Invited Paper

The Potential of Small Space Telescopes for Exoplanet Observations

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ABSTRACT

The imaging of faint exoplanets near bright stars requires the development of very high contrast detection techniques, including both precise wavefront control and deep starlight rejection. A system-level proof-of-principle experiment carried out at at the Palomar Observatory has recently demonstrated that exoplanets can be detected very near stars even with a fairly small (1.5 m diameter) telescope aperture, such as someday might be used by a first space-based exoplanet imaging mission. Using fine-scale wavefront correction across this small aperture, together with fine pointing and focus control, pre- and post-detection speckle reduction, and a vector vortex coronagraph, it has been possible to achieve extremely good starlight rejection within a small number of diffractions beams of the stellar position. This performance has recently allowed the imaging of the three HR8799 planets and the HD32297 disk, thus providing a first system-level validation of the steps needed to achieve high-contrast observations at very small angles. These results thus serve to highlight the potential of small space telescopes aiming at high-contrast exoplanet observations. Specifically, a small-angle coronagraph enables the use of smaller telescopes, thus potentially reducing mission cost significantly.

Keywords: coronagraphy, exoplanets, vortex coronagraph

1. INTRODUCTION

Great progress is being made in the detection and characterization of planets orbiting nearby stars with radial velocity and transit measurements, but these techniques are sensitive mainly to very close-in planets. On the other hand, coronagraphy, which aims at the high-contrast imaging of solar systems, is most sensitive at larger distances from stars. While the techniques are complementary in this sense, coronagraphically separating planet light from stellar light has the intrinsic advantage of someday being able to provide colors and spectra for arbitrary planets in nearby solar systems.

Detecting very faint planets very close to much brighter stars requires a high degree of starlight suppression, which calls for both a coronagraph with an intrinsic capability for observations at small angular separations from stars, and highly accurate wavefront correction. The high levels of scattered light present in typical stellar images that can be obtained at the present time generally preclude reaching very high contrasts with any type of coronagraph, but this situation is changing, as next generation "extreme adaptive optics" (ExAO) systems should be able to provide infrared Strehl ratios on ground-based telescopes exceeding ~ 90%, the regime where coronagraphs operate effectively. Even so, the imaging of faint terrestrial planets around nearby stars will likely require a dedicated coronagraphic space telescope to reach the needed ~ 10^{-10} contrast levels. For space missions, it is of course critical to keep the telescope as small as possible, so as to keep costs low. Therefore, an exoplanet imaging space mission must necessarily aim at using a coronagraph with the smallest possible angle of operation, or "inner working angle" (IWA), informally defined as the angle at which the transmission of the planet light drops to one half of its asymptotic large-angle value.

The theoretical IWA of any type of coronagraph, given perfect wavefronts, is typically a few diffraction beams, i.e., $f\lambda/D$, where f is typically in the range 1 – 4, λ is the wavelength, and D is the telescope diameter. The IWA is thus inversely proportional to telescope diameter, but the use of a coronagraph with a smaller value of f allows a given absolute IWA to be reached with smaller telescopes (Fig. 1). For example, to observe to within 100 mas of stars at λ = 800 nm, corresponding to 0.7 AU (the size of Venus's orbit) at a distance of 7 pc (or 1 AU at 10 pc), one needs a 6.4 m telescope if f = 4, but only a 1.6 m telescope is needed if f = 1. It is thus clear that the development of promising small-IWA coronagraphs is critical if potential exoplanet space missions are to be kept small and affordable.

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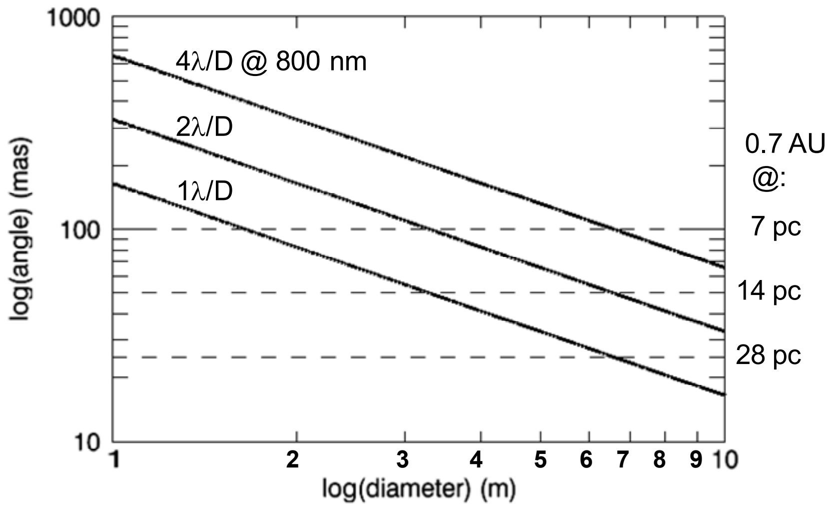

