Candidate concepts for exoplanet detection and characterization

ExoPAG-COPAG meeting
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Agenda

• Menagerie of exoplanet direct detection options
  - High level description of each concept
  - Impacts on telescope requirements

• Overview of constraints on synergy
Internal coronagraphs

- Lyot coronagraph
- PIAA or pupil remapping
- Shaped pupil
- Visible nulling (VNC)
- Optical Vortex Coronagraph (OVC)

External coronagraphs

*a.k.a. external occulters*

- Hypergaussian petal
- Optimized petal

Choice of method for exoplanet detection & characterization

- On-axis vs. off-axis
- Segmented vs. monolithic
- Optical quality & stability
- Coatings
- Instrument volume
- Fraction of mission time
Exoplanet Acronyms and Terminology

- **TXP** terrestrial exoplanet (roughly 0.5–10 $M_{\oplus}$, rocky)
- **HZ** habitable zone: range of orbital semi-major axis for which liquid water can exist on the surface of a TXP
- **$\delta$mag** star-planet brightness ratio expressed in stellar magnitudes. Earth-Sun $\delta$mag $\approx$ 25 at quadrature
- **IWA** Inner working angle = smallest angle from star at which a TXP can be detected. Given in multiples of $\lambda/D$ or in milliarcsec
- **Speckles** — faint variations of brightness in the image, or the optical fields giving rise to them, caused by residual wavefront errors
- **DM** Deformable mirror, used for real-time wavefront correction to minimize speckles
- **Sensitivity floor** — minimum detectable exoplanet brightness, even for very large integration times, limited by speckle variations
Coronagraph features using Lyot coronagraph as an example

- Image plane “field occulter”, followed by pupil plane “Lyot stop”
  - Blocks ordinary Fraunhofer diffraction from pupil edges
- Residual wavefront amplitude and phase errors cause speckles that can obscure exoplanets
- Deformable mirror enables optimized wavefront correction to drive down these speckles, and create a dark region in image plane
Rules of thumb for Internal Coronagraphs

• Wavefront sensing and control is paramount
  - Faint planets → faint speckles
    ➔ long integration times for wavefront sensing
  - long times for passive stability
    • Wavefront correction <0.1nm rms
    • Wavefront stability ~0.003nm rms passively for ~hours

• Throughput and image sharpness for exoplanets are key drivers
  - Background-limited detection
  - Need to resolve exoplanet from exozodi dust clouds
    ➔ large telescope diameter, narrow PSF, high throughput

• Trying to get smaller IWA with same telescope (fewer λ/D) makes requirements harder
  - Severely tightens wavefront tolerances
  - Most coronagraphs suffer in throughput, PSF width, & integration time

• Must minimize number of edges in the pupil
  - Pupil mask blocks a substantial area around each gap in pupil
  - More segments, smaller IWA drive sharply lower throughput and fatter PSF

# segments ↑
IWA ↓

{ Throughput ↓
PSF width ↑ }
Most internal coronagraphs demand a monolithic unobscured aperture

- Pupil mask blocks a substantial swath around each gap in pupil
- If $IWA = N \lambda / D$ for some (small) $N$, then half-swath $\propto \lambda / IWA = D / N$
- For $N=3$ (aggressive), we must block $\sim 1/3$ of width, $43\%$ of area

For Lyot coronagraph, as for *most* (not all) kinds of internal coronagraph, a monolithic unobscured aperture is *required*; the only practical option
• Band-limited 4\textsuperscript{th}-order CFO is used for IWA < 4\lambda/D
• First-tier technical maturity – ahead of the others
  - Current performance \~5e-10 in 10% passband
  - Instrument stability demonstration \~ meets requirement for TXPs
• Monolithic unobscured telescope with picometer stability for hours
• 15-20 mirror path \rightarrow silver coatings in exoplanet channel
PIAA or Pupil Remapping Coronagraph

- Highly aspheric optics remap the uniform top-hat pupil into an apodized beam
  - Focuses to an optimally compact amplitude profile
  - Blocked with hard-edge CFO
  - No Lyot stop needed
- Followed by similar optics to undo remapping and restore the original PSF with wide FOV
- Preserves high mask throughput and narrow PSF even for very small IWA (< 2\(\lambda/D\))
- Still demands
  - monolithic unobscured pupil
  - picometer stability for (fewer) hours
  - silver coatings in exoplanet channel
- 2\(^{nd}\)-tier technology maturity
Shaped pupil coronagraph

- Uses carefully tapered binary pupil mask to construct a compact PSF, then binary field mask to block star
  - Pupil mask is applied after secondary mirror
  - PSF is butterfly-shaped — sacrifices north & south while clearing east & west
- No Lyot stop, but significant loss of throughput at pupil mask
- Some designs compatible with obscuration and a few gaps across primary (chord folds)
- Successful designs at $4\lambda/D$
- 2nd-tier technology maturity
Visible Nulling Coronagraph (VNC)

- Achromatic nulling interferometer prepares destructive interference of 2 or 4 copies of telescope pupil, with relative lateral shear
- Exit pupil:
- Re-imaging 4-beam exit pupil (red) yields an image of exoplanet system multiplied by $\sin \times \sin$ function:
- The only candidate compatible with segmented telescope — when shear = segment spacing
- Bright-port control at 15 Hz
- IWA $\sim 2\lambda/D$ in some cases
- 2nd-tier technology maturity
Optical Vortex Coronagraph

- Uses photon orbital angular momentum (POAM) - vaguely like polarization
  - