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Detecting exoplanets with high contrast coronagraphy

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Abstract

The first images of exoplanets are now in hand, but the imaging of even fainter planets near bright stars requires the development of very high contrast detection techniques. The two necessary aspects are precise wavefront control and efficient starlight rejection. These essential aspects were recently demonstrated at the Palomar Observatory on a 1.5 m diameter "well-corrected subaperture" on the Hale telescope. "Extreme" adaptive optics wavefront correction was achieved using fine-scale wavefront correction on the subaperture, combined with phase-retrieval to reduce non-common path errors such as faint speckles. Starlight rejection has been maximized with a novel vector vortex coronagraph, precise tip-tilt and focus control within the coronagraph, and the "locally optimized combination of images" speckle calibration algorithm. The Palomar system provides small-angle contrast sensitivities comparable to those of much larger telescopes, allowing the imaging of e.g., the three HR8799 planets and the HD32297 disk. These results provide a first validation of the steps needed to achieve high-contrast in on-sky observations, and illustrate the promise of future ground- and space-based high-contrast instruments.

1 Introduction

Observations of faint exoplanets near much brighter stars require a very high-contrast observational capability. The ultimate goal of contrasts of order 10^{-10} at angles of order 100 milli-arcseconds (mas) and smaller, needed to enable the detection and characterization of terrestrial planets in nearby solar systems, is far beyond current observational capabilities. To reach such extreme contrast levels, a dedicated space telescope will likely be needed, but less demanding contrast levels will be achieved by ground-based observatories over the next several years as observational capabilities improve.

In order to reach high contrasts, progress is needed in two areas: use of the best possible coronagraph, and achievement of a very high degree of wavefront correction. The first is needed to suppress the ideal stellar diffraction pattern, while the latter is needed to suppress scattered starlight. Due to the combination of residual diffracted and scattered starlight, coronagraphic systems relying on current generation adaptive optics (AO) systems typically provide contrasts falling roughly in the range of 10^{-5} to 10^{-6} at 0.5 to 1 arcsec. Such contrasts have succeeded in detecting a small number of young, massive jovian-like planets [6, 10, 8], but more typical planets fall below these detection limits.

Due to their higher degree of wavefront control, next generation "extreme" adaptive optics (ExAO) systems [9, 1, 5, 2] will be able to reduce scattered starlight significantly, thus allowing coronagraphs to operate closer to their limits. Moreover, over approximately the last decade, several new types of coronagraph have been invented, many of which are superior to classical "Lyot" coronagraphs in inner working angle (IWA), i.e., the closest to a star that a planet can be detected, and/or in the throughput of planetary light [4].

However, the high-contrast ExAO systems planned at several large telescopes are novel, complex, and costly, and so preliminary demonstrations and validations on a smaller scale would be very advantageous. Over the past several years we have thus assembled a small-scale ExAO system at the Palomar Observatory [14, 15], in order to rapidly and inexpensively demonstrate and validate the techniques of high-contrast coronagraphy operating very close to stars. This paper summarizes recent progress with our ExAO system, which relies on a phase-based coronagraph to reach small angles even with our rather small (1.5 m) telescope aperture, and which relies on a number of wavefront correction steps to reduce the scattered starlight level significantly.

2 A vortex coronagraph on the Palomar "well-corrected sub-aperture"

To enable wavefront correction to ExAO levels (e.g., $<$ 100 nm rms) with an existing AO system, it is only necessary to reconfigure the optical system to correct a smaller part of the telescope, instead of the entire aperture [14]. This is the approach taken at Palomar, where we correct an unobscured 1.5 m off-axis section of the Hale 200 inch telescope (Fig. 1) with the existing AO system. This approach routinely provides infrared Strehl ratios of order 0.9, thus improving wavefronts to the point that coronagraphs can perform effectively. Moreover, the Strehl ratios are generally quite stable, with an rms of order 1%.