Figure 1. Absolute inner working angle (at λ = 800 nm) as a function of telescope diameter for several values of the theroretical inner working angle (λ/D, 2λ/D and 4λ/D). Also shown are the absolute inner working angles needed to see in to the size of Venus's orbit around a star at 7, 14, and 28 pc (or in to 1 AU at 10, 20 and 40 pc). Each factor of 2 in distance provides 8 times more stars. Within 7 pc, Allen lists ~ 90 stars, whereas Hipparcos lists several thousand stars within 30 pc.

While classical amplitude-based coronagraphs have IWAs of order 3 - 4 λ/D, phase mask coronagraphs have much smaller theoretical IWAs, because they rely on transparent masks. On the other hand, until about a decade ago, phase mask coronagraphs were relative unknowns. As a result, several years ago a program was initiated at JPL aimed at the development and demonstration of phase mask coronagraphs, with the aim being the on-sky testing and demonstration of phase mask coronagraphs as a confidence-builder for future coronagraphic space missions. Over the years this program has led not only to the successful development of novel phase mask coronagraphic devices, but also, because of the need for accurate wavefront control in coronagraphic systems, to the first working high-contrast ExAO system to be demonstrated on-sky. This paper thus describes the steps taken over the years to reach the goal of high contrast demonstrations with phase mask coronagraphy, reviews some recent observations obtained at Palomar with our very recent vector vortex phase masks, and then returns to the question of a small coronagraphic space mission.

2. PHASE MASK CORONAGRAPHY

We initially developed four-quadrant phase masks[1] (FQPM) for coronagraphy, using a variety of techniques, and then recently moved on to the even more promising vector vortex coronagraph[2,3]. As its name implies, the FQPM divides the focal plane into quadrants, and applies alternating relative phases of 0 and π radians in the quadrants. While indeed possessing a small IWA, this coronagraph unfortunately has discontinuities along the quadrant divisions, leading to discontinuities in the image plane. On the other hand, the vortex phase mask applies an azimuthal phase spiral in the focal plane. In the specific case of the vector vortex mask, this phase ramp is applied by means of a circularly symmetric half-wave plate (Fig. 2), which has the advantage of producing no discontinuities in the focal plane except for exactly on the optical axis. Our vortex masks to date have been manufactured using polymeric liquid crystal technology[4].

Note that the optical layout for a phase mask coronagraph is identical to that of an amplitude-based coronagraph (Fig. 3), so that both amplitude and phase based coronagraphic masks can share the same optical system (and space mission) in very straightforward fashion.

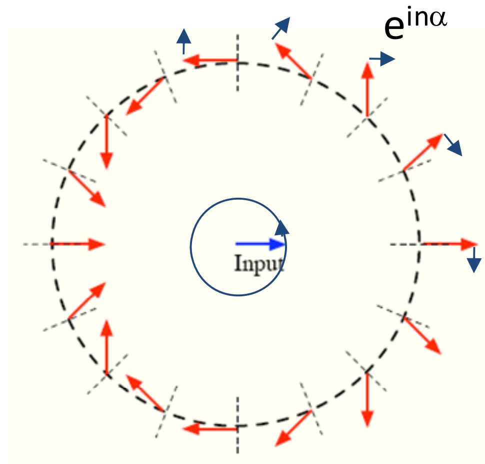

Figure 2. Operation of a vector vortex phase mask. A circularly symmetric half-wave plate (with radial (dashed) axes) applies an azimuthal phase spiral to the focal plane point spread function. The rotating red vectors show the phase shift induced in a circularly polarized wave.

