Coronagraphs in space

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STScI

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Clementine lunar orbiter star tracker image

Hahn et al. 2002
Las Campanas 2.5 m from the ground

Smith and Terrile 1984
Figure 1. Adaptive optics observations in the J band of the inner disc of β Pictoris, 1996 January 5. The axes are marked in au. Inward of 50 au, the disc mid-plane is inclined with respect to the outer disc mid-plane (dashed line).

Figure 2. The observed vertical deformation of the disc above the outer disc mid-plane. The axes are marked in au. The vertical deformation is measured from the centroid of the brightness distribution in the direction normal to the outer disc mid-plane. The value zero is adopted when the measurement is not possible (closer than 25 au and further than 110 au). The solid line is the linear fit for the inner part. We define the extent of the deformation as the distance at which the slope of the fit starts to decrease. The extent of the deformation is 50 au, and the corresponding inclination 3°.
To illustrate the limitation of current methods and algorithms, we compare the classical RDI subtraction result, the result from KLIP, and the NMF result. The classical RDI subtraction result shows that the north-eastern region is barely seen because of its faintness, and the central dark region is barely seen because of its faintness. The KLIP subtraction result, corrected in the same way as in (a) and (b), is able to reach higher SNR than the classical RDI subtraction result. The NMF result is able to reach higher SNR than the classical RDI subtraction result, even though it is fainter due to the over-fitting of KLIP.
Creating an empirical model of the disk of HD 38393 at one orientation, the synthetic disk was investigated in detail, and by selecting just 9 exposures at each orientation. In our simulation, all the data are described in the NMF method in detail, and Appendix §4 shows the results of NMF with modelized components from the references, and modeled the update rules proposed by Pueyo et al. (2016) and cut the exposures into scope orientations. We obtained all public HST data of classical and NMF results are both consistent with the known circumstellar disk example, where the applicability of NMF is necessary because of the relatively short wavelength of the derived implications. In terms of the radial profile for the HD 181327 disk (Stark et al. 2017), KLIP is not only unable to recover the radial profile and angular extent of the disk, but loses the details (e.g., the radial profile, the disk model; KLIP recovers the general morphology of the disk, but loses the details (e.g., the radial profile, the disk model)).

We aim at checking the effectiveness of NMF in Direct Imaging, and compare them with NMF, we took data from the Space Telescope Imaging Spectrograph (STIS) coronagraphic BAR5 mask of STIS. The disk is systematically dimmer than the other two methods (especially the radial slope of the disk): it is over-fitting the disk, but loses the details (e.g., the radial profile, the disk model). In the close-in regions (inside the primary ring), NMF is able to reach higher SNR than the classical result for the HD 181327 primary ring, which might be caused by 1) the classical subtraction may not be absolutely correct; and 2) the BFF procedure needs diskless pixels to find the subtraction result, which have in-exposure for the distance dependent illumination factor as in Jang-Condell & Turner (2012). Another disadvantage of the classical method is the residuals will be over-subtracted especially the northwest debris, might be biasing the result. The KLIP subtraction result, corrected in the same way as in (a) and (b). (Figure 10.)

KLIP recovers the general morphology of the disk, but loses the details (e.g., the radial profile, the disk model). In the close-in regions (inside the primary ring), NMF is able to reach higher SNR than the classical result for the HD 181327 primary ring, which might be caused by 1) the classical subtraction may not be absolutely correct; and 2) the BFF procedure needs diskless pixels to find the subtraction result, which have in-exposure for the distance dependent illumination factor as in Jang-Condell & Turner (2012). Another disadvantage of the classical method is the residuals will be over-subtracted especially the northwest debris, might be biasing the result. The KLIP subtraction result, corrected in the same way as in (a) and (b). (Figure 10.)
Leanings from HST:

• Stability and post-processing help a lot.

• Thinking about coronagraphs matters.
What is a modern stellar coronagraph?

- GPI/SPHERE
- JWST
- WFIRST
- Afterwards
Figure 1. Basic layout of an APLC is similar to a classical Lyot coronagraph, with an upstream apodized pupil in plane A. Hard-edged focal masks are placed in the focal plane B, and a Lyot stop identical to the entrance pupil in plane C. A remarkable difference between APLC and classical Lyot is that APLCs do not require to undersize the Lyot stop.

Figure 2. Two complementary approaches to improve the Lyot coronagraph where the pupil amplitude and the wave diffracted by the mask (Equation (3)) do not match one another (left). The subtraction can be improved by producing a flat diffraction term using a band-limited mask (Kuchner & Traub 2002; top right), or by using an optimal pupil apodization of the pupil (bottom left).

\[ \Phi(r) = \varphi_0(r) / \max_r(\varphi_0(r)) \]

If the focal plane mask \( M \) is symmetric, the Fourier transform of its index function, \( \hat{M} \), is symmetric and the eigenfunctions are real. If the mask is not symmetric, its Fourier transform is Hermitian and the eigenvalues \( \Lambda_n \) are real, but the eigenfunctions are complex. In the following, we will only consider symmetric focal plane masks (e.g., circular), since there is no particular reason to choose an asymmetric mask in most common cases, and the symmetry of the mask guarantees a real apodizer.

