# High Contrast Coronagraphy and Extreme Adaptive Optics Experiments at Palomar

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## ABSTRACT

The next generation of adaptive optics (AO) systems, often referred to as extreme adaptive optics (ExAO), will use higher numbers of actuators to achieve wavefront correction levels better than 100 nm, and so enable a variety of new observations, such as high-contrast coronagraphy. However, the number of potential coronagraph types is increasing, and selection of the most promising coronagraph is subject to many factors. Here it is pointed out that experiments in the ExAO regime can be initiated with existing AO systems, by correcting a subaperture on an existing telescope rather than the full pupil. With a 1.5-m diameter well-corrected subaperture (WCS) on the Palomar Hale telescope, we have recently achieved stellar Strehl ratios as high as 92% to 94% in the infrared, corresponding to wavefront errors of 85–100 nm, and have carried out visible wavelength AO observations. With a WCS, a wide variety of ExAO experiments can thus be carried out immediately, including infrared ExAO imaging and performance optimization, a comparison of coronagraphic approaches in the ExAO regime, and visible wavelength AO.

## INTRODUCTION

The direct detection of very faint companions close to much brighter stars requires very high-contrast observations at small angular separations, and a number of novel coronagraphs have recently been proposed to meet this requirement (e.g., Guyon, these proc.) The main limitation to high contrast coronagraphic observations on ground-based telescopes is the wavefront quality achievable after correction by the AO system, as scattering from both phase errors and pupil obstructions degrade the image quality. In particular, classical coronagraphs provide significant contrast improvement1 only for Strehl ratios above about 90%, a level not yet available with the current generation of AO systems. Thus, it had been thought that very high contrast coronagraphy might need to await the arrival of next-generation ExAO systems.

On the other hand, a more highly corrected wavefront can already be obtained by using an existing AO system to more finely correct a sub-aperture smaller than the full telescope pupil. Vignetting can also be eliminated by means of a clear off-axis sub-aperture. With such a clear off-axis, well-corrected sub-aperture (WCS) a dual image improvement is thus obtained: scattering due to both wavefront aberrations and pupil blockages is eliminated. Figure 1 shows the expected Strehl ratio improvement for the case of the Palomar 200-inch telescope, while Figure 2 shows potential Strehl ratio vs. wavelength. Evidently infrared Strehl ratios exceeding 90%, and visible Strehl ratios of order 50% are achievable with a WCS, implying that a WCS can be employed to immediately carry out ExAO-level experiments such as high-Strehl infrared imaging, high-contrast coronagraphy, and visible AO. Given this promise, we have recently implemented a WCS with a diameter of 1.5 m on the Hale telescope, using an appropriate set of relay optic[2, 3, 4].

## OBSERVATIONAL RESULTS

Several initial ExAO experiments have now been carried out with our WCS at Palomar. A few examples are presented here.

1. **High Strehl infrared observations:** Figure 3 shows an image of the single star HD 121107 obtained with our WCS. The image closely resembles a diffraction-limited Airy pattern. Strehl ratios as good as 92–94% were obtained, corresponding to wavefront errors in the 85 – 100 nm range.
2. **Visible AO:** Figure 4 shows a B-band image, obtained with our WCS, of a binary star with a separation of 0.34 arc sec. Our WCS clearly provides good AO correction even at blue wavelengths.

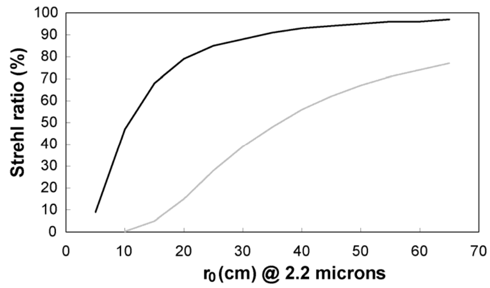


***Figure 1:*** *Strehl ratios obtainable with the full Palomar 200 inch telescope (bottom curve) and a sub-aperture of diameter 1.5 m (top curve) vs. $r_0$, the atmospheric seeing cell size.*

