Phase Induced Amplitude Apodization (PIAA) coronagraphy: recent results and future prospects

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ABSTRACT

The Phase Induced Amplitude Apodization (PIAA) concept uses aspheric optics to apodize a telescope beam for high contrast imaging. The lossless apodization, achieved through geometrical redistribution of the light (beam shaping) allows designs of high performance coronagraphs, ideally suited for direct imaging of exoplanets similar to Earth around nearby stars. The PIAA coronagraph concept has evolved since its original formulation to mitigate manufacturing challenges and improve performance. Our group is currently aiming at demonstrating PIAA coronagraphy in the laboratory to 1e-9 raw contrast at 2 λ/D separation. Recent results from the High Contrast Imaging Testbed (HCIT) at NASA JPL and the PIAA testbed at NASA Ames demonstrate contrasts about one order of magnitude from this goal at 2 λ/D. In parallel with our high contrast demonstration at 2 λ/D, we are developing and testing new designs at a complementary testbed at NASA Ames, and solving associated technical challenges. Some of these new PIAA designs have been tested that can further mitigate PIAA manufacturing challenges while providing theoretically total starlight extinction and offering 50% throughput at less than 1 λ/D. Recent tests demonstrated on the order of 1e-6 contrast close to 1 λ/D (while maintaining 5e-8 contrast at 2 λ/D).

Keywords: Exoplanets, Coronagraphy

1. PIAA CORONAGRAPH CONCEPT

Many coronagraph system concepts have recently been proposed to image exoplanets from ground-based or space telescopes.[1] Among these numerous options, the Phase-Induced Amplitude Apodization (PIAA) coronagraph[2] is particularly attractive thanks to the combination of high throughput, high contrast and small inner working angle.

1.1 PIAA principle: lossless apodization with aspheric optics

Phase-Induced Amplitude Apodization (PIAA) uses aspheric optics such as the ones shown in figure 1 to reshape the telescope beam into an apodized beam with no loss in throughput or angular resolution.[2–10] This coronagraphic approach offers very high performance, as it combines full throughput, small IWA and uncompromized angular resolution. With reflective PIAA optics, chromaticity can be very low. A challenging part of this approach is the manufacturing of the aspheric optics, which sometimes requires a "hybrid" approach where apodization is shared between a mild apodizer and PIAA optics.[8] A set of "inverse" PIAA optics is required at the back end of the coronagraph to cancel field aberrations introduced by the first set of PIAA optics. This inverse set plays no role in the coronagraphic process, but considerably extends the field of view over which the PSF is diffraction limited.

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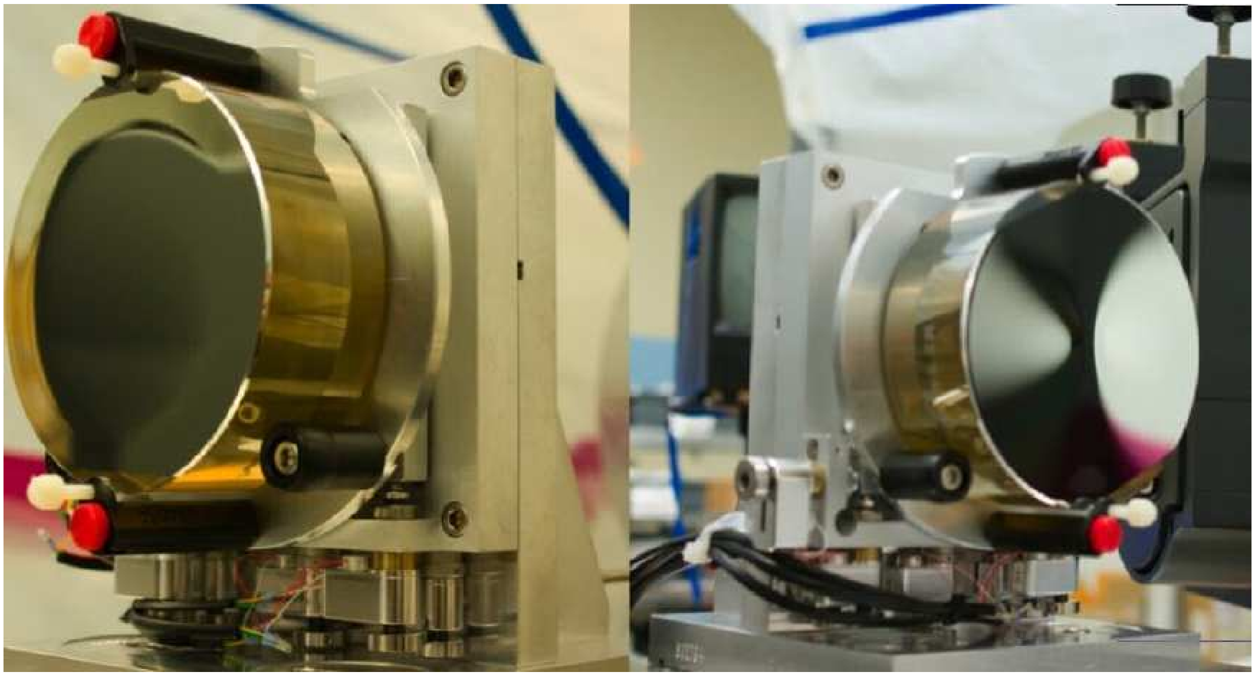

Figure 1. The PIAA coronagraph uses highly aspheric optics to apodize the beam with minimal light loss. This figure shows a set of such mirrors, and their unusual shape. This set was manufactured by Tinsley/L-3 for NASA Ames.

1.2 From simple to advanced PIAA coronagraphs

The simplest form of PIAA coronagraph, which we call the PIAAC, is one where the lossless apodization is used to produce a PSF with minimal diffraction wings. The central bright part of this PSF is then blocked by an opaque focal plane mask to remove starlight while preserving light from nearby sources. An inverse PIAA set may then be used to recover a sharp diffraction-limited image over a useful field of view. This scheme is shown at the top of figure 2.

The same lossless PIAA technique can also be used to replace the apodizer in coronagraph architectures where the starlight rejection is shared between several components (instead of relying entirely on the opaque focal plane mask). This leads to PIAA coronagraph types with higher performance, as the flexibility of using several masks for starlight rejection opens new possibilities. For example, an apodized pupil Lyot coronagraph (APLC) configuration with a PIAA front end is especially attractive, as the full throughput apodization of the PIAA optics greatly enhances the APLC's performance. This coronagraph architecture is shown in the center of figure 2. Performance can be further improved by allowing the focal plane mask to be smaller, partially transmissive and phase-shifting. This allows total on-axis coronagraphic extinction, and a very small IWA. This approach, shown in the bottom of figure 2, is referred to as the PIAA Complex Mask Coronagraph (PIAACMC) in this paper. The PIAACMC concept[11] is, theoretically, the highest performance coronagraph, as it can fully suppress starlight (contrast entirely limited by wavefront control and manufacturing limits) with an inner working angle equal to 0.64 λ/D.

2. CURRENT TECHNOLOGY STATUS

2.1 Testbed facilities

The PIAA coronagraph laboratory testing activities are shared between three facilities.

- The High Contrast Imaging Testbed (HCIT) facility at NASA JPL, which is currently testing a mirror-based PIAA system with wavefront control. The HCIT facility has been testing several coronagraphs, one of them being PIAA, and offers vacuum chambers for ultra-high contrast.

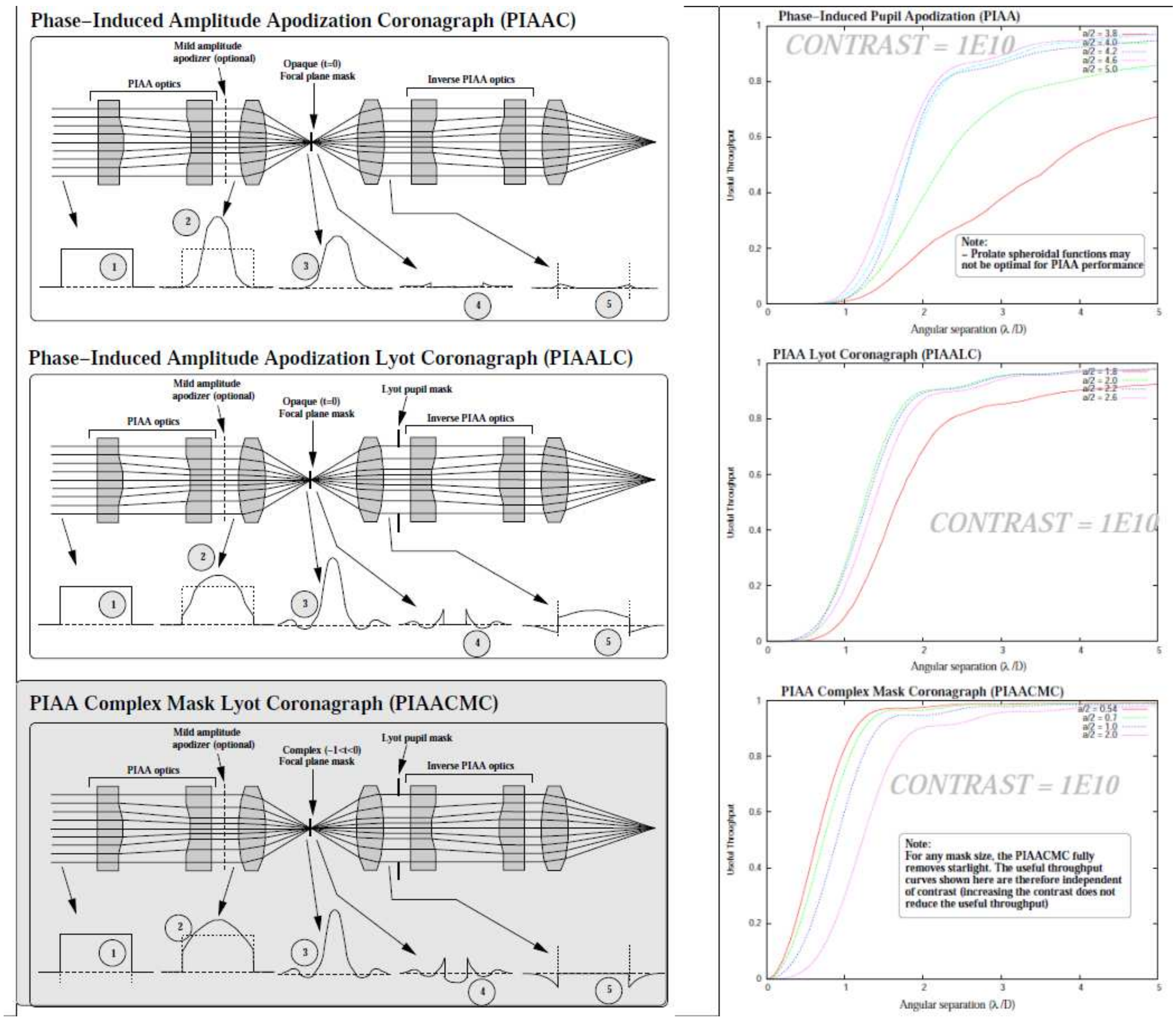

Figure 2. PIAA-based coronagraph architectures (left) and corresponding performance (right), expressed in useful throughput at a 1e10 contrast level. Top row: conventional PIAA coronagraph. Middle row: PIAA / Lyot coronagraph. Bottom row: PIAACMC. Different curves correspond to different focal plane mask sizes.