To compensate for the relatively small aperture, we make use of phase mask coronagraphs, which can reach small angles because of their lack of an opaque central blocker. We began our work with four-quadrant phase mask coronagraphs [10, 11] and then moved on to the vector vortex coronagraph [12] (Fig. 2), which is one of the most promising coronagraphs known [4], because of its simplicity, small inner working angle, high throughput and unobscured off-axis search space.

However, the use of finer correction of the pupil is only the first step toward ExAO. Indeed, every aspect of wavefront correction must be improved in order to reach ever deeper contrast levels. We thus also made a series of improvements to the non-common path wavefront errors [3], which arise because the wavefront sensor and the science camera are not coincident. These include reductions in the post-AO pointing and focus (Fig. 3) error terms,

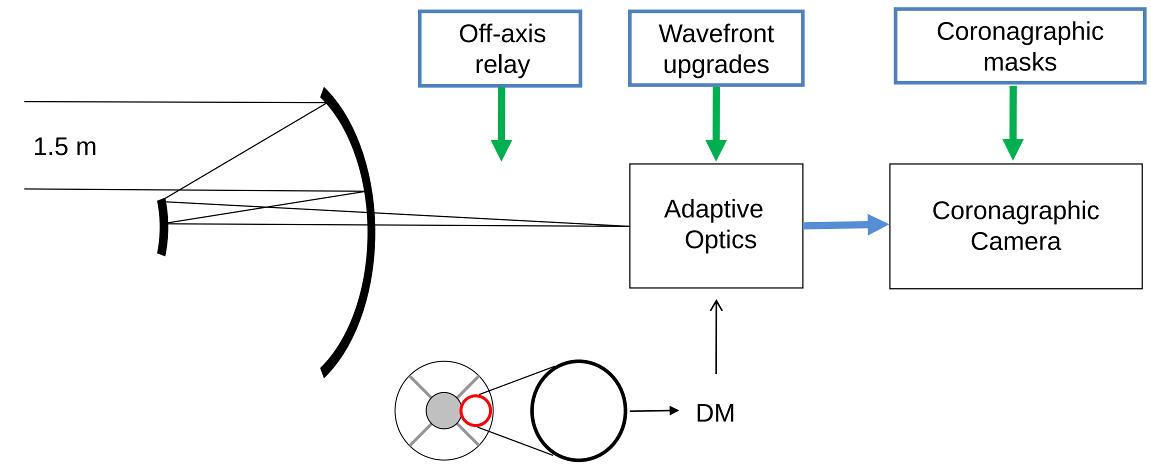

Figure 1: Layout of the Palomar Well-Corrected Subaperture. The resultant optical system is that of a coronagraphic 1.5 m off-axis telescope.