One of the possible criteria to evaluate the performance of a coronagraph here is residual energy inside the Lyot stop (here identical to the pupil), normalized to the apodizer throughput. This criterion finds a very simple expression as a function of the eigenvalue:

\[ e = \frac{\int P |\Psi_C(r)|^2 \, dr}{\int P |\Psi_A(r)|^2 \, dr} = (1 - \Lambda_0)^2. \]

As discussed by Ferrari et al. (2007), important analytical simplifications are obtained if the mask domain \( M \) is a scaled version of the pupil domain \( P \). More generally, prolate solutions exist in any case, and we will study in Section 3.2 the impact of the choice of the mask geometry on the overall performance.

2.3. Multistage APLC

It is remarkable that the Lyot stop amplitude is proportional to the entrance pupil amplitude, inside the aperture area \( P \), even in the presence of secondary mirror support structures.
Soummer et al., 2003

Linear optimization problem with “analytical” solution.
The subtraction can be improved by producing a flat diffraction term using a band-limited mask (Kuchner & Traub). The eigenfunctions are complex. In the following, we will only consider the prolate case, i.e., we will deal with eigenvalue problems and we can recognize the prolate apodizer. In broadband, with the optimum solution, the field amplitude be proportional to a prolate function. In the case where the support structures are not included in the design, the apodization is therefore a scaled hard-edged mask, this is only verified data. We calculate the eigenfunctions using a numerical algorithm and approximate the required wavelength variation (Soummer et al.). After the Lyot stop, the residual light is diffracted in the Lyot plane and has to be mitigated by the Lyot stop optimization. In the case of pupil rotation, small features like segmentation and the Lyot plane enables the possibility of multiple-stage coronagraphy. Once the geometry of the mask has been chosen, we calculate the eigenfunctions using a numerical algorithm and approximates the required wavelength variation (Soummer et al.).

**Figures and Images:**
- **Figure 1:** Basic layout of an APLC is similar to a classical Lyot coronagraph, with an upstream apodized pupil in plane A. Hard-edged focal masks are placed in the focal planes B, C, and D.
- **Figure 2:** Linear optimization problem with “analytical” solution.
- **Figure 3:** Hard edge at focus. Grayscale screen in pupil.
- **Figure 4:** Schematic representation of the iterative algorithm to generate prolate apodizers. Starting with an initial estimate, we propagate to the Lyot plane, and we detail the mathematical demonstration of this property in [Aime et al. 2002] and [Sivaramakrishnan & Yaitskova 2005].

**Equations:**
- \( r \overline{\Phi} = r \hat{\Phi} \)
- \( \hat{\Psi} r \hat{\Phi} = \hat{\Psi} r \overline{\Phi} \)
- \( \overline{\Lambda} r \overline{\Phi} = \overline{\Lambda} r \hat{\Phi} \)
- \( \hat{\Lambda} r \hat{\Phi} = \hat{\Lambda} r \overline{\Phi} \)
- \( \hat{\Lambda} r \hat{\Phi} = \hat{\Lambda} r \overline{\Phi} \)

**References:**
- Aime et al. 2002
- Sivaramakrishnan & Yaitskova 2005
- Soummer et al. 2007
have a nonzero projection onto the first eigenfunction consider the pupil itself these two regimes can be understood by comparing the scales of and by we obtain pupil complex amplitude is propagated to the Lyot plane, and Figures Depending on the obstruction and mask size, we identify two APLC to central obstruction in a circular aperture, with circular amplitude and limited to the pupil:

\[
\Psi_A(0) + \Psi_C(0), \quad \text{the convergence of the algorithm to the first eigenvalue is 0,}
\]

\[
\sum_{n=1}^{\infty} \lambda_n \Psi_n(0) \Psi_n(1) - \sum_{n=1}^{\infty} \Lambda_n \phi_n(0) \phi_n(1)
\]

\[
\mathbf{P}.
\]

\[
\mathbf{r}/\text{max} \quad \mathbf{D} \quad \hat{\mathbf{M}}
\]

\[
\mathbf{r}/\alpha \quad \mathbf{D} \quad \hat{\mathbf{A}}
\]

\[
\mathbf{D}/2
\]

\[
\mathbf{F}
\]

\[
\mathbf{LF}
\]

\[
\mathbf{D}/H20885
\]

\[
\mathbf{HST}/H11002
\]

\[
\mathbf{CFHT}
\]

\[
\mathbf{Palomar}
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\[
\mathbf{HST}
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\[
\mathbf{Subaru}
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\mathbf{Subaru}
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\[
\mathbf{VLT/Gemini}
\]

\[
\mathbf{AEOS}
\]

\[
\text{Soummer et al., 2007}
\]

\[
\text{Case of GPI/SPHERE: 10^{-6} contrast @ 300 - 400 mas}
\]
VLT 8 m from the ground

Lagrange et al., 2009
Wang et al., 2016
events, and in Figure 3. For an edge-on orbit that resides within 1\textdegree, it is more likely to find material within half a Hill sphere. Transit of the Hill sphere will occur. We pick five notable events to focus on: two are the ingress and egress of the host star. Assuming an angular diameter of the star, the Hill sphere of mass from our MCMC orbit fit, \(12\text{M}_\odot\) for \(59.7\text{M}_\odot\). Thus, regardless of systematic astrometric calibration, we direct the reader to Morzinski et al. (2015) and the feasibility of the FEB scenario proposed by Morzinski et al. (2015) and the results are shown in Table 2. Residuals to the orbit fit for the average of 500 randomly-chosen accepted orbits. The top row shows the residuals in red.

