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High-contrast Imaging with a Small, Well-corrected Subaperture and a Phase-mask Coronagraph

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Abstract. We used the 1.6-meter-diameter off-axis well-corrected subaperture (WCS) on the Palomar Hale telescope with a small inner-working angle (IWA) coronagraph to provide high-contrast images of known brown dwarf companions (HD 130948, HD 49197, and HR 7672) and the first images of the scattered light from HD 32297 debris disk obtained in the Ks band. While providing new constraints for this system, our observations also demonstrate the advantage of this particular instrument configuration.

Keywords: High-contrast imaging, adaptive optics, coronagraphy, brown dwarf, debris disk.

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INTRODUCTION

The Palomar well-corrected subaperture (WCS) has been described earlier [1]. In short, an unvignetted, off-axis WCS is provided by means of a set of relay optics inserted upstream of the Palomar adaptive optics system (PALAO). The off-axis relay (OAR) magnifies and shifts an off-axis sub-aperture pupil onto the PALAO deformable mirror (DM), yielding a roughly 10-cm actuator spacing in the selected pupil. This configuration, while reducing the effective aperture size from 5 meters down to 1.6 meters, allowed operation in the extreme adaptive optics (AO) regime before other such systems come online (e.g. SPHERE, GPI, etc.). While providing unprecedented image quality on a ground-based telescope (Strehl ratio above 90% are routinely obtained), this off-axis setup is also ideal for use with phase-mask coronagraphs such as, for example, the four-quadrant phase mask coronagraph [2, FQPM]. This is because phase masks work best with unobscured apertures, and allow for very small IWA. The FQPMs we used for these observations were manufactured at JPL. All astronomical observations were acquired using the K_s filter, for which those masks resulted in maximum peak-to-peak (constructive peak to highest residual peak) laboratory and stellar rejections of order 40 – 50.

BROWN DWARF IMAGING

This WCS-FQPM tandem system previously allowed us to reach an IWA of $\sim 2\lambda/d$, and so to enable observations of faint brown dwarf companions with a detection limit similar or slightly superior to the full Palomar pupil, and similar even to the much larger

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FIGURE 1. Left: our WCS-FQPM Ks band image of HD 130948. Middle: HD 49197. Right: HR 7672.

Keck telescope [3]. Figure 1 (left) shows our resulting WCS PSF-subtracted image of HD 130948. The (slightly resolved) BD companion pair is clearly easily detected in our image, with a separation from the primary of $2''.45 \pm 0.1$ at P.A. $\sim 105^\circ \pm 2^\circ$, and a flux ratio $\Delta K_s = 7.37 \pm 0.1$, all of which are very consistent with the earlier image [4]. As seen in Figure 1 (left), bright PSF residuals are confined to within a radius of $\sim 2\lambda/D$ of the stellar position, while beyond $\sim 2\lambda/D$, the image largely shows a fairly uniform field of faint speckles. HD 49197 has a known BD companion [5] much closer to the primary (at $\sim 3.4\lambda/D$ for the WCS). Figure 1 (middle) shows our large-scale image of HD 49197. In this image, the WCS inner working angle is $\sim 2\lambda/D$ of the center. The brightest spot in our image beyond $\sim 2\lambda/D$ (at radius $0''.96 \pm 0.1$ at P.A. $\sim 77^\circ \pm 2^\circ$, with $\Delta K_s = 8.2 \pm 0.2$) is fully consistent with the location and relative brightness of HD 49197C. The brown dwarf near HR 7672 was the most challenging case, because of its small angular offset and high contrast ratio: $r = 790 \pm 5$ mas at P.A. $= 157^\circ.5 \pm 0.5$; $\Delta K_s = 8.62 \pm 0.07$ mag; [6]. For the WCS, this BD thus lies at $\sim 2.8\lambda/D$. Figure 1 (right) shows our WCS image, in which an isolated bright spot (at $r = 750$ mas ± 80 mas, P.A. $= 155^\circ \pm 5$, with $\Delta K_s = 8.7 \pm 0.2$ mag) is found to coincide almost exactly with the known location of HR 7672B [6, 7]. This source is the brightest object in the immediate vicinity of the central $\sim 2\lambda/D$ "exclusion" zone, except for the wing of one of the two bright FQPM residuals centered inside the (arbitrarily selected) $2\lambda/D$ circle.