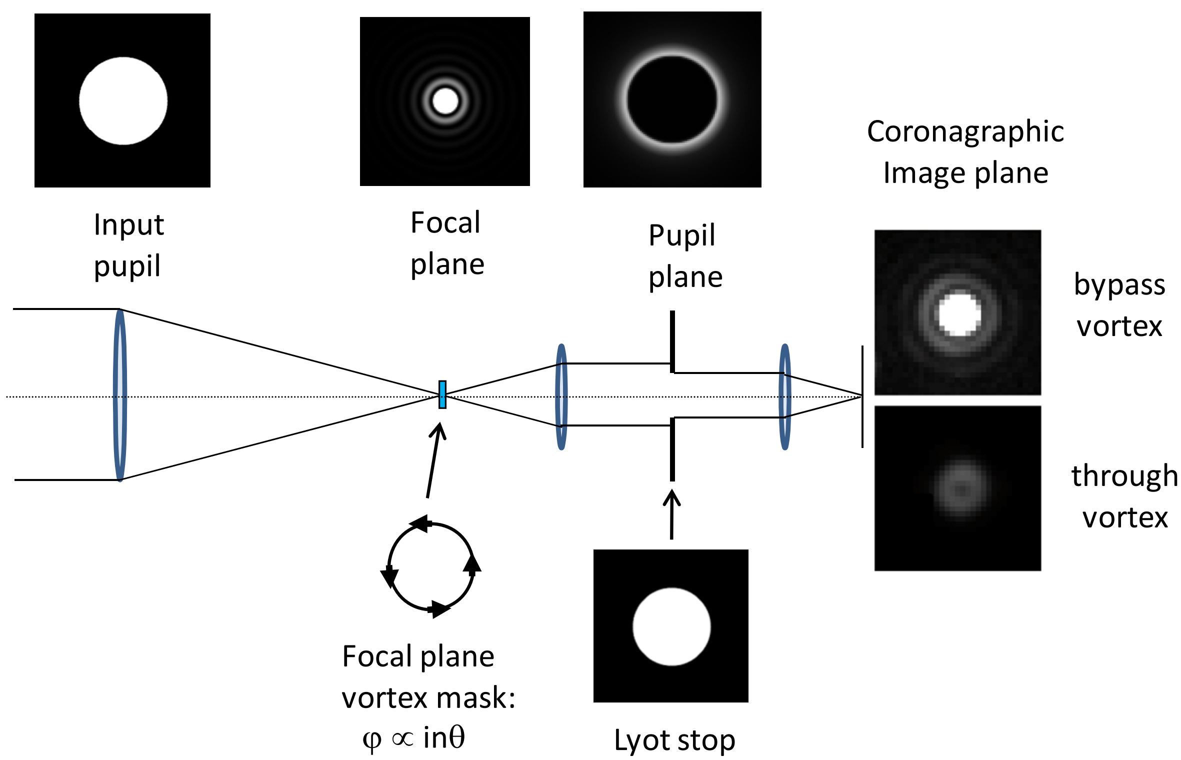

Figure 3. Layout and operation of the vortex coronagraph. A spiral phase ramp is applied in the focal plane and then a Lyot stop removes the stellar light from the edge of a subsequent pupil, just as for intensity-based coronagraphs. Both of the PSFs shown on the right were actually measured on the star HR8799.

3. THE PALOMAR "WELL CORRECTED SUBAPERTURE" (WCS): AN ANALOG FOR A SMALL EXOPLANET SPACE MISSION

To carry out on-sky demonstrations of high-contrast phase mask coronagraphy, the level of wavefront control needed calls for an ExAO system. While ExAO systems are planned at several large telescopes, these systems are complex and expensive, and will rely on several new and untested measurement techniques and algorithms. It was thus clear that an early on-sky high-contrast coronagrahic demonstrator operating at ExAO levels would be extremely valuable not only in terms of demonstrating phase mask coronagraphy, but also in terms of demonstrating the novel ExAO wavefront improvement techniques needed to make very high contrast observations possible. Luckily, it turns out that there is a very straightforward way to achieve ExAO performance levels very rapidly: one simply uses an existing adaptive optics system to correct part of a telescope aperture to extremely high accuracy, instead of using it to correct the entire telescope aperture to more modest levels[5]. Moreover, since the resultant "well-corrected subaperture" (WCS) could be configured as a clear off-axis subaperture (Fig. 4), it could serve directly as a demonstrator for a small coronagraphic space mission based on an off-axis telescope. As a result, such a WCS, with a diameter of 1.5 m, was set up on Palomar's Hale telescope.