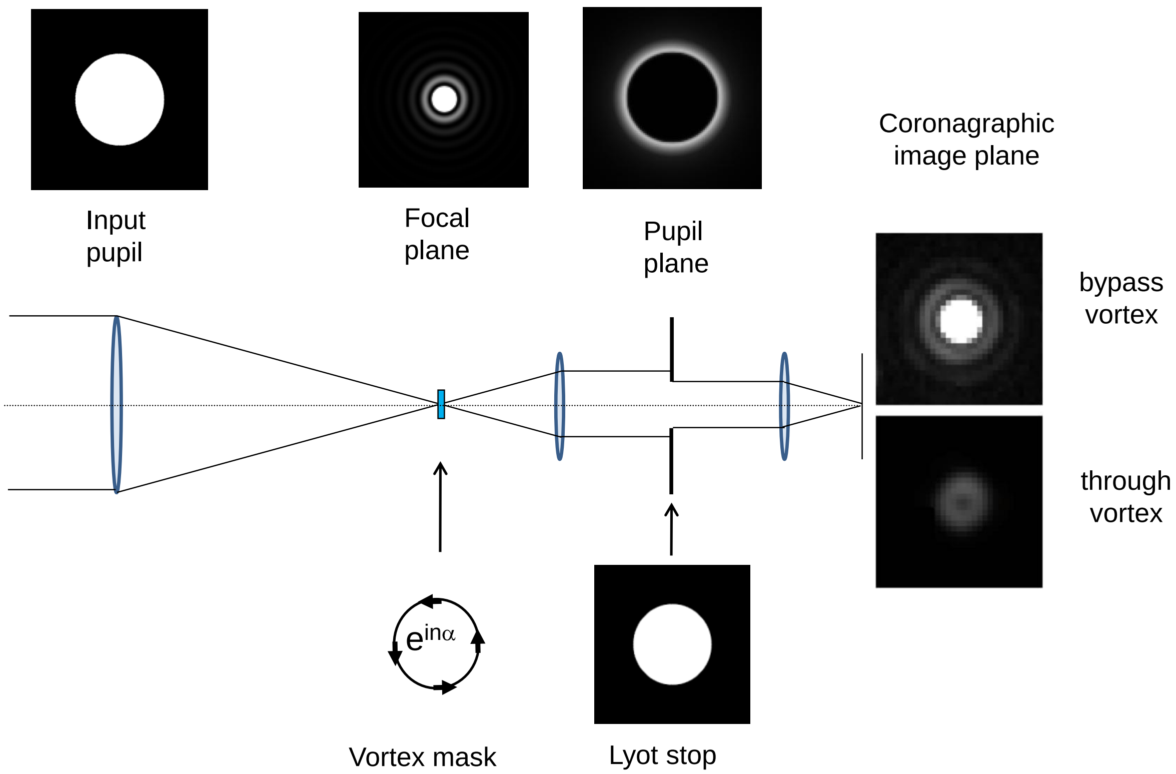

Figure 2: Layout and operation of the vortex coronagraph. Note that in the post-vortex Lyot plane, all of the starlight lies outside of the original pupil, and so can be easily rejected.

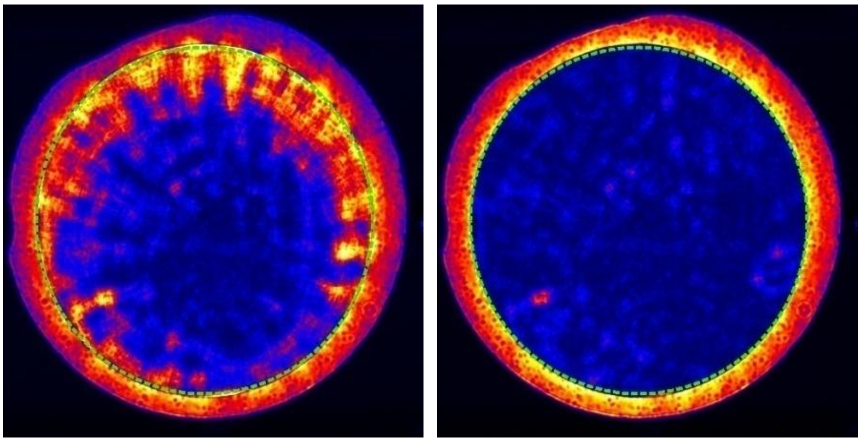

Figure 3: Focusing the starlight onto the vortex mask (*right*) instead of onto the detector plane (*left*) has led to significant darkening of the Lyot pupil plane, and so to much better rejection of starlight.

as well as in higher order non-common path errors that lead to focal-plane speckles (Fig. 4). The post-AO pointing system was thus upgraded with much finer actuators and sensors, leading to pointing stabilities of a few milli-arcsec over an integration, and the focus is now optimized onto the vortex mask, rather than onto the image plane. Finally, the modified Gerchberg-Saxton phase retrieval algorithm is applied to a white light source (implemented at the elevation of the astronomical source just prior to observing) to reduce higher-oder non-common path errors (speckles).

The net image quality improvement has been quite significant, as can be seen in Fig. 5, which shows deeper central contrasts due to speckle reduction ($\sim 10^{-5}$), as well as a more compact stellar residual (due to pointing and focus improvements), leading to the beginnings of a central dark hole, in which faint exoplanets can be searched for. Indeed, the speckles have been reduced to the point that the noise in our final reduced images (after application of reference star subtraction via the locally optimized combination of images algorithm [7]) is close to the level of the photon shot noise. Finally, the move from the four-quadrant phase mask to the vortex mask has eliminated the residual off-axis focal-plane linear features along the quadrant boundaries.

