Speckle Control with a Remapped-Pupil PIAA Coronagraph

FRANTZ MARTINACHE, OLIVIER GUYON, CHRISTOPHE CLERGEON, AND CELIA BLAIN

National Astronomical, Subaru Telescope, Observatory of Japan, Hilo, HI 96720; frantz@naoj.org

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ABSTRACT. Phase-induced amplitude apodization (PIAA) is a well-demonstrated high-contrast technique that uses an intermediate remapping of the pupil for high-contrast coronagraphy (apodization), before restoring it to recover classical imaging capabilities. This paper presents the first demonstration of complete speckle control loop with one such PIAA coronograph. We show the presence of a complete set of remapping optics (the so-called PIAA and matching inverse PIAA) is transparent to the wavefront control algorithm. Simple focal-plane-based wavefront control algorithms can thus be employed, without the need to model remapping effects. Using the Subaru Coronagraphic Extreme AO (SCExAO) instrument built for the Subaru Telescope, we show, using a calibration source, that a complete PIAA coronagraph is compatible with a simple implementation of a speckle nulling technique, and demonstrate the benefit of the PIAA for high-contrast imaging at small angular separation.

Online material: color figures

1. INTRODUCTION

Contrast limits for the direct imaging of extrasolar planets from ground-based adaptive optics (AO) observations are currently set by the presence of static and slow-varying aberrations in the optical path that leads to the science instrument (Marois et al. 2003). These aberrations, due to the noncommon path error between the wavefront sensor and the science camera, are responsible for the presence of long-lasting speckles in the image. Because extrasolar planets are unresolved sources, it is difficult to discriminate them among these speckles. One family of techniques, called differential imaging, is aimed at calibrating out some of these static aberrations, by using either sky rotation (angular differential imaging, or ADI), polarization (PDI), or wavelength dependence of the speckles (spectral differential imaging or SDI). Of these, ADI (Marois et al. 2006) seems very well adapted to the problem of the detection of extrasolar planets and has been successful, most notably producing the image of the planetary system around HR 8799 (Marois et al. 2008). ADI uses the rotation of the sky that naturally happens while tracking with an altitude-azimuthal telescope around transit. The position of static and slowly varying speckles, tied to the diffraction by the pupil, remains stable over long timescales, while the image of planetary companions rotates around the one of the host star.

The rotation of the field only leads to sufficient linear displacement for angular separations of the order of 1". And in practice, below 0.5", the performance of ADI quickly degrades below the threshold where planets can be detected.

One way to complement ADI toward small angular separation, is to use a deformable mirror (DM) to modulate speckles and introduce the diversity that will distinguish them from genuine structures like planets and lumps in disks. This type of technique is regularly used for high-contrast experiments (Guyon et al. 2010b) and appears as the technique of choice for a spaceborne mission dedicated to the direct imaging of high-contrast planets. This is also the approach we propose to use for the detection of extrasolar planets at small angular separation during ground-based adaptive optics (AO) observations. With this in mind, we are integrating and testing the Subaru Coronagraphic Extreme AO (SCExAO) project, whose optics have been described by Lozi et al. (2009) and Martinache et al. (2011).

In comparison with other extreme-AO projects (Macintosh et al. 2008; Beuzit et al. 2010), SCExAO implements an aggressive PIAA coronagraph, using a remapping of the pupil (Guyon et al. 2005; Martinache et al. 2006) optimized for high-contrast detection at small angular separations (down to 1 λ/D).

Laboratory high-contrast experiments relying on PIAA have already demonstrated high-contrast imaging capability in the 2–4 λ/D angular separation range, and achieved raw contrast of ~10⁻⁷ and beyond (Guyon et al. 2010b; Kern et al. 2011; Belikov et al. 2011) that are several orders of magnitude beyond what a ground-based instrument is expected to produce (Guyon 2005). The SCExAO project attempts to apply some of the technology, tools, and techniques originally developed for spaceborne coronagraphy to ground-based AO. While space coronagraphy targets the ambitious goal of 10⁻¹⁰ raw contrast, required for the detection of an Earth-like planet around a Sun-like star, ground-based coronagraphy is done in a much less favorable and much more unstable environment. Raw contrasts achieved so far by coronagraphy downstream AO are of the order of 10⁻² at a few λ/D, and in practice the direct maging...
of planetary candidates relies heavily on postprocessing techniques like ADI to reach the published $10^{-5}$ to $10^{-6}$ contrast detection limits.

From a reasonably good starting point, high-contrast laboratory experiments can produce high-contrast images in a fairly small number of iterations, using an electric field conjugation (EFC) framework that relies on an acute knowledge of the system’s complex amplitude response matrix (Give’On 2006; Bordé & Traub 2006). Ultimately, these techniques seem implementable at the telescope once an extreme AO system produces a continuous stream of stable high-Strehl images. For now, they remain limited to the pampered environment of the laboratory. At this stage of its development (referred to as SCExAO Phase 1), SCExAO does not include a fully functioning high-order wavefront sensor. The 32x32 DM it implements can nevertheless be used to actively generate speckle diversity and supplement ADI at small angular separations. SCExAO Phase 1 relies on iterative speckle nulling, to produce a region of higher contrast, often referred to as a “dark hole” (Malbet et al. 1995) in the field.

2. SPECKLE CONTROL WITHIN A PIAA CORONAGRAPH

The Phase-induced amplitude apodization (PIAA) coronagraph (Guyon 2003) is a high-contrast imaging device that enables the detection of faint sources down to an angular separation of $\sim 1 \lambda/D$. A PIAA coronagraph is made of a set of aspheric optics designed to apodize the pupil by geometrically redistributing the light while preserving the overall collimation of the beam for an on-axis source. Because it alters the pupil, the point spread function (PSF) of such a system is, however, no longer translation-invariant. On SCExAO, the impact of the PIAA on the pupil is quite dramatic, as it goes as far as filling the void left by the 30% central obscuration of the Subaru Telescope pupil to produce an apodized pupil better suited for high-contrast imaging. The impact for off-axis sources is therefore also quite spectacular, as it produces strongly elongated pineapple-shaped PSFs beyond a few $\lambda/D$ (Lozi et al. 2009).

While successful wavefront control experiments using PIAA have already been reported (Guyon et al. 2010b; Kern et al. 2011; Belikov et al. 2011), these experiments have all used a DM located downstream of the PIAA. The outer working angle (OWA) of this type of control is imposed by the total number of available actuators across one pupil diameter. By placing the DM downstream of the remapping optics, the OWA is reduced by a factor $\sim 3$, due to the plate scale change induced by the remapping (Guyon et al. 2010b). The resulting $5\lambda/D$ OWA (since there are 32 actuators across the pupil) would be a very serious limitation for any direct imaging instrument. Instead, the SCExAO project implements a complete PIAA coronagraph, with a DM located before any of the remapping optics (see Fig. 1). After the focal plane mask, a copy of the PIAA optics plugged backwards (referred to as the inverse PIAA) is introduced to undo the remapping of the pupil after the focal plane mask. This setup allows the recovery of the wide field-of-view imaging capability of the instrument (Guyon & Roddier 2002; Guyon 2003; Vanderbei & Traub 2005). Indeed, despite the drastic transformation of the wavefront operated by the PIAA, the remapping of the pupil remains a geometric operation. The inverse PIAA simply guarantees that what is known since the end of the 19th century as “Abbe’s sine condition” is met after the remapping by the PIAA.

The SCExAO instrument is a flexible platform, installed after Subaru Telescope’s facility AO system, and designed to be used with the coronagraphic imager HiCIAO (Hodapp et al. 2008), and increase the size of the parameter space currently explored by the SEEDS survey (Tamura 2009; Tamura & SEEDS Team 2010), toward small angular separations. The infrared arm of SCExAO alone (Martinache et al. 2011) supports multiple optical configurations (see Fig. 1), from straightforward imager (with or without a focal plane mask), to a complete PIAA coronagraph.

