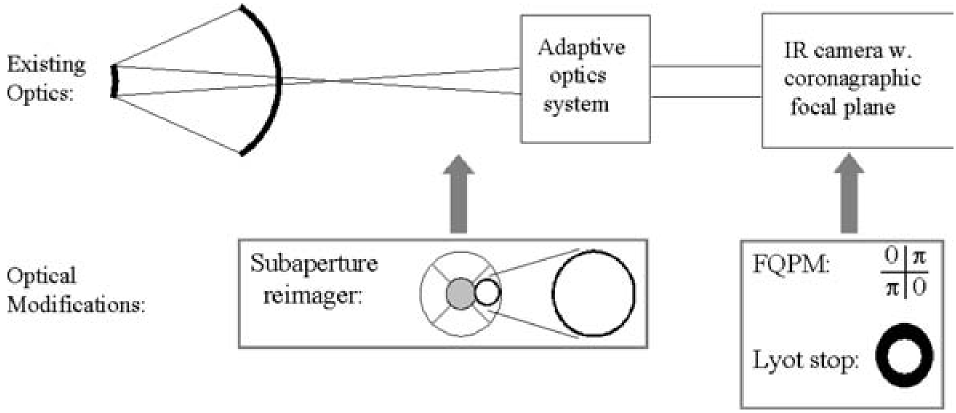

Figure 1. Optical schematic. Relay optics are inserted ahead of the existing AO bench to reimage the sub-pupil onto the DM, and the coronagraphic components are inserted into PHARO.

is no opaque starlight blocker in the FQPM approach (the star sits at the crosshairs of the phase plate), this approach is suited to observations very close to the optical axis (Riaud *et al.* 2001). However, the performance of a FQPM coronagraph is degraded by the presence of an on-axis secondary mirror (Lloyd *et al.* 2003). Thus, our proposed combination of an off-axis pupil with a FQPM coronagraph provides a solution for exploring the regions close to a bright star, by combining a high degree of wavefront control from the denser AO system, the total elimination of diffracted light from vignetting optical elements, and a small IWD from the phase-based coronagraph.

We therefore decided to test the performance of this off-axis FQPM approach on the sky. Fig. 1 shows the necessary components: a set of relay optics to magnify an off-axis sub-pupil onto the AO system's DM, a FQPM in the coronagraphic focal plane, and a clear, undersized Lyot stop in the pupil plane. The masks were fabricated and the optics tested at JPL over the past two years, after which the equipment was installed at Palomar (Haguenauer *et al.* 2005): the ambient-temperature relay optics module on the Palomar AO bench, and our phase and pupil masks in the cryogenic near-IR camera PHARO (Hayward *et al.* 2001). We carried out our first observations with this instrumentation on the Palomar 200-inch telescope on the nights of June 13–15, 2005.

2. Results

First we observed single stars, in order to determine the image quality obtainable on a well-corrected, unobscured sub-aperture. One of our "subaperture" images of the single star HD121107 is shown in Fig. 2, where an almost classical Airy pattern is evident. Indeed, as many as 7 Airy rings are seen quite distinctly, and bits of rings as far out as the 9th ring can be discerned. The Strehl ratio for our best images were in the 93% to 94% range, corresponding to a wavefront correction of $\approx$ 85 to 90 nm, significantly better than has previously been possible from the ground with the wider actuator spacings.

Next, we sent the light from this (and other) stars through the crosshairs of our FQPM coronagraph. One of our resultant images is shown in Fig. 3 (top center), where a peak rejection of 85 was obtained. The rejection depended somewhat on the seeing, as well as on our alignment onto the crosshairs, and in other images the rejection exceeded 100:1 slightly. However, this image is presented here because the symmetry of the residuals in this image allowed better stellar suppression after the next step – subtraction across

https://doi.org/10.1017/S174392130600980X Published online by Cambridge University Press

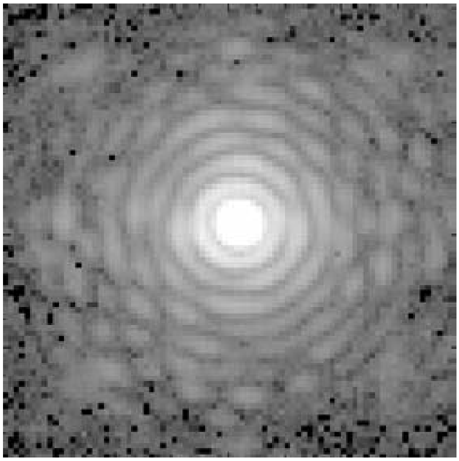

Figure 2. Image of the star HD121107 using our 1.5 m subaperture reimager on the Hale 200 inch telescope. The image is the sum of 20 individual integrations, each of 1.4 s duration. The best Strehl ratios obtained on such images were in the 93% to 94% range.

an image diagonal. In the top right-hand image, the central image has been subtracted across the diagonal of greatest symmetry, resulting in a final stellar supression of 220:1.