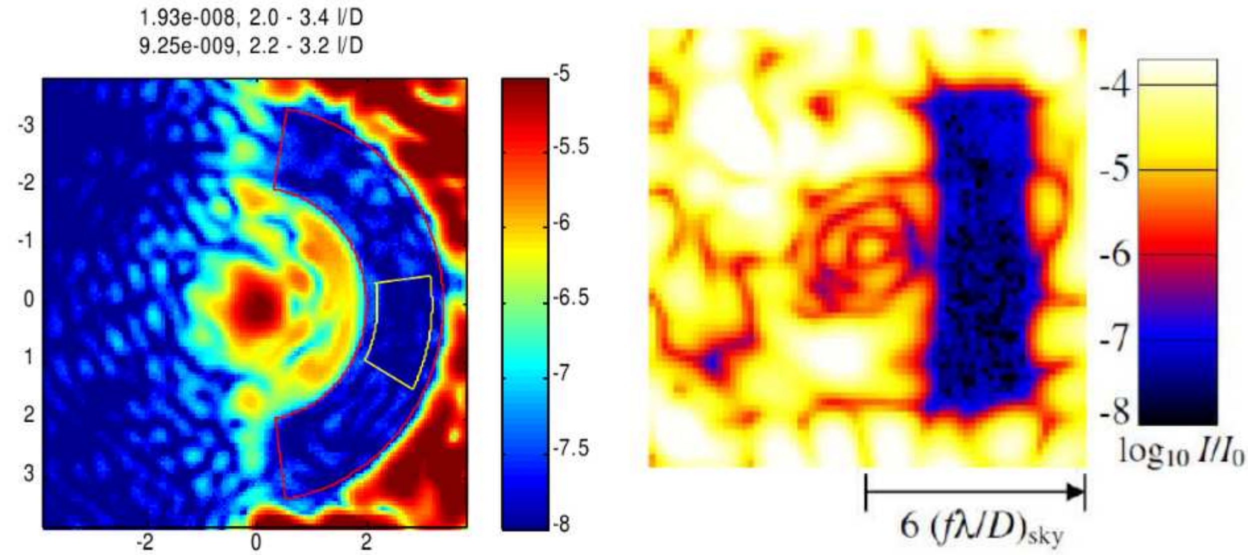

Figure 3. Recent high contrast images obtained with PIAA coronagraphy at the NASA Ames (left) and NASA JPL (right) testbeds. In both images, the central star is located at the center of the image, and the high contrast region is on the right. These images demonstrate contrast around 1e-8 in the 2 to 4 λ/D separation range.

- The coronagraphy laboratory at NASA Ames is a flexible testbed dedicated to the PIAA coronagraph development. It operates a mirror-based PIAA coronagraph in stabilized air, with a MEMS-type deformable mirror for wavefront control.
- The Subaru Telescope, where a refractive PIAA coronagraph system is part of the ground-based Subaru coronagraphic Extreme-AO (SCExAO) instrument, the first system to use a PIAA coronagraph for on-sky observations.

The technology development effort is shared between these facilities, taking advantage of clear complementarity between the testbeds.

2.2 Demonstrating high contrast at 2 λ/D

The main focus of our current NASA-funded effort is to demonstrate 1e-9 raw coronagraphic contrast at 2 λ/D in monochromatic light, and this effort is carried out at the NASA Ames and JPL laboratories. Figure 3 shows high contrast images obtained at these testbeds with PIAA coronagraphy. The current contrast at 2 λ/D is about an order of magnitude from the goal, and has been steadily improving at both testbeds.

Figure 3 shows high contrast images recently obtained at the NASA Ames and JPL testbeds. More details can be found about these results and the testbeds in publications within this conference.

2.3 Ground-based demonstration of PIAA coronagraphy

In addition to laboratory validation of the PIAA at high contrast (aimed at meeting the performance required for direct imaging of potentially habitable planets from space), the PIAA coronagraph is also being implemented for use on a ground-based telescope. The Subaru coronagraphic Extreme-AO (SCExAO) project uses a PIAA coronagraph for high contrast imaging in the near-infrared on the 8.2-m diameter Subaru telescope. This system is described in more detail in separate papers in this conference. Figure 4 shows a top view of the SCExAO coronagraph bench, illustrating the fact that, for such a system, wavefront control is at least as large a part of the effort as are the coronagraph optics (which occupy a very small fraction of the optical bench).