Thus, the well-behaved residuals of our GPI measurements. The lack of increase in residuals is consistent with zero, the lack of change indicates that this technique is both accurate and precise. The consistency of repeated measurements, the lack of increase in residuals, the validity of BKA all indicate that this technique is both accurate and precise. The weighted mean, \(4.1\), the consistency of repeated measurements, the lack of increase in residuals, the validity of BKA all indicate that this technique is both accurate and precise.

Drift Phoenix

\(T_{\text{eff}} = 1700\text{ K}\)
\(R = 1.41\ \mathcal{R}_{\text{Jup}}\)
\(\log g = 3.5\ [\text{dex}]\)
\(\log L_{\text{bol}}/\mathcal{L}_{\odot} = -3.81\)
\(\chi^2 = 1.55\)

Chilcote et al., 2017

\(T_{\text{eff}} = 1700\text{ K}\)
\(R = 1.41\ \mathcal{R}_{\text{Jup}}\)
\(\log g = 4.0\ [\text{dex}]\)
\(\log L_{\text{bol}}/\mathcal{L}_{\odot} = -3.80\)
\(\chi^2 = 1.81\)
match one another (left). The subtraction can be improved by producing a flat diffraction term using a band-limited mask (Kuchner & Traub 2009).

Two complementary approaches to improve the Lyot coronagraph where the pupil amplitude and the wave diffracted by the mask (Equation 2) is symmetric, the Fourier transform is obtained for the Lyot as well as the general case. A formal proof of its inflexion is obvious in Figure 1 (b) reductions. The contrast on the y-axis refers to the companion to host star brightness ratio with a 50% completeness and a false positive rate of 0.05 per epoch. The detection threshold is set to 5 \times 10^{-6} contrast respectively, in order to always yield the same number of false positives. A total of 330 GPIES simulated planets.

The mask sizes are optimized for broadband and have a typical diameter of 10% of the wavelength for coronographs for the T-type and L-type reductions respectively, in order to always yield the same number of false positives. A total of 330 GPIES planets.

The peak value of the PSF is normalized to the one without focal mask sizes are optimized for broadband and have a typical diameter of 10% of the wavelength for coronographs.
GPI/SPHERE:

• Coronagraphs work, we can find and characterize planets!

• Can we make coronagraphs more robust to observing conditions?

• What do these planets look at longer wavelengths?
Grayscale at focus.
Hard edge in Lyot plane.

Linear optimization problem with analytical solution on a circle.
Trauger and Traub, 2007

Iteration #1

Contrast (normalized by the occulter transmission)

D shape region
Small box

Iteration
events, and in Figure transits the star, we should see no significant change in dial extent. Almost all stable prograde circumplanetary significance. This tight constraint on the inclina-

we need in order for the planet to tran-

in the bris disk and the FEB scenario, we direct the reader to Figure 5 and considering the of 0.736 mas (Pic b will transit its orbit of +0

The biggest improvement in our understanding of the masses from our MCMC orbit fit,

Thus, regardless of systematic astrometric calibration have ruled out the possibility that in the satellite spot ratio in that band was used. We using Equation (1) to explain redshifted absorption features on the resolution of GPI, was used to approximate the

Thus, the well-behaved residuals of our GPI mea-

Figure 8 rating bodies (FEBs) scenario proposed by Millar-Blanchaer et al.

To deviate from unity. Due to systematic astrometric calibration have plotted the measured data and 500 randomly-chosen accepted orbits from the MCMC sampler. 

result of the preliminary high-pass filter step before the KLIP PSF subtraction, carried out in order to mitigate on the spatial frequencies. The best fit results span a large parameter space. We present in this study are plotted as light gray points. Synthetic photometry (open blue and red squares) was computed for each of the di

Figure 5

0 6 12 18
Wavelength (µm)
0 .0
0 .2
0 .4
0 .6
0 .8
1.0
⇥
Drift Phoenix Photo. only
T eff = 1700 K
log g =3.5 [dex]
R =1.41 R Jup
log L bol / L ⊙ = 3.80
χ 2 ν =1.55

GPI & Photo.
T eff = 1700 K
log g =4.0 [dex]
R =1.41 R Jup
log L bol / L ⊙ =3.80
χ 2 ν =1.81

Chilcote et al., 2017
HR8799 characterization with HST

Fig. 4.—

Top: Model fits to HR8799b data. In the figure the red circles are HST photometry, and the blue squares are ground-based photometry, with the filter width shown as cyan bars at the bottom of the plot. The black and green lines (and corresponding circles) are the model spectra fitted to the full dataset. Bottom: The black line is the Konopacky et al. (2013) HR8799c model. The ground-based photometry in this paper comes from Marois et al. (2008); Currie et al. (2011); Oppenheimer et al. (2013); Currie et al. (2014); Skemer et al. (2012, 2014); Galicher et al. (2011). The blue star for HR8799c is the J-band photometry from Oppenheimer et al. (2013).

There are two prior reported values for HR8799c - a P1640 spectrum (Oppenheimer et al. 2013) and a Keck J-band flux (Marois et al. 2008). The ground-based J-band photometry for HR8799c is approximately twice as bright as the measured HST flux. Integrating the HR8799c flux calibrated P1640 spectrum through the F127M filter matches the HST photometry to within 2–.

A potential solution for this discrepancy might be intrinsic photometric variability caused by heterogeneous cloud layers, which we find is not required in our model fits. The early ground-based photometry might also have suffered from calibration issues which combined by the intrinsic variability of the star might explain some of the difference in flux measurement.

Efforts to match synthetic spectra to the ensemble of photometric data for HR8799b result in effective temperatures and corresponding radii that are smaller by \( \sim 50\% \) (0.69 – 0.92 \( R_{\text{Jup}} \)), than predicted by theoretical brown dwarf and giant planet cooling tracks (see Marley et al. 2012, for a summary). Difficulty finding a model spectrum that simultaneously matches the near and mid-IR photometry could be due to the non-contemporaneous nature of the observations or perhaps the model-observation inconsistencies at multiple bands are an indication of large-scale flux variations. Large variability would bias such model comparisons. For example, the bright J-band flux from Marois et al. (2008) is more consistent with higher effective temperatures than our HST F127M flux. The deep water absorption demonstrates that the atmospheres of both b and c are not enshrouded in high altitude hazes or clouds many pressure scale heights thick, important for many transiting exoplanets (Kreidberg et al. 2014). Nonetheless, clouds are important in shaping the overall SED of the planets. Both best-matching models plotted in Fig. 4 (top panel) have clouds composed primarily of Iron and Magnesium-Silicate grains, located in the near-infrared photosphere. The cooler model has a cloud located at \( P_{\text{gas}} \sim 1 \) bar and extending upward 1 pressure scale-height. The warmer (and higher gravity) model has a cloud base near 10 bar, extending upward 2 pressure scale-heights. Using single models to reproduce the observations assumes global cloud coverage which is probably an overestimation.

With spectral energy distributions well sampled observationally and with model spectra that match reasonably well, the bolometric luminosities of both planets can be estimated, and we determine \( L_{\text{bol}} \) values of -5.1 ± 0.1.
Case of JWST NIRCam: 10^{-4} contrast @ 500 - 600 mas

1-5 µm
5 Band-limited coron.
3 circular; 2 wedge

- Optimized for 2.1 - 4.6 µm.
  22 wide, medium, narrow filters from 0.7-4.8 µm
- Spot occulters provide 360° azimuthal coverage for disk observations and planet search.
- Wedge occulters provide better diffraction suppression at small separations for characterization of known planets, and allow selection of inner working angle.
- Inner working angles ~ 4-6 lam/D
- See Krist et al. 2007, 2010; Beichman et al. 2010.
JWST MIRI

- 4 coronagraphs.
- Ammonia on/off
- + “continuum” at 15 microns

\[ \text{~10 microns NH}_3 \text{ feature, Saumon et al. (1999)} \]
One of the possible criteria to evaluate the performance of a coronagraph here is residual energy in the Lyot stop (here, not shown). The subtraction can be improved by producing a flat diffraction term using a band-limited mask (Kuchner & Traub, 2002 PASP, 114, 1479-1486).

Figure 1. Two complementary approaches to improve the Lyot coronagraph where the pupil amplitude and the wave diffracted by the mask (Equation (10)) the coronagraphic image where the companion is clearly visible. Images are displayed with nonlinear scale.

A remarkable difference between APLC and classical Lyot is that APLCs do not require to the entrance pupil in plane C. A remarkable difference between APLC and classical Lyot is that APLCs do not require the radial symmetry of the Airy pattern. However, it must be clear that the AIC, an advantage is the lack of image flip that could be otherwise perfect. However, the performance of the APLC, an advantage is the lack of image flip that could

The phase-mask shape of Equation (9) is displayed in intensity, as illustrated in Figure 3, where the monochromatic radial profile is shown in the standard aperture (FQ-PM) using IDL (a color version of this figure is available in the online journal.).

No. 1, 2009 APLCs FOR ARBITRARY APERTURES. II. 697

The focal plane mask is no particular reason to choose an asymmetric mask in most cases and in the case where an FQ-PM is used. Compared to the classical coronagraph, the main advantage is that the AIC, an advantage is the lack of image flip that could be an advantage. However, a faint companion lying exactly along an axis of the mask is attenuated by about 2.15 mag owing to the star. However, a faint companion lying exactly along an axis of the mask is attenuated by about 2.15 mag owing to

The focal plane mask is symmetric, the Fourier transform is Hermitian and the eigenvalues of its index function, we obtain a new set of equations for the four planes: If the focal plane mask is symmetric, its Fourier transform is real and the eigenfunctions are complex. In the following, we will only consider symmetric focal plane masks (e.g., circular), since there is no particular reason to choose an asymmetric mask in most common cases, and the symmetry of the mask guarantees a real rejection factor is more than 10.5 even in the presence of secondary mirror support structures:

![Phase at focus. Hard edge in Lyot plane.](image)

Linear optimization problem with analytical solution on a circle.
MIRI Coronagraphs: Quad Phase Masks + Lyot

5-25 μm

3x4 quadrant phase masks at 10.65, 11.4, 15.5 μm
to get NH₃ abundances and continuum slope

Inner working angle ~ 1 lam/D

Classical Lyot coron for 23 μm

Inner working angle = 2.1 arcsec

Also: imaging with any other NIRCam filter, using the spot or its narrow support bar but no matching Lyot stops

Case of JWST MIRI: 10^-3 contrast @ 500 - 600 mas
-45°: cold pitch

+5°: hot pitch

Worst Case Thermal Slew

Wavefront Drift (nm)

Time (days)

Courtesy of M. McElwain, S. Knight
-45°: cold pitch

+5°: hot pitch

WFE after 10 ksec

WFE after 1 day

WFE after 14 days

Courtesy of M. McElwain, S. Knight
Courtesy of M. McElwain, S. Knight
Small Grid Dithers

See: https://blogs.stsci.edu/newsletter/files/2016/01/Lajoie.pdf

HCIS Workshop, Nov 14th 2016

Lajoie et al., 2014
Small Grid Dithers

See:
https://blogs.stsci.edu/newsletter/files/2016/01/Lajoie.pdf
http://spie.org/Publications/Proceedings/Paper/10.1117/12.2057190
HCIS Workshop, Nov 14th 2016

Monday, November 14, 16

Lajoie et al., 2014
JWST:

- Can we make coronagraphs optimized for on-axis/segmented apertures?
- Active wavefront control (or lack thereof) really matters!
- We will learn a lot about thermal stability at L2.
Sunlike star with a Jupiter at 2 AU shepherding dust clumps

Courtesy of M. Rizzo
The analysis of extrasolar planet reflection spectra (as of 2010) has been preformed to date by Oberg et al., and the retrievals have been preformed to date by Marley et al. In this section we provide a brief overview to a few of the techniques that have been developed for estimating albedo, cloud properties, and atmospheric thermal profile.

The retrievals were designed to estimate geometric albedo, cloud properties, and atmospheric thermal profile. We aim to develop a method for estimating these characteristics from reflected light spectra for extrasolar giant planets. We present a first step in this development as we have generated a first set of exoplanet albedo spectra. The results of this study are given in Section 8.

The retrieved results from the Bayesian retrieval scheme, followed by its validation in Section 6, and the atmospheric thermal profile will all be unknown. As this will be a complex endeavor we approach the problem computationally as well. As this will require the application of retrieval methods to the available data.

The geometric albedo is the ratio of light received from a planet when observed at full phase to that which would be measured from a perfectly reflective Lambert disk of the same size as the planet. Because the angular distribution of light scattered by a real atmosphere differs from that scattered by a Lambert disk, the geometric albedo of even a perfectly scattering atmospheres is not unity. For a conservative, infinitely deep Rayleigh scattering atmosphere, the geometric albedo of a perfectly reflective Lambert disk is 0.75. The fractional reflectivity of light reflected from a planet is determined by metallicity, e.g., the C/O ratio. In future papers we will add retrievals for orbital period, star-planet distance, planet size, additional absorbers, and methane mixing ratio. In future papers we will add retrievals for orbital period, star-planet distance, planet size, additional absorbers, and methane mixing ratio. We believe that a Bayesian approach to this problem is the best choice.
Effect of $fCH4$ variation

Courtesy of R. Lupu, M. Marley

- $fCH4 = 10^{-1}$
- $fCH4 = 10^{-2}$
- $fCH4 = 10^{-3}$
- $fCH4 = 10^{-4}$

Geometric Albedo

Wavelength ($\mu$m)

0.4 0.5 0.6 0.7 0.8 0.9 1.0
\[ \log(fCH_4) = -2.35^{+1.38}_{-0.59} \]

\[ \log(g) = 1.11^{+0.86}_{-0.73} \]

\[ \log(P) = -1.86^{+1.44}_{-1.56} \]

Courtesy of R. Lupu, M. Marley
complex obscuration pattern significantly affects the design and performance of the coronagraph, and most current techniques require modifications to handle it.

Fig. 1 - The AFTA telescope obscuration pattern. The "old" pattern on the left includes metrology markers along the edge of the secondary obscuration. Because the primary and secondary mirrors will be refigured and recoated, these will be removed so that the pupil will look like the "new" pattern on the right. All of the coronagraph designs presented here are for the "old" pattern except for the revised PIAACMC, which uses the new one (the markers do not significantly affect the performance either way).

A variety of configurations we proposed for the AFTA coronagraph: the hybrid Lyot coronagraph (HLC), phase-induced amplitude apodization with complex mask coronagraph (PIAACMC), shaped pupil coronagraph (SPC), and a combination of a vector vortex coronagraph (VVC), shaped pupil mask, and obscuration apodization using deformable mirrors (Active Compensation of Aperture Discontinuities, or ACAD). Two varieties of interferometric coronagraphs were also considered: a DAVINCI visible nuller coronagraph (VNC) and a phase-occulting VNC (POVNC). All of these techniques are still technologically immature to some degree, along with the wavefront sensing and control methods that will be required to compensate for optical aberrations and pointing errors. None of these have yet been demonstrated on testbeds with obscured pupils with the performance necessary in an AFTA flight instrument (some only exist in conceptual form). In order to meet the goal of deciding in the next couple of years if a coronagraph is a valid additional instrument for AFTA, any design would have to undergo accelerated development and hardware demonstrations.

Given the resource constraints of time, funding, and facilities, not all of these techniques could be supported, so an informed downselect was necessary. NASA formed the AFTA Coronagraph Working Group (ACWG) in 2013 to undertake an intensive study of their predicted performances and likelihoods of hardware flight readiness in the required timescale. Key to this was numerical modelling of each technique in a simulated system with realistic optical aberrations and wavefront control. All of the systems in the downselect were evaluated over a $\Delta \lambda/\lambda = 10\%$ bandpass of 523–578 nm. The results were converted to science performance metrics (e.g., number of planets that could be detected and characterized in a given time span). Each coronagraph had an advocate who provided the design (focal and/or pupil plane mask parameters, wavefront remapping functions) to be evaluated. The selected techniques had to be: 1) capable of operating within a $10\%$ bandpass somewhere between $\lambda = 430$–980 nm; 2) be able to detect at least $10$ radial-velocity-detected gas giant planets of between 4–14 Earth radii in reflected light with contrasts $>10^9$ assuming 1.6 mas RMS of pointing jitter and a factor of 10 reduction in the background speckle noise from post-processing; 3) detect circumsolar disks with $6 \times 10^{-9}$ contrasts (equivalent Airy WFIRST
Binary pupil mask
Hard edge in focal plane.

Kasdin et al., 2004
Zimmerman et al., 2015
Krist et al. 2015

Linear optimization problem.
The contrast results are given in Table 1.

The characterization SPC produces a field rebinned. This is interpolated to a higher sampling, the stop applied as a binary mask that multiplies the wavefront to the entrance pupil in plane C. A remarkable difference between APLC and classical Lyot is that APLCs do not require to ask is applied.

Kasdin et al., 2004
Zimmerman et al., 2015
Krist et al. 2015

Linear optimization problem.
Binary Lyot Mask. Grayscale amplitude and phase focal plane mask. Deformable Mirrors.

Non-linear optimization problem.

Trauger et al., 2015
Krist et al., 2015
Binary Lyot Mask.
Grayscale amplitude and phase focal plane mask.
Deformable Mirrors.

Convergences (WFIRST aperture, Ch. 6 PAVC, 10% BW)

- Lyot stop IR=55%, N_{oct}=48, F=4.2\times10^3 (WFIRST setup)
- Lyot stop IR=55%, N_{oct}=48, F=5.4\times10^2 (optimal setup)
- Lyot stop IR=46.1%, N_{oct}=48, F=5.4\times10^2 (optimal setup)
- ACAD-OSM stops and builds a new interaction matrix
Simulations in Section 2 are then by exploring the parameter space using numerical techniques, we will start by comparing the performance of the DM setup on the performance of the ACAD-OSM solution obtained by ACAD-OSM with different discreet wavelengths equally sampled. This was effective and allowed for better contrast after jitter.

Figure 1.

<table>
<thead>
<tr>
<th>Aperture</th>
<th>Downselect HLC radial mean contrast ($\lambda = 523 \text{ nm}$)</th>
<th>Downselect HLC contrast ($\lambda = 523 \text{ nm}$)</th>
<th>Final PSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM-1</td>
<td>$3.6 \times 10^{-9}$</td>
<td>$3.6 \times 10^{-9}$</td>
<td>$3.6 \times 10^{-9}$</td>
</tr>
<tr>
<td>DM-2</td>
<td>$4.1 \times 10^{-9}$</td>
<td>$4.1 \times 10^{-9}$</td>
<td>$4.1 \times 10^{-9}$</td>
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</tbody>
</table>

Note that running EFC on the aberrated system after running EFC an influence on the final performance of ACAD-OSM, we did not discuss at all the impact of how to optimize the ACAD-OSM technique in the case of “small” wavefront aberration control. We use several metrics to describe the performance of the ACAD-OSM I. The wavefront estimation in focal plane correction; (middle) aberrated system after running EFC; (right) with EFC solution and adding 1.6 mas RMS of jitter. This was effective and allowed for better contrast after jitter.

Trauger et al., 2015
Krist et al., 2015

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Trailler

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Deformable Mirrors.
- Disturbance: WFIRST Cycle 5 CBE
- ACS LoS drift
- LoS jitter @ RW of 10 rev/sec (worst case)
- Small plot shows the zoomed in region

Shi et al., 2015
WFIRST:

• WFIRST will measure atmospheric properties of exoplanets very similar to our outer solar system.

• WFIRST will mature technologies for future missions.

• We are entering the real of nonlinear optimizations applied to coronagraphy.
LUVOIR/HabEx
ExoEarth candidates as function of aperture

Stark et al. (2014)

Stark et al., 2014
Figure 1. Basic layout of an APLC is similar to a classical Lyot coronagraph, with an upstream apodized pupil in plane A. Hard-edged focal masks are placed in the focal plane B, and a Lyot stop identical to the entrance pupil in plane C. A remarkable difference between APLC and classical Lyot is that APLCs do not require to undersize the Lyot stop.

(A color version of this figure is available in the online journal.)

Figure 2. Two complementary approaches to improve the Lyot coronagraph where the pupil amplitude and the wave diffracted by the mask (Equation (3)) do not match one another (left). The subtraction can be improved by producing a flat diffraction term using a band-limited mask (Kuchner & Traub 2002; top right), or by using an optimal pupil apodization of the pupil (bottom left).