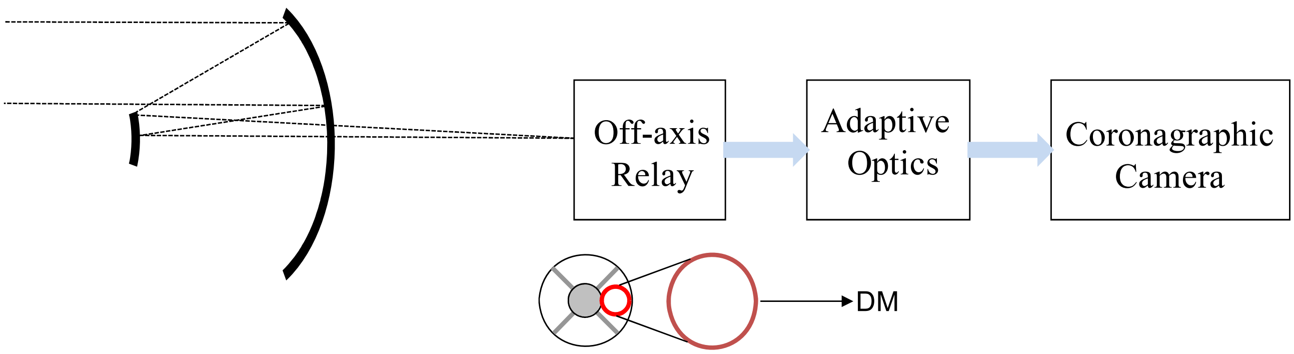

Figure 4. Schematic of the layout of a well-corrected subaperture. An off-axis relay selects and magnifies an off-axis pupil subaperture and sends it to the the AO system's deformable mirror for fine scale correction.

Note that in order to achieve high contrast at small angles, a systematic approach to wavefront error suppression is needed, including accurate tip-tilt and low order aberration control, as well as high frequency speckle suppression. Thus while higher actuator density is critical to achieving high contrast, it is only a first step, resulting in a decrease of the root-mean-square (rms) wavefront error from ~ 200 - 250 nm with the adaptive optics [AO] system coupled to the full telescope, to ~ 80 - 100 nm on the more densely corrected sub-aperture. The next crucial step was then the reduction of non-common path (NCP) wavefront errors arising from the non-coincidence of the science and wavefront-sensor cameras, including differential pointing and focus, and quasi-static scattered-light speckles[6]. The differential pointing drift was reduced by approximately an order of magnitude, to ~ 2 mas/min, by means of improved mirror actuation in the Palomar AO system. This resulted in a much improved ability to stay pointed at the center of the coronagraphic mask. The focus onto the coronagraphic mask plane is optimized by minimizing residual light in the post-coronagraphic-mask pupil (Lyot) plane, and the wavefront sensor is then translated accordingly. Finally, the quasi-static speckles are reduced from ~ 110 nm to ~ 40 nm using the science camera as a secondary wavefront sensor in a modified Gerchberg-Saxton phase retrieval algorithm[6,7].

The net result of all of these improvement steps can be seen in Fig. 5, which compares an older stellar image acquired with our earlier FQPM coronagraph with a recent image acquired with our more recent vortex coronagraph after all of the aforementioned upgrades. One can clearly see the effects of many of these improvements individually: the pointing and focus improvements led to the smaller residual stellar core, the MGS algorithm cleaned the speckles out of the central region well enough to allow a central smooth square "dark hole" coincident with the domain of influence of the deformable mirror to be seen, and the dark stripes along the axes seen in the FQPM image are no longer present in the vortex image. As shown in Fig. 6, these improvements have yielded very good on-sky contrast performance, with 1σ H-band contrast detectabilities of a few 10^{-6} in to ~ 2λ/D on bright stars.