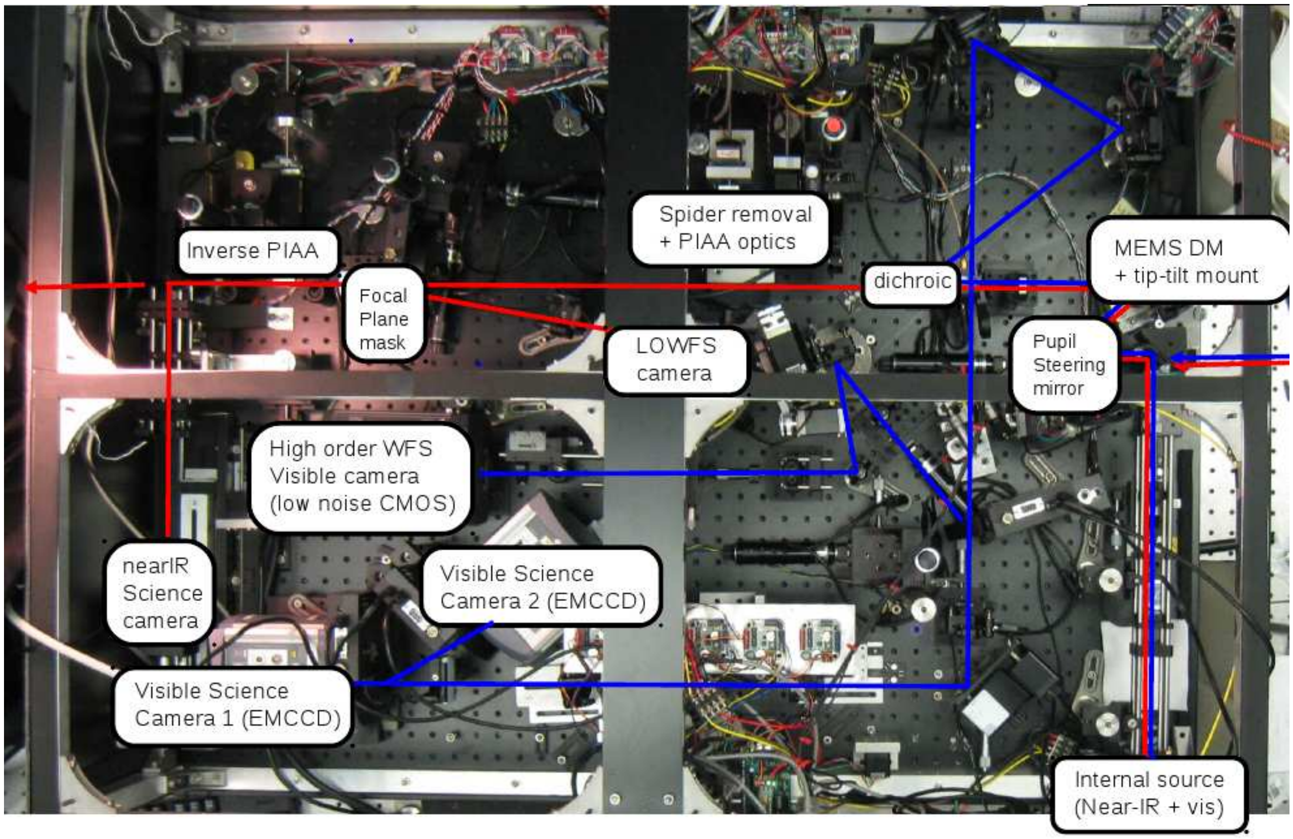

Figure 4. Top view of the SCExAO optical bench. SCExAO is the first ground based coronagraph system using a PIAA, and is used on the 8.2-m Subaru Telescope. Note that most of the components on the optical bench are for wavefront control and calibration, and that the PIAA optics (top center) occupy a small fraction of the bench area.

3. CONCLUSION AND FUTURE DIRECTIONS

Technology development for the PIAA coronagraph is currently aimed at demonstrating 1e-9 contrast at 2 λ/D, using testbeds at NASA Ames and JPL. In parallel to this focused effort, a recent mission concept study[12] as well as the development of the ground-based SCExAO instrument have greatly increased our understanding of how to integrate a PIAA coronagraph with a full coronagraph/wavefront control system.

Current and future technology advances for PIAA include:

- Gaining a better understanding of the interaction between the PIAA coronagraph and the high contrast wavefront control system
- Demonstrating polychromatic high contrast imaging with PIAA coronagraph
- Advancing the technological maturity of more advanced, higher performance (smaller IWA), PIAA architectures, such as the PIAACMC concept. The main challenges to achieving smaller IWA are (1) control of low order aberrations and (2) chromaticity at the focal plane mask level. For both of these challenges, major progress has been achieved recently, and sub-2 λ/D coronagraphy at high contrast thus appears possible

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