(A color version of this figure is available in the online journal.)

\[
\Phi(r) = \frac{\phi_0(r)}{\max_r(\phi_0(r))},
\]

and writing as \( \Lambda_0 \) the associated eigenvalue, we obtain a new set of equations for the four planes:

\[
\begin{align*}
\Psi_A(r) &= P(r) \Phi_0(r), \\
\Psi_B(r) &= \hat{\Psi}_A(r)(1 - M(r)) , \\
\Psi_C(r) &= (1 - \Lambda_0) \Phi_0(r) P(r), \\
\Psi_D(r) &= (1 - \Lambda_0) \hat{\Psi}_A(r),
\end{align*}
\]

If the focal plane mask \( M \) is symmetric, the Fourier transform of its index function, \( \hat{M} \), is symmetric and the eigenfunctions are real. If the mask is not symmetric, its Fourier transform is Hermitian and the eigenvalues \( \Lambda_n \) are real, but the eigenfunctions are complex. In the following, we will only consider symmetric focal plane masks (e.g., circular), since there is no particular reason to choose an asymmetric mask in most common cases, and the symmetry of the mask guarantees a real apodizer.

One of the possible criteria to evaluate the performance of a coronagraph here residual energy inside the Lyot stop (here identical to the pupil), normalized to the apodizer throughput. This criterion finds a very simple expression as a function of the eigenvalue:

\[
e = \frac{\int P \vert \Psi_C(r) \vert^2 dr}{\int P \vert \Psi_A(r) \vert^2 dr} = (1 - \Lambda_0)^2.
\]

As discussed by Ferrari et al. (2007), important analytical simplifications are obtained if the mask domain \( M \) is a scaled version of the pupil domain \( P \). Generally, prolate solutions exist in any case, and we will study in Section 3.2 the impact of the choice of the mask geometry on the overall performance.

2.3. Multistage APLC

It is remarkable that the Lyot stop amplitude is proportional to the entrance pupil amplitude, inside the aperture area \( P \), even in the presence of secondary mirror support structures:

\[
\begin{array}{c}
\text{Working angle range 4 - 9 } \lambda/D, 10\% \text{ bandpass, } T_{0.7/\text{circ}} = 7.65\%
\end{array}
\]
the tools presented in this paper and provide an example simulations in Section

then by exploring the parameter space using numerical ACAD-like techniques, first theoretically in Section

the influence of the DM setup on the performance of

then address the most important point of this article, throughput performance of the resulting DH. We will

can choose to optimize preferentially the contrast or the

Section

the same aperture in Section

obtained by ACAD-OSM with di

technique, we will start by comparing the performance

of future large missions.

However, in ACAD-OSM I, we did leave open three

•

ments misalignments as well as for phase and am-

providing a simple active framework to compensate

Wavefront control commands can be superposed on

lan & Green OSM follows the theoretical predictions from

fied that there exists a well behaved regime of DM

ultimate BW of such and instrument will be driven

The contrast obtained by the ACAD-OSM solution

3 discreet wavelengths. Once the DM shape solutions

amplitude and phase errors directly in the focal plane

is assumed to be perfect. Several method have been de-

ACAD-OSM I. The wavefront estimation in focal plane

tered around the central wavelength and equally spatially

are obtained, we use a large number of wavelengths cen-

3 discreet wavelengths. Once the DM shape solutions

cases built at di

the interaction matrix is the concatenation of several ma-

\( \lambda \)

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\( z \)

\( D_M \)

\( D_{ap} \)

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\( D \)
Throughput (encircled energy) (%) vs. Angular offset ($\lambda/D$)

- **Coronagraph Only (Flat DMs)**
- **Coronagraph + optimized DM shapes**

Courtesy of K. Fogarty and J. Mazoyer
2. Planets move detectable planets may not stay detectable

<table>
<thead>
<tr>
<th>Visit</th>
<th>$\Delta t$</th>
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<th>$t_{detect}$</th>
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<td>0.00 y</td>
<td>0.053</td>
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<tr>
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<td>0.053</td>
<td>0.22 h</td>
</tr>
<tr>
<td>4</td>
<td>0.32 y</td>
<td>0.053</td>
<td>0.25 h</td>
</tr>
<tr>
<td>5</td>
<td>0.61 y</td>
<td>0.035</td>
<td>0.18 h</td>
</tr>
</tbody>
</table>
A long journey:

• We have learned a lot about coronagraphs since 1932! We can know build a coronagraphs pretty much for any telescope.

• The hard part is to put coronagraph and wavefront control all together in an instrument.
Historical perspective on Extreme AO systems

On 19 June 2004, 2M1207 and its GPCC were simultaneous reductions using NACO spectroscopic mode. The spectra of 2M1207 and its GPCC were extracted and calibrated down to 3σ. In Fig. 1 and 2, we displayed the extracted spectra by the spectra of a standard star. The spectra of 2M1207 and its GPCC were extracted and calibrated in wavelength with a platescale of 27.03 and 27.12 mas.

The spectra of 2M1207 and its GPCC were simultaneous. The contrasts between 2M1207 and its GPCC are reported for multiple lines of evidence point toward membership of 2M1207 in the TWA. The radial velocity is also consistent with TW Hydrae Association. The motion of 2M1207 is consistent with membership in the TW A. The TWA. The companion of 2M1207. The radial velocity is also consistent with membership in the TW A. The companion was not detected in J band.

