Don’t Heckle My Speckle: A Coronagraph Design Study for the SEAL testbed

Jules Fowler . ExoExplorer Seminar Series . 5/14/21
Talk Outline

- Extreme Adaptive Optics
- SEAL testbed
- Optics refresher
- Coronagraphy primer
- Simulations
- Current state of the coronagraph design
- Next steps
Direct Imaging and Extreme Adaptive Optics
Directly Imaged Planets are Few and Far Between

![Graph showing planet mass vs. orbital period with data points and methods indicated: 1995, Transits, Radial Velocity, Direct Imaging, Microlensing.](image)
Directly Imaged Planets are Few and Far Between
Direct Imaging Resolves the Light of a Planet

HR8799 Planetary System
Direct Imaging Unlocks Exoplanet Characterization

HR8799 Planetary System

(Janson, 2010)
Ground-based Imaging Requires Adaptive Optics

Feedback loop: next cycle corrects the (small) errors of the last cycle
Ground-based Imaging Requires Adaptive Optics

Without Adaptive Optics

Feedback loop: next cycle corrects the (small) errors of the last cycle
Ground-based High Contrast Imaging Requires EXTREME Adaptive Optics
HD 95086b and a Speckle are Hard to Distinguish

(Rameau, 2013)
The Santa Cruz Extreme AO Laboratory (SEAL)
SEAL Tests Novel Wavefront Sensing, Wavefront Control, and Coronagraphy in Synergy with Keck

- Part of the UCSC Lab for Adaptive Optics
- PI: Rebecca Jensen-Clem
- Supported by Renate Kupke, Daren Dillon, and Sylvain Cetre
- Predictive wavefront control (Maaike Van Kooten)
- Focal plane wavefront sensing (Benjamin Gerard)
- Pyramid wavefront sensing (Dominic Sanchez)
- Zernike wavefront sensing (Maaike Van Kooten, soon to be Maissa Salama, and Jules Fowler)
- Coronagraph Design (Jules Fowler)
SEAL Includes ...

- Laser (633nm)
- Pinhole
- Halfwave plate
- Rotating phase plate
- Nothing!
- Linear polarizer
- SLIM

Filter wheel to be populated by a Keck pupil mask
IrisAO segmented DM (Keck primary simulator)
LODOM (ALPAO DM97-15)
HODOM (BMM Kilo-DM)

50/50 Beam Splitter
Flip-in mirror to optionally send the beam to FAST
Focal plane with filter wheel (to be populated by coronagraph FPM)
Pupil plane with filter wheel (to be populated by Lyot mask)
Camera optics & science detector

FAST testbed area (3x6 feet)

The 50% of the light that goes to the WFS arm should be split equally between these three systems:
- Commercial Shack-Hartmann WFS
- Modulated Pyramid WFS
- Zernike WFS

Renate Kupke
SEAL Includes Atmospheric Turbulence Generation

- Laser (633nm)
- Pinhole
  - Halfwave plate
  - Linear polarizer
  - SLM
  - Selectable turbulence options
- Filter wheel to be populated by a Keck pupil mask
- IrisAO segmented DM (Keck primary simulator)
- LDCM (ALPAO DM-97-15)
- HOCM (BIMI iolo-DM)
- 50/50 Beam Splitter
- Flip-in mirror to optionally send the beam to FAST
- Focal plane with filter wheel (to be populated by coronagraph FPM)
- Pupil plane with filter wheel (to be populated by Lyot mask)
- Camera optics & science detector

The 50% of the light that goes to the WFS arm should be split equally between these three systems:
- Commercial Shack-Hartmann WFS
- Modulated Pyramid WFS
- Zernike WFS
SEAL Includes Keck-like Pupil Shaping

Laser (633nm) → Pinhole

Halfwave plate → Linear polarizer → SLM

Rotating phase plate

Nothing!

Filter wheel to be populated by a Keck pupil mask → IrisAO segmented DM (Keck primary simulator)

LODM (ALPAO DM97-15) → HODM (BIMM Kilo-DM)

50/50 Beam Splitter

Flip-in mirror to optionally send the beam to FAST

Focal plane with filter wheel (to be populated by coronagraph FPM)

Pupil plane with filter wheel (to be populated by Lyot mask)

Camera optics & science detector

The 50% of the light that goes to the WFS arm should be split equally between these three systems:

- Commercial Shack-Hartmann WFS
- Modulated Pyramid WFS
- Zernike WFS

Selectable turbulence options
SEAL Includes High/Low Order Deformable Mirrors

- Laser (633nm)
- Pinhole
- Halfwave plate
- Rotating phase plate
- Linear polarizer
- SLM
- Filter wheel to be populated by a Keck pupil mask
- IrisAO segmented DM (Keck primary simulator)

LODM (ALPAO DM 97-15)
HODM (BIM Iko-DM)

FAST testbed area (3x5 feet)

50/50 Beam Splitter
Flip-in mirror to optionally send the beam to FAST
Focal plane with filter wheel (to be populated by coronagraph FPM)
Pupil plane with filter wheel (to be populated by Lyot mask)
Camera optics & science detector

The 50% of the light that goes to the WFS arm should be split equally between these three systems:
- Commercial Shack-Hartmann WFS
- Modulated Pyramid WFS
- Zernike WFS

Renate Kupke
SEAL Includes This Very Coronagraph!