Lozi et al. (2009) have already demonstrated that the inverse PIAA, once aligned and conjugated to the PIAA, indeed restores wide field-of-view imaging capability of the system, at least up to $20 \lambda/D$, which is beyond the outer working angle defined by the number of DM actuators across the instrument pupil. With this in mind, it seems reasonable to assume that the remapping optics should therefore be completely transparent for the wavefront control. The results presented in this article demonstrate that indeed, with a complete PIAA coronagraph (including the inverse PIAA), a simple wavefront control loop (speckle nulling) converges while being oblivious to the two remappings of the pupil.
2.1. Optical Configurations of SCExAO

To illustrate the impact of the remapping optics on the wavefront control, we use three distinct optical configurations of the SCExAO infrared arm, shown in Figure 1. All results reported in this paper were obtained with the SCExAO instrument fed by an external Subaru Telescope simulator (single-mode fibered laser source, $\lambda = 1.55 \, \mu m +$ static turbulence phase screen) in an unstabilized environment. The reader will observe that in its current implementation, the 32x32 MEMS DM of SCExAO is not located in a pupil plane. This design was chosen for the simplicity of the optical layout, as well as to minimize the total number of reflections in the system. The design, however, also has some drawbacks. First, it requires a somewhat conservative beam size projected on the DM, to account for beam walk effects that would otherwise significantly vignette the field. The DM also needs to be horizontally tilted ($\sim$24°), so the density of actuators is not the same in horizontal and vertical directions. In practice, instead of illuminating all 32 available actuators across one pupil diameter, the beam spreads over a 27.2 × 24.8 actuator ellipse. SCExAO can afford to have its DM away from the pupil, since it is used downstream from an AO system that not only stabilizes the pupil but also considerably reduces the total amount of aberrations the system needs to correct for.

While the DM is always part of the optical train, both the PIAA and the inverse PIAA are mounted on motorized stages that can swing in and out of the beam with excellent repeatability, thus allowing for quick alternation between the three configurations: no remapping, PIAA only, and PIAA + inverse PIAA (see Fig. 1). In a speckle control loop, the DM is used to introduce spatial frequencies that destructively interfere with speckles induced by wavefront aberrations from the input beam. The DM can also be used to create speckles and, in turn, provide a very instructive demonstration of how (see Fig. 2) aberrations propagate through the SCExAO coronagraph.

Panel (a) of Figure 2 shows the 32x32 voltmap sent to the DM for this experiment. In addition to the voltmap that has been determined to produce the best output wavefront in the absence of input aberrations (what will now be referred to as the DM flat-map), two sine waves of amplitude 0.4 radians and maximal spatial frequency (in the Nyquist sense) are added, along the horizontal and vertical directions. These additional sine functions on the DM create four bright speckles, clearly visible in the focal plane visible on Panel (b) of Figure 2, in the absence of remapping optics. The oversized focal plane mask effectively hides the brightest area, but in the absence of Lyot stop, the diffraction by the spider arms bearing the secondary mirror of the telescope are left. Because the speckles result from the highest spatial frequency that can be introduced by the DM, their locations in the image also mark the edges of the region that can be controlled by the DM. In the absence of amplitude defects, appropriate actuation of the DM could clear the speckles over the entire 27.2 × 24.8 $\lambda/D$ box centered on the on-axis target. In practice, because the beam includes amplitude as well as phase defects, the DM can only operate over a half of this entire region. For the results reported in this work, we arbitrarily chose to work on the left-hand side of the field. Speckles located beyond 13.6 $\lambda/D$ along the horizontal axis and 12.4 $\lambda/D$ along the vertical axis simply will not be affected by the DM. Note that with a 0.04″ diffraction limit in the H band, 12.4 $\lambda/D$ on the Subaru Telescope closely matches the range of angular separation where ADI becomes usable ($12.4 \times 0.04 = 0.5$ arcsecond).

2.2. Impact of the Remapping Optics

The introduction of the PIAA dramatically impacts the structure of these image (see panel (c) of Fig. 2). While the diffraction spikes created by the spider remain, most of the diffraction rings due to the sharp edge of the telescope pupil disappear, and are more effectively hidden by the focal plane mask whose size now better matches the on-axis PSF. Off-axis, however, the bright diffraction-limited images of introduced speckles are turned into complex pineapple-shaped aberrated structures. The benefit of the PIAA remapping will be better demonstrated when comparing the performance of the speckle nulling loop with and without using the remapping optics in § 3.2.
The complete PIAA coronagraph (configuration 3) includes, after the focal plane mask, a copy of the PIAA optics mounted backwards to restore the geometry of the pupil back to what it was before entering the coronagraph. From geometric optics principles only, one expects this restoration to be perfect, but diffraction and the presence of the occulting mask in the focal plane will impact the output wavefront. Panel (d) of Figure 2 shows the resulting image: the bright off-axis speckles have been fully reconstructed by the inverse PIAA, and have recovered their Airy-disk shape. The dark disk left by the focal plane mask that was visible in the other two images is no longer obvious, as the disk is remapped by the inverse PIAA.

