Vortex Coronagraphy

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Small-Angle Observations

Goal: observe as close as possible to bright stars

Stars to 1.1 $\lambda$/D
$\epsilon$ Ceph
contrast $\approx$ 50:1
(Mawet et al. 2011)

Planets seen to 2 $\lambda$/D
HR8799
contrast $\approx$ 10^{-5}
(Serabyn et al. 2010)
Desirable capabilities of a space coronagraph & potential solutions provided by vortex phase masks

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The (Single) Vortex Coronagraph

**Advantages:**
- Phase mask $\Rightarrow$ Small inner working angle
- High throughput
- Clear $360^\circ$ azimuth FOV
- Simple layout (common to Lyot)

**Nearly ideal performance:**
\[
\int J_0(r) J_1(r) \, dr \rightarrow \int J_2(r) J_1(r) \, dr \Rightarrow r^2 \text{ field outside aperture}
\]
Infrared Coronagraphic Testbed (IRCT)
Single Vortex IRCT Pupil Measurements

Input Pupil

Output Pupil

\[ l = a \left( \frac{b}{c-x} \right)^4 + d \]

and

- \( a = 42580 \)
- \( b = 68.9 \) (expected 68)
- \( c = 386.5 \) (expected 386)
- \( d = 0 \)

\( r^{-4} \) fit
What about an On-Axis Telescope?
The Dual-Stage Vortex

Mawet et al. 2011
Optics Letters
Starlight intensity (Airy pattern) reduced by $(d/D)^4$
Double Vortex on the IRCT

- Fiber source
- Collimating OAP
- Input pupil mask
- Focusing OAP 1
- Vortex mask 1
- Re-collimating OAP
- Lyot stop
- Focusing OAP 2
- Vortex mask 2
- 2:1 relay
- CCD camera
- Re-imaged pupil
- Re-imaging lens
IRCT Measurements of On-Axis Dual-Vortex

Input Pupil

1st Lyot Pupil

After 1st Lyot Stop

2nd Lyot Pupil

1st Lyot plane:
Residual light outside primary & secondary diameters
- the latter light lies within the primary

2nd Lyot plane:
Residual light concentrated in center
- it can be blocked.

Serabyn et al. 2011, SPIE
Modeling the Effect of Secondary Support Legs

0.5%D

2%D
Speckle Phase Sensing with a Double Vortex

- Use of the residual central light as a reference beam:

- Use phase-shifting interferometry between inner and outer pupils to measure speckle phases

\[ t_{\text{sec}} \approx 10^{0.4m-9} / (C(d')^2) \]

For an \( m = 5 \) star, and \( d' = 1 - 0.1 \) m,
\( C = 10^{-7} \Rightarrow \sim 1 - 100 \text{ sec} \)
\( C = 10^{-9} \Rightarrow \sim 100 \text{ sec} \) to \( 10^4 \text{ sec} \).
# Masks and Performance

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Vortex Phase Masks

Scalar Vortex:

- Longitudinal (dielectric) phase ramp
  - e.g. EBL; Palacios et al. 2005, Masarri et al. 2011

Vector Vortex:

- Geometric (Pancharatnam-Berry) phase (polarization direction)
  - e.g. Mawet et al. 2005
The Vector Vortex: A Rotationally Symmetric HWP

Half-wave plate (HWP):
- flips field across fast axis
- reverses circular polarization state

Alteration of fast axis orientation changes the phase of the CP state

“Geometric” phase shift

Rotationally symmetric HWP:
Phase of CP increases linearly with azimuth

$e^{ilp\theta}$
Liquid Crystal Polymer Vector Vortex Masks

Orientation defined by rotating polarizer & Substrate (JDSU)

Cross-Section:

Central disorientation region:

Vortices between crossed polarizers (mask at center):

Theory  JDSU First Gen.  JDSU Second Gen.
Central Disorientation Region Reduction

Beam Co.
Broadbanding

1) Three-layer half-wave-plate vortex mask
   - First attempt has acceptably achromatic (flat) response, but at \( \sim 182^\circ \)

2) Polarization Filtering:
   - LCP starlight outside pupil
   - RCP spectral leakage inside pupil
   - LCP planet light inside pupil
   - Lyot stop
   - LCP polarizer
   - both

\[ \text{Nominal contrast at } 2.5\lambda/d \]

Achromatic designs

- 1-layer design
- 3-layer design
- 5-layer design
Polarization Components in the HCIT

- Polarizer1
- QWP1
- Polarizer2
- QWP2
- Lyot stop wheel
Contrast & Bandwidth Tests in HCIT

Polarization filtering: Pol 0/QWP 45/vortex/QWP -45/Pol 90
Vortex Mask Test Results in the HCIT

- Optical wavelengths
- 4\textsuperscript{th} order mask (8\pi in one circuit)
- IWA = 1.7 \lambda/D vs. 0.9 \lambda/D

Monochromatic: 785 nm laser
Median contrast = 3.4 \times 10^{-9}
between 2.5-12 \lambda/d:

TPF-C goal: 10^{-10}
Potential precursors: 10^{-9}
Broadband HCIT Results

- Setup:
  - Seven 2% filters
  - Optimized DM at central $\lambda$
  - Dark hole: 2.75-6.3 $\lambda/D$
    - limited by upstream QWP & pol.

- Red curve: results for the entire dark hole

- Blue curve:
  - top half of dark hole ($y = 0$ to 6.3 $\lambda/D$),
    (less residual light there)

- Contrasts:
  - $1.0e^{-8}$ in best 2% passband
  - $1.6e^{-8}$ for a 10% passband.
  - $3.8e^{-8}$ for a 20% passband
Potential Mission Configuration
Desirable capabilities of a space coronagraph & potential solutions provided by vortex phase masks

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Summary

• Vortex devices:
  – Small inner working angle
  – High contrast ($3.4 \times 10^{-9}$ monochromatic)
  – Broadband performance (few $10^{-8}$)

• System-level: tandem vortex coronagraph
  – Possibility of an on-axis telescope
  – Possibility of the direct measurement of speckle phases

• Very promising:
  – Vortices beginning to be used on ground-based telescopes
  – Performance already close to sufficient for small first-generation exoplanet imaging mission in space
  – TPF flagships do not need to be prohibitively large