Renate Kupke
Everything You Wanted to Forget About Optics
Pupil and Focal Images are a Fourier Transform Apart

$\mathcal{F}(f(x,y)) \leftarrow \mathcal{F}^{-1}(F(\theta_x, \theta_y)) \rightarrow$
Natural Units Intuitively Describe the Focal Plane

Airy Rings at $1\lambda/D$ intervals

Diffraction Limited Resolution of a Telescope System:

$$\theta = \frac{\lambda}{D}$$
Coronagraphy Basics
Starlight Is Suppressed by a Coronagraph

Star + planet to observe

You, hoping for a planet
Starlight Is Suppressed by a Coronagraph

Star + planet to observe

Focal Plane Mask
planet

You, hoping for a
Starlight Is Suppressed by a Coronagraph

Star + planet to observe

Lyot Stop in the pupil plane

Focal Plane Mask

planet

You, hoping for a
Only Starlight is Visible, Despite an Injected Companion

Focal Plane

Pupil Plane
Starlight is Diffracted to the Edge of the Aperture

Focal Plane

Pupil Plane
The Planet Appears!

Focal Plane

Pupil Plane
The Planet Appears!

Focal Plane

Pupil Plane
Focal Plane Masks Vary for Classical Lyot and Vortex Coronagraphy

Classic Focal Plane Mask

Vortex Focal Plane Mask

(Delacroix, 2014)
Focal Plane Masks Vary for Classical Lyot and Vortex Coronagraphy

Classic Focal Plane Mask

Vortex Focal Plane Mask

(MarbulaOne, 2020)
Contrast Curves Across the Image Plane are a Coronagraph Performance Metric

Contrast normalized by throughput

- Jensen-Clem 2018

\[
\text{contrast} = \left( \frac{\text{factor} \times \text{noise}}{\text{stellar aperture photometry}} \right) \times \left( \frac{1}{\text{throughput}} \right)
\]
Simulating a Coronagraph with HCIPy
High Contrast Imaging for Python

github.com/ehpor/hcipy

HCIPy: High Contrast Imaging for Python
Our Simulations Use a Circular Aperture

Keck Aperture

Circular Aperture
Designing a B- Lyot Coronagraph

\[ \frac{D_{LS}}{D_{\text{aperture}}} < 1 - \frac{1}{D_{FPM}} : D_{FPM} = 3 \Rightarrow D_{LS} < 0.67 \]

- Sivaramakrishnan, 2001
Designing an A+ Vortex Coronagraph

We expect to see no contrast difference past a certain threshold (~0.98).

- Ruane, 2018
Wavefront Error from Imperfect Optics Creates Speckles

High Order WFE

Low Order WFE

Realistic WFE
Wavefront Error Impacts Contrast, Especially for the (low charge) Vortex
Wavefront Error from Impacts the Final Coronagraphic Image

Perfect vortex:

WFE:

Vortex with
Typical Vortex Masks are Imperfect

perfect vortex:

vortex + spot:
Imperfect Vortex Masks Impact Contrast
Atmosphere Imparts Phase Errors But Can be Corrected with Deformable Mirrors

No Correction  50 Actuators  Kilo DM
Atmosphere Imparts Phase Errors But Can be Corrected with Deformable Mirrors

No Correction 50 Actuators Kilo DM
Current State of the Design
Large FPM Allows for Larg(er) Lyot Stop

FPM: $3\lambda/D$

LS: 0.6
Optimal Vortex Will be Difficult to Integrate and Align: Lyot Stop $0.98 \rightarrow 0.9$

LS: 0.9
Optimal Vortex Will be Difficult to Integrate and Align: Lyot Stop 0.98 → 0.9

A new performance metric is coming to a coronagraph near you!
Next Steps

- Incorporate cost function to minimize exposure time as secondary metric
- Model and design additional elements, including a pupil mask optimized for Keck-like apertures and an apodizing phase pattern we could apply with Deformable Mirrors
- Simulate and design a preliminary Lyot Coronagraph for the Thirty Meter Telescope (TMT)
- Use our setup to compare predictive wavefront control methods side-by-side
Acknowledgements

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In Conclusion

- Lyot Coronagraphs: stand up well to system errors but rule out close in companions.
- Vortex Coronagraphs: on paper offer stunning performance but don’t hold up as well to practical systems.
- Other coronagraphic elements and algorithms will be vital for high contrast, and practical integration will bring other affects we haven’t yet thought to model.

- Feel free to contact me with any further questions (or heckling):

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