The PIAA + inverse PIAA combination successfully restores the image of the off-axis speckles back into translation invariant copies of the central PSF. For speckles that would be sufficiently far from the edge of the focal plane mask, it is expected that any type of focal-plane-based wavefront control can ignore the presence of these remapping optics. It is, however, not obvious for the speckles located nearby the original footprint of the focal plane mask that they should behave as simply. Section 3 will show, however, that speckle control can be achieved within the entire control region of the DM.

3. SPECKLE NULLING RESULTS

3.1. The PIAA Coronagraph is Transparent to the Speckle Control

To test the impact of the remapping (PIAA + inverse PIAA) optics for a focal-plane-based wavefront control loop, we use a simple iterative speckle nulling algorithm inspired from the original “dark hole” coronagraphy work by Malbet et al. (1995). Our implementation however targets specific speckles (up to a dozen speckles are simultaneously probed). This approach seems fairly inefficient in comparison with more sophisticated electric field conjugation (EFC) approaches that can achieve the same result in just a few iterations (Give’On 2006). Speckle nulling was nevertheless chosen because of its robustness and ease of implementation.

Indeed, complete EFC-based techniques rely on the knowledge of a response matrix that relates the complex amplitude of the on-axis source in the focal plane to the input wavefront. With an extreme AO loop effectively stabilizing the wavefront entering the coronagraph into something predictable, this matrix is likely to be quite stable and therefore reliable. However in its first phase of deployment at the telescope, SCExAO does not include the fast wavefront sensor. The simple speckle nulling approach should, despite the presence of a dynamic atmospheric component, calibrate out the wavefront features responsible for the presence of static speckles in the images (Guyon et al. 2010b).

Iterative speckle nulling works as follows: in a given image, up to $n$ speckles are identified and their positions marked, relative to the central source. With a conventional imaging system, each speckle position corresponds to a two-component $(x, y)$ spatial frequency on the DM, while its brightness indicates the amplitude $a_0$ of this spatial frequency. The only real unknown is the phase $\varphi$ of each speckle, that can take any value between 0 and $\pi$. In the following four acquisitions, to each speckle is added a speckle probe of same amplitude $a_0$, but each time with a different phase: 0, $\pi/2$, $\pi$ and $3\pi/2$. The intensity of the four speckles resulting from the interference of the original speckle and the probes is used to determine its true phase $\phi_0$. For the next image, also used as the input for the next iteration, a spatial frequency of opposite phase $\phi_0 + \pi$ and of amplitude $g \times a_0$, where $g$ is the loop gain ($0.0 < g < 1.0$) is added so as to suppress the speckle.

The result of a series of 50 such speckle nulling iterations is presented in Figure 3. The starting point, shown in the left panel, shows the structure of the speckles due to amplitude and phase defects that filtered through the coronagraph. One will observe that all ring-like structures due to the sharp inner and outer edge of the pupil have been erased from the image, showing that the PIAA—focal plane mask—inverse PIAA combination achieves its purposes. Although faint (the average contrast over the entire control region is $2 \times 10^{-3}$), the most striking features can almost entirely be attributed to the spider arms bearing the secondary. After about 50 speckle nulling iterations (see right panel of Fig. 3), the average contrast inside the control region is brought down to $4 \times 10^{-4}$. The algorithm manages to suppress the diffraction features due to the spider arms, along which the gain in raw contrast is over $10^2$. Overall, the speckle nulling loop improves the contrast by a factor of 10 over the entire control region.

![Fig. 3.](image-url) Example of high contrast result achievable with the SCExAO coronagraph using a simple speckle nulling control loop. Panel (a) shows the starting point of the loop, with the deformable mirror in its nominal flat-map configuration. Note that in addition to some low-spatial frequency aberrations (created by a static turbulence plate), most of the speckles present at the starting point are located along the diffraction spikes created by the spider arms of the telescope pupil. Panel (b) shows the result of about 50 speckle nulling iterations, working on up to 10 speckles at a time, effectively clearing a box-shaped region of speckles, from 0 to 14 $\lambda/D$ in the horizontal direction and within $\pm 14 \lambda/D$ in the vertical direction. See the online edition of the PASP for a color version of this figure.
3.2. The Coronagraph Relieves the Wavefront Control

Figure 4 shows the DM voltmaps resulting from the speckle nulling algorithm for the Lyot coronagraph (left panel) and the PIAA coronagraph (right panel) configurations of SCExAO. Despite being ignorant of the pupil geometry, the speckle nulling produces a DM voltage-induced phase pattern that resembles the original telescope simulator pupil.