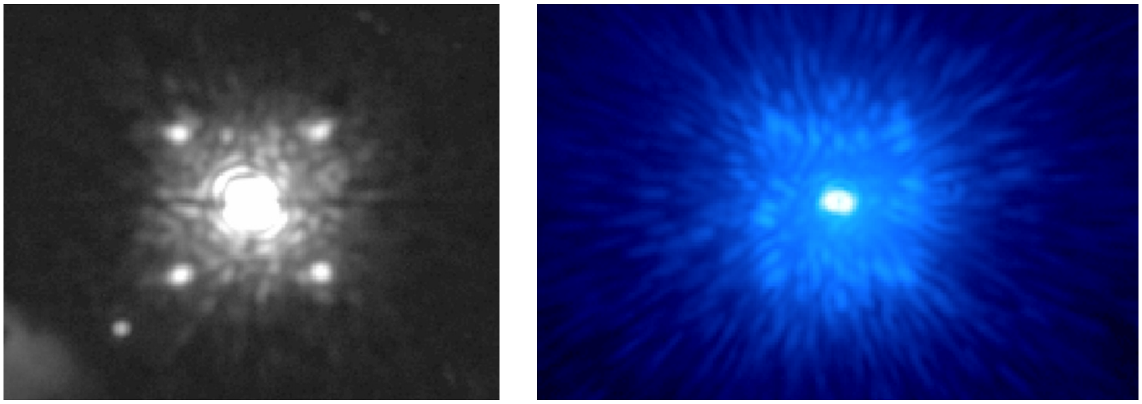

Figure 5. Image quality improvement on the Palomar WCS over the past couple of years. Pointing and focus improvements have led to the smaller residual stellar core, the MGS algorithm cleaned the speckles out of the central region well enough to allow the beginnings of a central smooth square "dark hole" coincident with the domain of influence of the deformable mirror, and the dark stripes along the axes seen in the FQPM image are no longer present in the vortex image. Note also that the earlier left-hand image is at K-band, while the one on the right-hand side is at H-band, and on a brighter star.

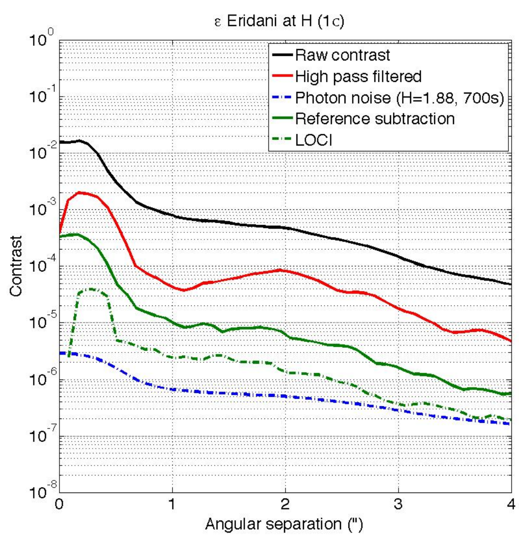

Figure 6. Recent H-band contrast curves obtained on ε Eridani, with final 1σ contrasts of order a few 10^{-6} in to ~ 0.5", or ~ 2λ/D.

4. OBSERVATIONAL RESULTS

After optically testing our phase masks in the lab, and verifying that the phase masks survived cryogenic cooling, they were installed in the cryogenic camera PHARO at Palomar. With these we were able to obtain observations of increasing contrast over the years, eventually allowing the detection of faint disk structures[8] and exoplanets[9] as close as ~ 1 - 2 λ/D from the stellar position (Fig. 7). Indeed, the resultant performance is comparable to that of much larger (8 – 10 m class) telescopes in terms both of inner working angle and contrast. Thus it is clear that small telescope apertures, equipped with the right equipment, are quite capable of detecting exoplanets very close to the stellar position.

