Vortex coronagraphs for segmented aperture space telescopes

Garreth Ruane\textsuperscript{1}, Dimitri Mawet\textsuperscript{1,2}, Jeff Jewell\textsuperscript{2}, Stuart Shaklan\textsuperscript{2}, Johan Mazoyer\textsuperscript{3}, Laurent Pueyo\textsuperscript{3}

\textsuperscript{1}California Institute of Technology
\textsuperscript{2}Jet Propulsion Laboratory
\textsuperscript{3}Space Telescope Science Institute
Outline of talk

1. Background on vortex coronagraphs
2. Optimization of coronagraphic masks
3. Wavefront control with aperture discontinuities
4. Outlook for future work
1. Background
The vortex coronagraph

Focal plane vortex phase mask provides theoretically perfect starlight cancellation for an unobstructed, circular pupil and \( l = 2, 4, 6, \ldots \)


Sensitivity to tip-tilt and finite sources

Fraction of energy transmitted through the Lyot stop for an off-axis point source.

Fraction of energy transmitted through the Lyot stop assuming a 12 m diameter aperture and $\lambda = 550$ nm.

Dashed lines indicate the size of a sun-like star at 10 and 100 pc.

**Need at least charge 4 for a 12 m space telescope**

Sensitivity to aperture shape

Telescope, fore optics

(on-axis source, perfect wavefront)

Entrance pupil
Phase mask
Lyot plane
Lyot stop

Annular aperture

Annular aperture + spiders (Palomar)

Need advanced designs for segmented aperture space telescopes
Apodized vortex coronagraphs

Ring apodizers

Starlight cancellation with a ring apodizer

Circular pupil

Annular pupil

Input pupil

Output pupil

charge 2 VC

Starlight cancellation with a ring apodizer

Circular pupil

Input pupil

Output pupil

Annular pupil

charge 2 VC

charge 2 VC

Starlight cancellation with a ring apodizer

Apodizer optimization

Relative throughput within 0.7 λ/D of source location

Ring apodizer

Field at PP2

Yields theoretically perfect starlight cancellation for annular aperture
Apodized VC performance with segmented apertures

Analytically-inspired, ring-apodized VC (RAVC) with charge 4

Leaked starlight owing to segment gaps
2. Optimizing the masks
Option I: Optimizing the apodizer

Unity padding of aperture discontinuities
**Option I: Optimizing the apodizer and Lyot stop**

- Unity padded, $t = 0.77$, $R_1 = 0.4R$.
- Pupil plane: 1000 samples per $D$.
- Focal plane: 8 samples per $\lambda_0/D$.
- FPM is median filtered ($3 \times 3$ samples).

Determined via irradiance thresholding.
Option I: Optimizing the apodizer and Lyot stop

Unity padded, \( t = 0.77, R_1 = 0.4R \)

- Pupil plane: 1000 samples per \( D \)
- Focal plane: 8 samples per \( \lambda_0/D \)
- FPM is median filtered (3×3 samples)

Determined via irradiance thresholding
**Option I: Optimizing the apodizer and Lyot stop**

- az. averaged
- peak normalized to PSF w/o coronagraphic masks

<10^{-7} stellar irradiance for angular separations >3 \( \lambda_0/D \)

>10% encircled energy throughput for angular separations >3 \( \lambda_0/D \)
(w.r.t the telescope)
Option II: Optimizing the focal plane mask

- Optimized for 10% passband
- ~30% max. E.E. throughput
- Pupil plane: 1000 samples per $D$
- Focal plane: 8 samples per $\lambda_0/D$
- FPM is median filtered (3×3 samples)

Ring only, $t = 0.77$, $R_1 = 0.4R$

Focal plane mask

Focal plane corrector

Lyot stop

$P-V = 0.28 \pi$

radius = 20 $\lambda_0/D$
Option II: Optimizing the focal plane mask

Field in PP2 (at $\lambda_0$)

leaked energy fraction at $\lambda_0$ = $1.3 \times 10^{-4}$
**Option II: Optimizing the focal plane mask**

Stellar irradiance in FP2

\[ \Delta \lambda / \lambda_0 = 0.01 \]

\[ \Delta \lambda / \lambda_0 = 0.05 \]

\[ \Delta \lambda / \lambda_0 = 0.1 \]
Option II: Optimizing the focal plane mask

>10% encircled energy throughput for angular separations >3 \(\lambda_0/D\) (w.r.t the telescope)
Optimizing the *sensitivity* to planets