These improvements, carried out with the aim of full system optimization, have now allowed our 1.5 m system to achieve high contrasts in to a rather small inner working angle ($\sim \lambda/D$ or 300 milli-arcsec for the K-band). Examples of observations enabled with this system are the imaging of the HD32297 debris disk [11] (Fig. 6) in to $\sim 1.5\lambda/D$, the detection of the HR8799 exoplanets [16] (Fig. 7), and most recently, the detection of a faint binary companion at $\sim \lambda$/D from the primary star (Fig. 8; [13]).

Interestingly, because of these improved capabilities, our 1.5 m ExAO-level well-corrected subaperture now typically achieves inner working angles quite similar to those of the largest existing telescopes equipped with current generation AO systems. This directly shows that it

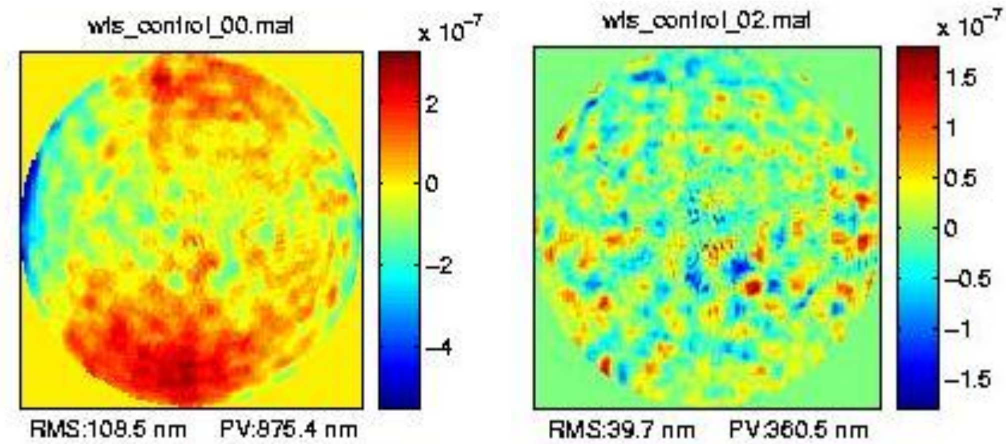

Figure 4: Non-common path speckle reduction by means of phase retrieval [3] has led to improvement in wavefront quality from (*left*) ≈ 110 nm rms to (*right*) ≈ 30-40 nm rms.

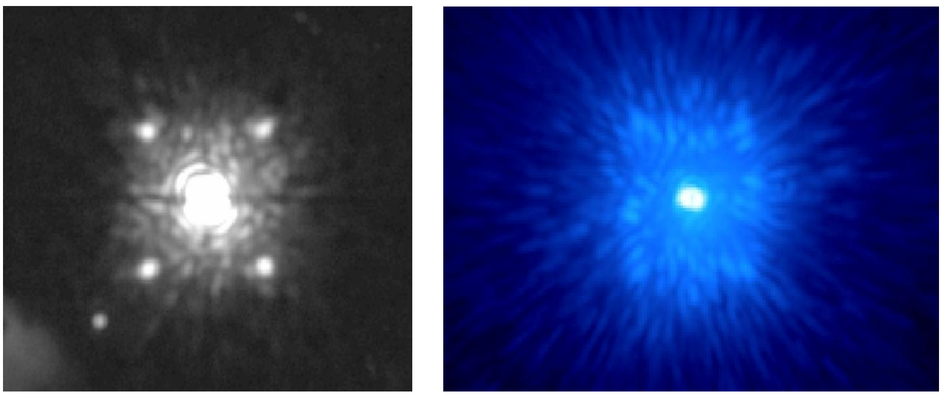

Figure 5: Net image quality improvement of the Palomar well-corrected subaperture over the past few years. *Left*: The "before" image shows a wide stellar residual surrounded by bright speckles. *Right*: A recent "after" image shows a very compact stellar residual and the beginnings of a square "dark hole" surrounding the star, with contrasts of order 10^{-5}.