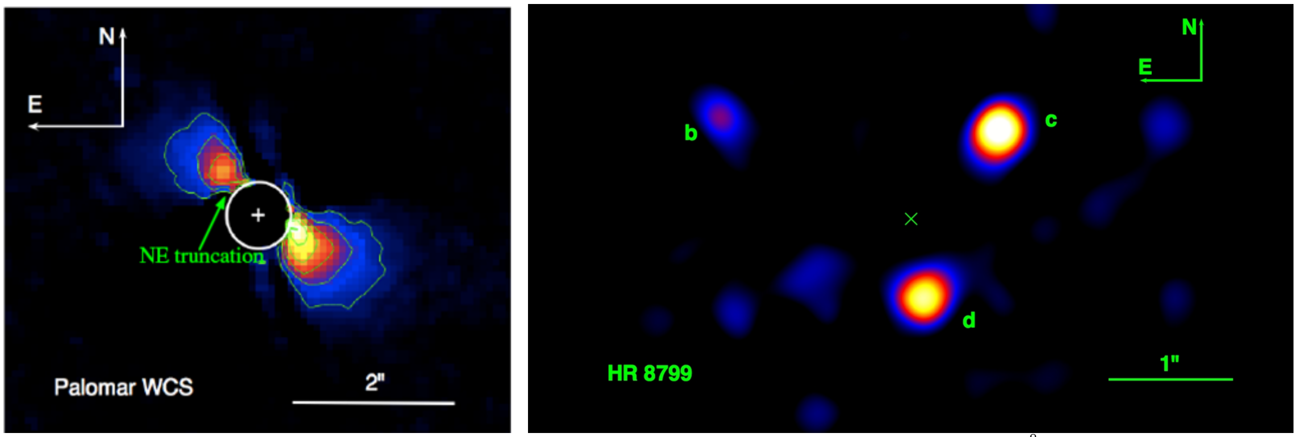

Figure 7. Recent high contrast images acquired with the Palomar WCS. The left-hand image[8] shows the disk HD32297, while the right-hand image shows the three exolanets in the HR8799 system[9].

Table 1

Larger Telescope		**SmallerTelescope**
Higher SNR	**System:**	Smaller volume/structure
Larger number of stars		No unfolding
Higher angular resolution		Smaller launch vehichle
Smaller IWA		Focused mission
More stable telescope (inertia)		Simpler I&T
Better exozodi discrimination	**Telescope:**	Simpler (monolithic) telescope
Better orbit		More accurate telescope
Larger instrument complement		More rigid telescope
		Off-axis telescope straightforward
		Active primary easier
		Easier pointing req't. (larger λ/D)
		Less stellar diameter leakage
		Higher focal ratio
		Lower polarization sensitivity
		Lower aberration sensitivity
	Backend:	Smaller deformable mirror
		Less sensitive to beam shear
		Smaller instrument complement
	Schedule:	Faster
	Budget:	Cheaper

5. ADVANTAGES OF SMALL SPACE TELESCOPES

Given these observational validations of the capabilities of phase-mask coronagraphy, it is clear that small telescope apertures do indeed have a powerful potential for high-contrast science observations in to small enough angles (of order 50 - 100 mas across the optical regime) to be able to observe parts or all of the habitable zones around a sizeable number of nearby stars. Of course, large telescopes have many obvious advantages due to their larger collecting areas and higher angular resolutions (Table 1), but these tend to come at a high cost. On the other hand, as shown in Table 1, small space telescopes also have a very significant number of advantages. These fall in many areas, from the system level to the telescope level to the backend instrumentation to the schedule and budget aspects. The bottom line is that while a large space telescope would certainly be better in terms of science potential, a small space telescope would likely be much faster and cheaper to build. Moreover, as a small IWA phase-mask coronagraph allows for a significant science potential[10] even with a telescope as small as about 1.5 m, the steep rise in mission cost with telescope diameter makes a small coronagraphic space mission very attractive as a near-term, affordable option for imaging nearby solar systems.

6. PERFORMANCE LIMITATIONS

The ultimate contrast performance attainable by a vortex coronagraph in practice will be determined by several factors[11]. Obscuration by a secondary mirror will not be an issue for a small off-axis telescope. Control of tip-tilt and low-order aberrations will be critical, but these effects can be greatly reduced by using higher order vortex masks, at the cost of some degradation in inner working angle. Moreover, solutions do exist for stellar rejection with vortex coronagraphs that is both deep and broad (10 – 20%) in bandwidth. Polarization may become an issue at very high contrasts, but these can be avoided by splitting the polarization states. Thus, solutions have been identified that mitigate these factors.

7. SUMMARY

The vortex coronagraph has a number of significant advantages, including simplicity, a small inner working angle, a high throughput, and a clear 360° discovery space around the center. The vortex coronagraph has also already provided a proof of concept demonstration for the imaging of exoplanets within 2 λ/D of a star, and debris disk structures within 1 λ/D. With some further development to reach even deeper contrast levels, the vortex's demonstrated small-angle capability can thus be taken advantage of in order to reduce the telescope size needed for extra-solar planetary system imaging and characterization, allowing a small, relatively inexpensive, space-based telescope to do the job.

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