In photon-noise limited regime:

\[
\text{SNR} \sim \frac{\text{planet energy}}{\sqrt{\text{star energy} + \text{noise terms}}} \approx \frac{\text{planet energy}}{\sqrt{\text{star energy}}}
\]

sensitivity metric: \[
= \frac{\eta \times B}{\sqrt{s \times B}} = \eta \sqrt{\frac{B}{s}}
\]

\(\eta\) – Max. encircled energy throughput (within 0.7 \(\lambda_0/D\) of source position, normalized to telescope throughput)

\(s\) – Residual stellar energy in the image plane
(averaged over 3-10 \(\lambda_0/D\) annulus and passband)

\(B\) – Percent bandwidth \(B = \Delta\lambda/\lambda_0 \times 100\)
For example: optimizing the Lyot stop

Undersizing the Lyot stop

optimal sensitivity
Optimization via a sensitivity metric

\[
\text{sensitivity metric } B = \eta \sqrt{\frac{B}{s}}
\]

Goal sensitivity: 100-200×
3. Wavefront control for segmented apertures
Active Compensation of Aperture Discontinuities (ACAD)

DM2
(relay optics)

Ring apodizer
(phase mask
(charge 4 vortex))

L1

DM1

Lyot stop

f

f

f

f

L2

L3

PP1

FP1

PP2

FP2

Original pupil

Goal pupil

ACAD

Active Compensation of Aperture Discontinuities (ACAD)

DM1, DM2, PP1, PP2, FP1, FP2, L1, L2, L3,

Pupil, Ring apodizer, phase mask, Lyot stop

Apodized pupil, Lyot stop, On-axis PSF

Active Compensation of Aperture Discontinuities (ACAD)

Surface height DM1 (nm) (flat DM)

Surface height DM2 (nm) (flat DM)

On-axis PSF

(located in pupil)

Active Compensation of Aperture Discontinuities (ACAD)

Surface height DM1 (nm)

Surface height DM2 (nm)

On-axis PSF

(Located in pupil)

\[ \lambda = 500 \text{ nm} \]

\[ N_{\text{act}} = 64 \]
Active Compensation of Aperture Discontinuities (ACAD)

DM2

Apodized pupil

Ring apodizer

phase mask (charge 4 vortex)

Lyot stop

On-axis PSF


Active Compensation of Aperture Discontinuities (ACAD)

Active Compensation of Aperture Discontinuities (ACAD)

DM1

DM2

pupil

(relay optics)

Ring apodizer

phase mask

(charge 4 vortex)

Lyot stop

PP1

FP1

PP2

FP2

\( f \)

\( L1 \)

\( L2 \)

\( L3 \)

Surface height DM1 (nm)

Surface height DM2 (nm)

On-axis PSF

\( \lambda = 500 \text{ nm} \)

\( N_{act} = 64 \)


Active Compensation of Aperture Discontinuities (ACAD)

DM2

(relay optics)

DM1

pupil

PP1

L1

f

PP2

L3

FP1

phase mask

FP2

Lyot stop

Ring apodizer

ACAD results from Mazoyer, Pueyo, et al.

Telescope Pupil

Raw PSF

Contrast

DM1, ACAD solution

μm

DM2, ACAD solution

μm

ACAD PSF

Final PSF

Contrast

DM1, adjustment

nm

DM2, adjustment

nm

Active Compensation of Aperture Discontinuities (ACAD)

ACAD results from Mazoyer, Pueyo, et al.

SCDA Pupil_1 Vortex

- Flat DMs: 10-100x
- 10% passband
- Monochromatic

Expected gains with wavefront control

Expected performance after ACAD+EFC as demonstrated by Mazoyer et al. (potentially up to $300 \times$ sensitivity)
Outlook for future work

1. Develop numerical optimization of grayscale apodizers for VCs.

2. Optimize broadband performance of wavefront control algorithms for VCs on segmented apertures.

3. Investigate potential performance gains by combining wavefront control and optimized coronagraphic masks.
Extra slides
Active Compensation of Aperture Discontinuities (ACAD)

ACAD results from Mazoyer et al. (2015)

Active Compensation of Aperture Discontinuities (ACAD)

pupil

DM2

DM1

(relay optics)

apodizer

phase mask

Lyot stop

PP1

FP1

PP2

FP2

\( f \)

\( f \)

\( f \)

\( f \)

\( L1 \)

\( L2 \)

\( L3 \)

ACAD results from Mazoyer et al. (2015)

ATLAST pupil offaxis Vortex

Normalized contrast

10-100x

10% passband

monochromatic

flat DMs

Apodized VC performance with segmented apertures

Analytically-inspired, ring-apodized VC (RAVC) with charge 4
Apodized VC performance with segmented apertures

Analytically-inspired, ring-apodized VC (RAVC) with charge 4

Relative energy within 0.7 λ/D radius of planet, Normalized to case with focal plane mask removed.