In addition to the spider vanes, in the Lyot configuration the algorithm attempts to cancel the diffraction rings induced by the sharp inner and outer edge of the pupil. The corresponding voltmap exhibits some sharp voltage changes from one actuator to its direct neighbor near the projection of these edges on the DM. Despite these sharp changes, this configuration fails to seriously cancel the innermost rings that would require more range than the DM can actually provide. The PIAA coronagraph voltmap, on the other hand, exhibits smoother features near the edge of the pupil, and only the effort to interfere with the speckle due to the spider vanes are very obvious. The coronagraph succeeds in relieving the wavefront control device by effectively suppressing a major fraction of the diffraction in the focal plane.

Note that the regions of the DM that obviously fall outside of the pupil do not need to be actuated at all. A more sophisticated DM control software should regularize the DM shape so as to preserve stroke on the DM.

3.3. Inner Working Angle

To further characterize the performance of the SCExAO coronagraph, and estimate its inner working angle, we look at the evolution of the throughput as a function of the position of the source relative to the focal plane across the field. While applying the DM voltage map resulting from a sequence of speckle nulling iterations, the source is translated along the horizontal axis. Figure 5 shows six snapshots of the PSF as it moves across the “dark hole” created by the speckle nulling loop for the first $5 \lambda/D$ away from on-axis. Within $1 \lambda/D$ and a little beyond, ring-like structures remain erased by the coronagraph. At $2 \lambda/D$, the core of the PSF clears the coronagraph and diffraction rings reappear in the image. Beyond $3 \lambda/D$, the PSF is essentially translation invariant, and only the shadow of the focal plane mask betrays the presence of the coronagraph.

To complete this qualitative analysis of post coronagraph images, Figure 6 shows a curve of the system throughput, integrated over the left-hand side of the field, as the source is moved across the entire $14 \lambda/D$ control region and slightly beyond. The 100% throughput reference is determined on-axis by

![Fig. 4.—Speckle nulling voltmaps for configurations (1) Lyot coronagraph and (3) PIAA coronagraph of SCExAO (see Fig. 1). See the online edition of the PASP for a color version of this figure.](image)

![Fig. 5.—Evolution of the PSF as a function of off-axis position near the focal plane mask from on-axis to $5 \lambda/D$ off-axis. At $2 \lambda/D$, the core of the PSF has almost entirely cleared the focal plane mask, and the diffraction rings associated with it become visible again. Beyond $3 \lambda/D$, the PSF morphology is essentially translation-invariant. Images use a common logarithmic intensity scale to reveal both bright and faint features of the PSFs.](image)

![Fig. 6.—Throughput of the SCExAO coronagraph as a function of angular separation. Using an iterative speckle nulling algorithm, the voltage map that cancels speckles within the control region of the DM has been identified. This curve shows how the throughput of the coronagraph evolves as the source is progressively translated off-axis, across the entire $14 \lambda/D$-wide control region.](image)
removing the focal plane mask. Matching our qualitative description of snapshots in Figure 5, we confirm that within \(1 \lambda / D\), the throughput only varies at the percent level. The most rapid variation of throughput happens around \(2 \lambda / D\), where the PSF core clears the focal plane mask as shown in Figure 5: the throughput quickly rises from a few percent to 60%.

One convenient definition of the inner working angle (IWA) of a coronagraph is the angular separation at which its transmission reaches 50% (Guyon et al. 2006). According to the measurements summarized in Figure 6, SCExAO’s current IWA is \(2.2 \lambda / D\). The focal plane mask currently used is 40% oversized, compared to the \(1.6 \lambda / D\) IWA the PIAA optics have been manufactured for. It will therefore be replaced before SCExAO’s next observing run.