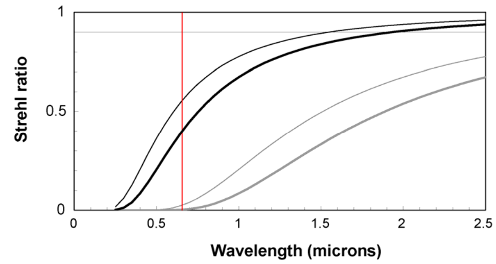


***Figure 2:*** *Strehl ratios obtainable with a WCS for rms wavefront accuracies of 80, 100, 200 and 250 microns (curves, top to bottom). The Hα wavelength is marked by the vertical red line, and the dotted horizontal line is at a Strehl ratio of 90%, above which coronagraphic contrast improvement begins to become significant.*

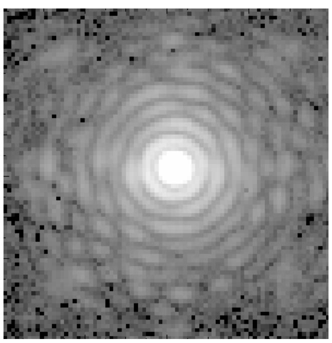

***Figure 3:*** *Image of HD 121107 with our WCS in the 2.17 mu Br γ filter.*

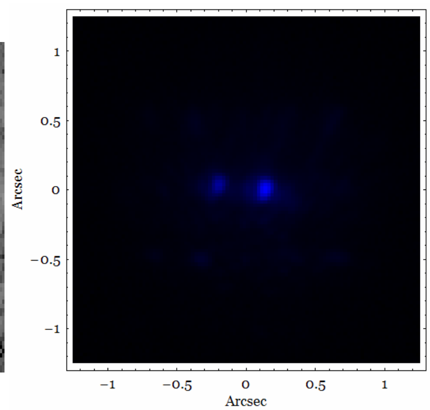


***Figure 4:*** *B band AO-corrected image of SAO 37735 through our WCS.*

3. **Coronagraphy:** We also carried out initial infrared coronagraphic observations with our WCS using a four-quadrant phase mask (FQPM) coronagraph[5,6], because this type of coronagraph calls for an unobscured circular aperture for high rejection. Figure 5 shows our observations of the binary star HD 148112: the left-hand panel shows the normal "off-coronagraph" image, the central panel shows the "through-FQPM" image, and the right-hand panel shows the through-FQPM image after cross-diagonal subtraction. The coronagraph allows the fainter companion at ≈ 2λ/D to emerge as the brightest source in the field by a factor of 10.

**SUMMARY**

With a WCS of diameter 1.5 m on Palomar's Hale telescope, we have been able to carry out several ExAO-level experiments, including high-Strehl IR imaging, high stellar rejec–tion with an infrared coronagraph, and visible AO. Many other experiments are now also possible, such as dark hole generation, implementation of other types of coronagraph, and wave front sensor optimization in the ExAO regime. Of course, implementing such a system on a larger telescope is also an option.

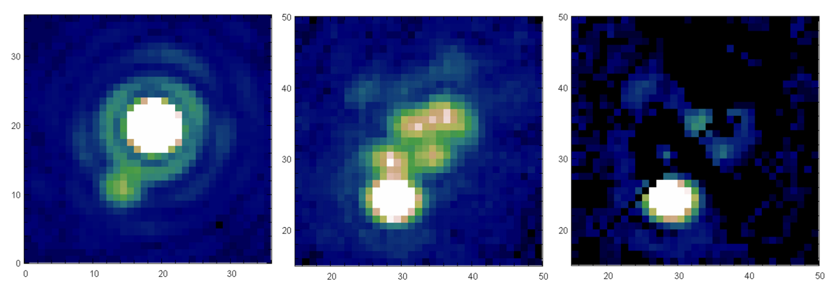

***Figure 5:*** *WCS observations of the binary HD 148112 in the Br γ filter. Left: normal (no FQPM) image. Center: through-FQPM image. Right: cross-diagonal subtraction of FQPM image. The highest residual peak is down by 235:1.*

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