Azimuthal average of monochromatic on-axis PSF
Option I: Optimizing the apodizer

\[ VC_1 \{ P(x, y) \} = P(x, y) * FT^{-1} \left[ e^{i\phi} \right] \]

\[ FT^{-1} \left[ e^{i\phi} \right] = \frac{1}{r^2} e^{i\theta} \]

Option I: Optimizing the apodizer

\[ VC_1 \{ P(x, y) \} = P(x, y) \ast FT^{-1} \left[ e^{i\phi} \right] \]

Convolution with a circular pupil

\[ \frac{1}{r^2} e^{i2\theta} \]

Occurs for nonzero even values of \( l \)

**Option II: Optimizing the focal plane mask**

Broadband FPM optimization process

1. **Initial phase**
   
   (charge 4 vortex)

2. **Solve for new phase at each \( \lambda \)**
   
   \[
   \Phi_1 (\lambda_1) \\
   \Phi_2 (\lambda_2) \\
   \vdots \\
   \Phi_i (\lambda_i) \\
   \vdots \\
   \Phi_N (\lambda_N)
   \]

3. **Take weighted average of solutions**
   
   **Achromatic (e.g. liquid crystal):**
   
   \[
   \Phi = \sum_i c_i \Phi_i (\lambda_i) \\
   M = \exp(i\Phi)
   \]

   **Dielectric material:**
   
   \[
   h = \sum_i \frac{c_i \lambda_i}{n(\lambda_i)} \Phi_i (\lambda_i) \\
   M = \exp\left(i\frac{2\pi}{\lambda} n(\lambda)h\right)
   \]

4. **Update phase mask**

5. **Repeat steps 2 - 4**
Optimized focal plane masks and Lyot stops for various bandwidths

Sensitivity metric

\[ \eta \sqrt{\frac{B}{s}} \]

Residual stellar energy

Planet energy

Apodized vortex

10%

5%

1%
Alternate apodization schemes

**Zernike amplitude apodizers**

(a) \(Z_n^2 + iZ_n^{-2} = r^2 e^{i2\theta}\)

(b) \(Z_n^2 = r^2 \cos(2\theta)\)

(c) \(Z_n^3 = r^3 \cos(3\theta)\)


Rules:

- If \(l\) is even:
  
  \[P = \sum a_{nm}Z_n^m(\rho, \theta)\]
  
  \[|l| > \max\{n + |m|\}\]

- Or \(P = \sum b_m r^{|m|} e^{im\theta}\)

  \[\text{sgn}(l) = \text{sgn}(m)\]

Monochromatic focal plane mask optimization

RAVC4 w/ focal plane corrector (FPC)

The focal plane mask (FPM) is numerically optimized to improve starlight suppression at a single wavelength.
Phase corrections needed for monochromatic suppression. This will inform the basis used for broadband optimization.
Monochromatic focal plane mask optimization

Azimuthal average of on-axis PSF

Normalized encircled energy throughput

Monochromatic energy within 0.7 λ/D
Phase-shifting Lyot plane masks for RAVC4

Phase masks optimized for angular separations of 5-20 $\lambda/D$

On-axis PSF in normalized log irradiance, 10% bandwidth

Optimized LPMs for the VC improve the suppression over a substantial spectral bandwidth (achromatic phase shifts assumed)
Theoretically, suppression is broadband owing to achromatic vortex FPM, but the improvement comes at the cost of off-axis PSF quality.
Phase masks designed for apodization

Phase masks may be used to apodize segmented aperture telescopes, effectively erase aperture discontinuities, and maintain high throughput (e.g. w.r.t. shaped pupils).
Achromatic phase mask technologies

Vector phase masks
photo-aligned liquid crystal

Vector phase mask imaged through crossed polarizers

Otten et al., *Opt. Express* 22, 30287 (2014)
Achromatic phase mask technologies

**Vector phase masks**
subwavelength gratings

Phase shift depends on direction of grating.

**Annular groove phase masks (AGPM)**
L band (Sep 2012)

1.4 µm period

4.7 µm depth