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S54 camera (54 mas filters K results are reported in Table 2. The transformations between H, K and L previously observed using the NACO spectroscopic mode. The low errors.

Deconvolution algorithm time and the number of integrations. SR and FWHM correspond respectively to an individual integration. SR and FWHM correspond respectively to a platescale of 27.03 and 27.12 mas. DI Table 1.

Divided the extracted spectra by the spectra of a standard star and calibrated in wavelength with instrument, we divided the extracted spectra by the spectra of a standard star.

The spectra of 2M1207 and its GPCC were extracted and calibrated in wavelength with historical perspective on extreme AO systems.

On 19 June 2004, 2M1207 and its GPCC were simultaneously observed using the NACO spectroscopic mode. The low average throughput of the atmosphere and the instrument, we divided the extracted spectra by the spectra of a standard star.

2M1207, showed impressively strong H emission in J-band (αW type of TW A and found two late M-type objects which he identified as brown dwarfs. The one of interest in the present paper, the brown dwarf 2M1207.

The contrasts between 2M1207 and its GPCC are reported for multiple lines of evidence point toward membership of 2M1207 in the TWA. Although L-band observations of Jayawardhana et al. (2003) did not reveal significant IR excess at 3.8 μm, recent mid-IR observations of Sterzik et al. (2004, accepted) found strong 3.8 μm emission consistent with an embedded object between 1 and 10 AU.

Chauvin et al. (2004) undertook a 2MASS-based search for isolated late-type objects within 20 pc. They detected a narrow Na D line indicating low surface gravity. Finally, the spectrum of 2M1207 showed a strong Na D line indicating low surface gravity. Although L-band observations of Jayawardhana et al. (2003) did not reveal significant IR excess at 3.8 μm, recent mid-IR observations of Sterzik et al. (2004, accepted) found strong 3.8 μm emission consistent with an embedded object between 1 and 10 AU.

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2MASSWJ1207334–393254

GPI/H–band

GPI/J–band

Macintosh et al. (2015)

Chauvin et al. (2004)

5.5 AU at 70 pc

Historical perspective on Extreme AO systems

Gizis et al. (2004)
S54 camera (54 mas resolution) was used to observe the NACO spectroscopic mode. Low errors were achieved during our observations.

Macintosh et al. (2015) obtained the GPCC in H band. The spectrum of 2M1207 and its GPCC were extracted and calibrated in wavelength with the throughput of the atmosphere and instrument. We divided the extracted spectra by the spectra of a standard star.

Table 1 provides the night log of the observations. S27 and L27 correspond respectively to a platescale of 27.03 and 27.12 mas. DI and FWHM correspond to the strehl ratio and the full width at half maximum intensity.

Fig. 1 and 2 show the contrasts between 2M1207 and its GPCC. The companion was not detected in J band. The contrasts of 10^-6 were achieved during our observations. Subsequently, Mohanty et al. (2003) obtained echelle spectra of 2M1207, showing impressively strong H-alpha emission in addition to signs of low surface gravity, which both are characteristic of very young objects. Gizis (2002) noted that the proper motion of 2M1207 is consistent with TW Hydrae (TWA). Multiple lines of evidence point toward membership of 2M1207 in the TWA. Mohanty et al. (2003) did not reveal significant IR excess at 3.8 µm. New mid-IR observations of Sterzik et al. (2004, accepted) found excess emission at 8.7 µm and 21.0 µm, suggesting the occurrence of ongoing accretion onto (a young) brown dwarf. Although L-band observations of Jayawardhana et al. (2003) did not reveal significant IR excess, the H-alpha line (8200 Å) absorption was observed, which plays various He I lines. Detections of Na I k and Na I α emission lines are also observed, indicating low surface gravity. Finally, the spectrum of 2M1207 was found to be different from that of the brown dwarf 2M1207.

In Fig. 1, we display a composite image and the detection limits achieved during our observations. On 19 June 2004, 2M1207 and its GPCC were simultaneously observed using the NACO spectroscopic mode. The low errors were achieved during our observations.

Fig. 1 and 2 show the contrasts between 2M1207 and its GPCC. The companion was not detected in J band. The contrasts of 10^-6 were achieved during our observations. Subsequently, Mohanty et al. (2003) obtained echelle spectra of 2M1207, showing impressively strong H-alpha emission in addition to signs of low surface gravity, which both are characteristic of very young objects. Gizis (2002) noted that the proper motion of 2M1207 is consistent with TW Hydrae (TWA). Multiple lines of evidence point toward membership of 2M1207 in the TWA. Mohanty et al. (2003) did not reveal significant IR excess at 3.8 µm. New mid-IR observations of Sterzik et al. (2004, accepted) found excess emission at 8.7 µm and 21.0 µm, suggesting the occurrence of ongoing accretion onto (a young) brown dwarf. Although L-band observations of Jayawardhana et al. (2003) did not reveal significant IR excess, the H-alpha line (8200 Å) absorption was observed, which plays various He I lines. Detections of Na I k and Na I α emission lines are also observed, indicating low surface gravity. Finally, the spectrum of 2M1207 was found to be different from that of the brown dwarf 2M1207.
Thank you.