4. CONCLUSION

We have, for the first time, demonstrated focal plane wavefront control capability in a complete PIAA—focal plane mask—inverse PIAA system. Using a simple iterative speckle nulling algorithm, we successfully produced a high-contrast region in the field (the so-called dark hole), and therefore confirmed that the complete set of remapping optics (PIAA and inverse PIAA) are transparent to the focal-plane-based wavefront control. We have also confirmed that the outer working angle allowable by the number of actuators of the deformable mirror is preserved during the double remapping. This implies that PIAA-type coronagraphs can be very well be used on ground- and space-based telescopes with no loss of outer working angle and do not require complex wavefront control algorithms. High-performance, high-efficiency coronagraphy therefore does not translate into increased system complexity.

Note that while we tested PIAA with a large mask imposing a \(2.2 \lambda / D\) inner working angle, the conclusions of this article will hold for more IWA-optimized coronagraphs, including the PIAACMC (Guyon et al. 2010a) that exhibit IWA <\(1\lambda / D\). Aggressive designs combining focal-plane-based wavefront control with what this article demonstrates make coronagraphy on board small telescopes (~ 2 m) in space a relevant option for the direct detection of extrasolar planets. They also offer the potential for imaging reflected-light planets at very small separation with the forthcoming generation of extremely large telescopes.

The results presented in this article do not address broadband operation of the coronagraph and control system, which is necessary for efficient on-sky operation. At the moderate raw contrast at which the system is designed to operate (\(\sim 10^{-3}\) to \(10^{-4}\) at a few \(\lambda / D\)), the PIAA lenses and relay optics are indeed designed to operate in a 20% wide band (\(H\) band, centered around 1.65 \(\mu m\)) in the absence of aberrations. Other issues that are not limited to SCExAO but are common to all high-contrast coronagraphs operating in broad band must nevertheless be carefully considered for broadband operation of the system:

1. Wavefront sensing in the focal plane must be robust against speckle elongation in broadband light, an issue that becomes important when attempting to measure the complex amplitude of speckles beyond \(\sim 5\lambda / D\) from the optical axis in a 20%-wide band. We note that in the near future, SCExAO will feed an integral field spectrograph, which is not limited by this effect and can therefore be used for broadband light focal plane wavefront sensing.

2. The focal plane mask size, if fixed, should ideally scale with wavelength. Our current \(2.2 \lambda / D\) IWA design is compatible with the 20% band at the required contrast level.

3. Atmosphere-induced wavefront errors are chromatic, principally due to the differential atmospheric refraction and the chromatic diffractive propagation between turbulence layers. While this effect is of concern when using a visible wavefront sensor for correction in the near-IR, it does not limit the instrument performance when both sensing and correction are performed, like in speckle nulling, within the same near-IR band, where variations of the refractive index of air remain small.

4. Wavefront chromaticity due to optical defects is expected at some level in any system using refractive optics. These are believed to be sufficiently small to not affect the instrument performance with our current design, since the relative variation in refractive index for most optical glasses is \(\sim 0.3%\) across the 20% wide \(H\) band. Defects on the surface of refractive elements are expected produce a chromatic error which is 0.3% as large as the defect itself. Even if such defects limit the contrast to \(10^{-2}\) without wavefront control (a conservative assumption for our system), the chromatic residual after wavefront correction will correspond to a \(10^{-2} \times 0.03^2 \sim 10^{-7}\) contrast limit, which is well below our raw contrast goal.

The coronagraph currently in place in SCExAO does not take into account the spider vanes in the pupil, while these are responsible for most of the light observed in the final focal plane of the instrument. Consequently, the wavefront control algorithm must use pupil phase introduced by the deformable mirror to remove, over half of the focal plane, light diffracted by the spider vanes, as shown in Figure 4. This approach is simply not optimal in a broad spectral band, and the SCExAO coronagraph will be updated to a PIAACMC type coronagraph to solve this issue.

Finally, while the results presented in this article demonstrate the raw contrast required for ground-based system, it is unclear to which extent the approach adopted in this work is suitable for the \(\sim 10^{-9}\) contrast level that future space-based missions hope to reach in order to image and study Earth-like planets. While remapping propagation effects specific to the PIAA coronagraph can be included in the wavefront control algorithm (Krist et al. 2011), it is unknown to what extent such effects need to be accounted for. The approach presented in this article should be tested, both in simulations and in laboratory experiments, at higher contrasts than required for a ground-based system. This work will be conducted over the next 2 years on existing PIAA coronagraph testbeds.
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