USING THE VECTOR VORTEX CORONAGRAPH IN THE EXAO REGIME AT PALOMAR: LESSONS LEARNED

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5+ years effort:
Recipe for high contrast imaging from the ground

* High Strehl Ratio => Extreme AO
Extreme AO

- Keep pupil location at DM
- Magnify pupil (by f1/f2)
- Center sub-pupil on DM
- Maintain F# to AO system ⇒ post-AO optics unchanged

Result: >90% SR, best image quality ever on a ground-based telescope
Recipe for high contrast imaging from the ground

- High Strehl Ratio => Extreme AO ✓
- Pointing stabilization => new SSM
New SSM

SSM are responsible for pointing accuracy and stability (≠ tip-tilt), which is the most fundamental requirement in high contrast imaging:

- Old SSM had 20 mas accuracy, and intrinsic drifts.
- New SSM have **mas-level** pointing accuracy and very little drift.
- Are now commanded with feedback from the science image.

- **Dynamic tip-tilt is fundamentally limited by the tip-tilt mirror inertia, but can be specifically addressed by fine tuning the tip-tilt loop gain in real time.**
Recipe for high contrast imaging from the ground

★ High Strehl Ratio => Extreme AO ✓
★ Pointing stabilization => new SSM ✓
★ Low-order aberration (focus) => pupil imaging
Fine focus tuning

Pupil imaging capability

No control loop correction, one time fine tuning. Then relying on AO to keep it steady.
Recipe for high contrast imaging from the ground

- High Strehl Ratio => Extreme AO ✓
- Pointing stabilization => new SSM ✓
- Low-order aberration (focus) => pupil imaging ✓
- Quasi-static aberrations measurement and correction => Modified Gerchberg Saxton phase-retrieval
Autonomous Phase Retrieval Calibration

- Modified Gercherg-Saxton (MGS):
  - takes out-of-focus pairs of images with science camera (sense aberrations down to the final focal plane).
  - Off-line process (internal white light of the AO bench).
  - Performed for each new target.
Best result: 11.71 nm rms within the DM bandwidth
APRC limitation

- Turbulence on the AO bench itself!

- APRC only senses and correct phase aberrations...
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* Small Inner Working Angle Coronagraph => Vector Vortex Coronagraph
Vector Vortex Coronagraph

\[ e^{il\theta} \]

“Phase screw dislocation” at focal plane

\[ l = \text{topological charge} \]

Clears out the relayed pupil

Selling points: small IWA (~1 \(\lambda/d\)), efficiency, clear 360° off-axis discovery space, rapid implementation
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- Small Inner Working Angle Coronagraph => Vector Vortex Coronagraph ✓
- Observing strategy oriented towards speckle calibration => RDI
The good ol’ RDI with GOCI
Observing strategy based on speckle decorrelation

1 ppm / min

Extreme AO on sky data!
Strategy - RDI

What is the best one can do without a CAL system and (quasi)simultaneous differential imaging?

<table>
<thead>
<tr>
<th>MGS 1-3 iter.</th>
<th>Target</th>
<th>Ref</th>
<th>Target</th>
<th>Ref</th>
<th>...</th>
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</thead>
<tbody>
<tr>
<td>10-30 min</td>
<td>~ 10 min</td>
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Reference chosen with:
- same Vmag, K/H mag as the target.
- same dec, ΔRA ~ 10 min
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- Observing strategy oriented towards speckle calibration => RDI ✓
- Smart data reduction method => GOCI & LOCI
A few results
Contrast analysis

\[ \epsilon \text{ Eridani at H (1c)} \]

- Raw contrast
- High pass filtered
- Photon noise (H=1.88, 700s)
- Reference subtraction
- LOCI

Contrast vs Angular separation (")

- Contrast range from \(10^{-8}\) to \(10^{0}\)
- Angular separation range from 0 to 4 degrees
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Future

* P3K - P1640 - Pharo/Vortex: finest ExAO system in the world (64x64 DM for a 5 m aperture), only one in the Northern hemisphere, best correction and largest outer working angle!

* WCS at Keck (18 x 18 DM on a 3.6-meter off-axis portion of Keck)
Wanna know more about the vortex? Come see my posters!