Finally, we observed binary stars, including HD148112. In the raw image of this binary shown in the bottom left panel of Fig. 3, the binary separation is seen to be $\approx 2\lambda/D$. The bottom center image shows the image of HD148112 transmitted by the FQPM coronagraph, and the lower right-hand image shows the subtraction across the diagonal of greatest symmetry in the coronagraphic residuals. While the dim companion is already visible in the raw (bottom left) image, the central and right hand images show the great contrast improvement which results from the FQPM coronagraph. The brighter star has a final peak suppression of 235:1, changing the binary contrast ratio from 23:1 to 1:10 in the opposite direction. In the final image, the dim companion completely dominates over the primary residuals, indicating that it should be possible to use this approach to detect much fainter companions even closer to bright stars.

3. Conclusions

Our first observing run with our off-axis FQPM coronagraph has allowed the demonstration of a well-corrected off-axis 1.5 m subaperture with Strehl ratios as high as 93% to 94%, and wavefront accuracies as good as 80 nm. Instantaneous peak stellar rejections of 100:1 were obtained, and the best (diagonal-subtracted) stellar rejection was 235:1. It is evident from the lower row of images in Fig. 3 that this approach allows high contrast observations very close to bright stars. We expect to obtain significant performance improvements beyond this level as we improve our instrumentation. Moreover, use of this technique on an off-axis section of a ten-meter class telescope should really bring its advantages to light, because an IWD of even $1\lambda/D$ with a 4 m off-axis sub-aperture is significantly closer to the axis than an IWD of e.g., $4\lambda/D$ using the full aperture.

Acknowledgements

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

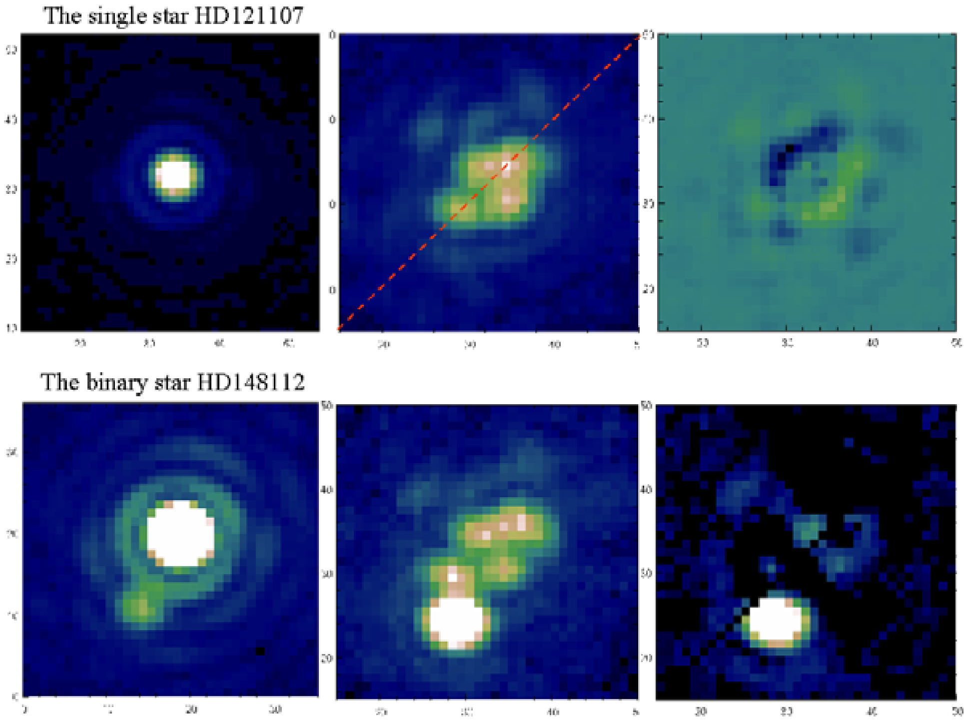

Figure 3. Top row: images of the single star HD121107. Top left: raw image, bypassing the coronagraph. Top center: raw image through the FQPM coronagraph. Top right: center image subtracted across the diagonal of greatest symmetry in the residuals. Bottom row: images of the binary star HD148112. Bottom left: raw image, bypassing the coronagraph. Bottom center: raw image through the FQPM coronagraph. Bottom right: center image subtracted across the diagonal of greatest symmetry in the residuals.

Observations at the Palomar Observstory were made as part of the continuing collaborative agreement between the Palomar Observatory and the Jet Propulsion Laboratory.

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