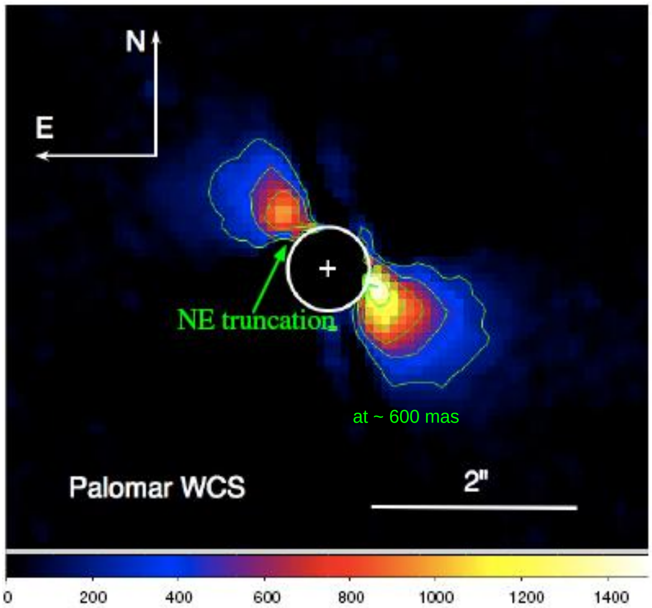

Figure 6: The HD32297 disk imaged with the the Palomar well-corrected subaperture.

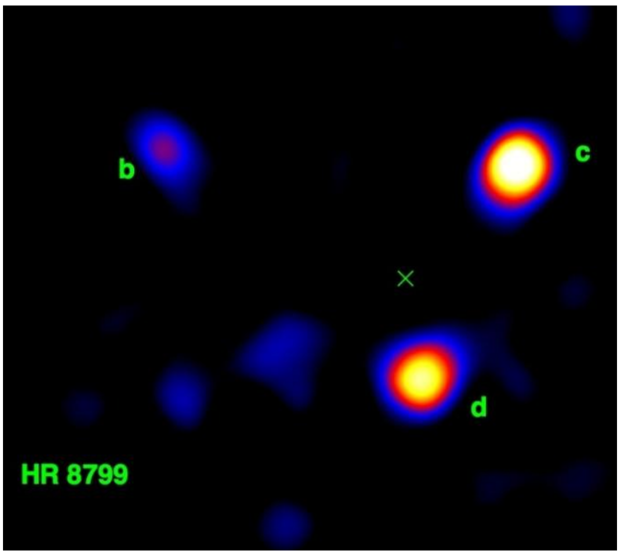

Figure 7: The HR8799 exoplanets imaged with the Palmar well-corrected subaperture.

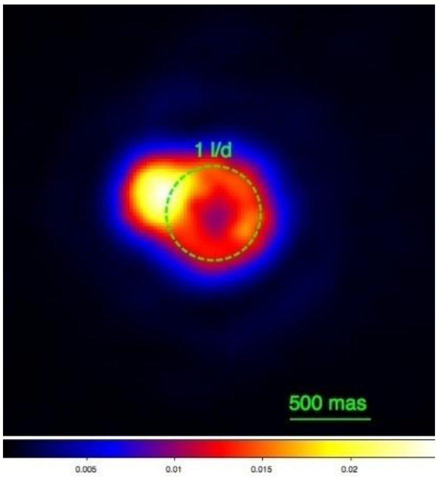

Figure 8: A close binary imaged recently with the Palomar well-corrected subaperture. The primary residuals are seen as a faint ring of emission.

is in fact possible to image exoplanets with fairly small telescopes. This is extremely important in the space-based case, where costs must be constrained as much as possible. Moreover, it also provides a first glimpse of the potential of future ground-based ExAO systems on large telescopes, for which the inner working angles will be correspondingly reduced.

Acknowledgments

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