THE DEBRIS DISK AROUND HD 32297

HD 32297 is an A5 star [8] located at a distance $d = 113 \pm 12$ pc [9]. This star presents a far-infrared excess emission above the photospheric level, $f_{ir} = L_{d,ir}/L_{*,ir} \geq 0.0027$, calculated from 25 and 60 μm fluxes obtained with IRAS. It was observed quasi-simultaneously by [10] in the near-infrared J band with NICMOS (*HST*) and by [11] in the R band with the University of Hawai'i 2.2-meter telescope, respectively. Both observations showed the scattered light originating from a nearly edge-on disk. The NICMOS image revealed an asymmetric edge-on disk detected at about 300 mas from the star (34 AU) to $3''.3$ from the star (400 AU) to the northeast (NE) and $2''.5$ toward the southwest (SW). The major axis position angle is reported to be $47.6^\circ \pm 1^\circ$. From the photometric standpoint, [10] report a $f_{ir} = L_{d,1\mu\text{m}}/L_{*,ir1\mu\text{m}} \geq 0.0033$ in the J band. The

FIGURE 2. Calibrated Ks band image of HD 32297, resulting from our data reduction pipeline (see text for details). The disk is resolved from our inner working angle of 400 mas (~ 45 AU) to $\sim 1''.5$ (~ 170 AU). The NE truncation is detected, as well as the NE-SW asymmetry. The linear scale is in ADU.

asymmetry is marked by the integrated photometry, with $3.14 \text{ mJy} \pm 0.57 \text{ mJy}$ for the southwest side and $1.67 \text{ mJy} \pm 0.57$ for the NE. [12] and [8] report images of HD 32297 at mid-infrared wavelengths, and both show rather symmetric disk lobes extending up to 150 AU in radius. The common conclusion of these papers is a ring of warm dust, with a density peak at $0''.5\text{-}0''.6$, suggesting a depletion inside this radius (~ 70 AU). A recent paper from [13] presenting the high angular resolution mm map shows the same SW-NE asymmetry as the J-band image of [10].

We observed HD 32297 at Palomar in September and November 2008 in the Ks band with our WCS-FQPM tandem. This instrumental configuration allowed us to observe the innermost region of HD 32297 in the Ks band for the first time. Our resultant calibrated Ks-band image is shown in Figure 2. The disk is clearly detected from our IWA of ~ 400 mas ($\sim 1.5 \lambda/d$), i.e. ~ 45 AU to $\sim 1''.5$ (~ 170 AU). Our observation compares favorably to the *HST* image in terms of IWA and quality [10], although the resolution is a factor of three lower due to our smaller aperture and longer wavelength. The measured position angle of 50 ± 3 degrees is consistent with previous values [10, 8, 12]. Furthermore, the NE lobe of our disk image appears to extend no closer to the center than $\sim 0''.6$ (65 AU), suggesting an inner hole in the disk, consistent with inferences in [10], and [8, 12]. Finally, a SW-NE asymmetry is clearly present in our image, both in terms of brightness and minimum emission radius (< 400 mas or < 45 AU for the SW lobe and $\sim 0''.6$ or ~ 65 AU for the NE lobe). The contrast between asymmetry at short and long wavelengths and symmetry at mid-IR wavelengths is in qualitative agreement with predictions of resonant debris disk models such as that of [14]. As stressed by [13], HD 32297 provides a unique testbed for theories of grain and planetary dynamics, and could potentially provide strong multi-wavelength evidence for an exoplanetary system (Mawet et al., in prep).

CONCLUSIONS

We obtained near-infrared images of brown dwarfs and a disk using a small well-corrected subaperture on a large telescope, which concentrates the power of the existing AO system to correct the off-axis section of the primary to ExAO levels. In conjunction with very small inner-working angle coronagraphs such as the four quadrant phase-mask coronagraph, this instrumental configuration can evidently provide valuable scientific results, e.g. for HD 32297, completing a picture that seems more and more consistent with an outward migrating planet trapping planetesimals in a mean motion resonance [14]. The results obtained here are certainly a motivation to further investigate this amazing HD 32297 system, which is clearly showing its applicability as a testbed to understand planet/disk interactions. On the instrument side, further observations can of course be obtained on the well-corrected subaperture at shorter wavelengths to improve resolution, but even more interesting would be the implementation of one on a much larger telescope. Moreover, even better phase mask coronagraphs are being developed [15] allowing much improved performance to be anticipated. Finally, planned ExAO systems on 8-10 meter class telescopes will no doubt provide further improvements.

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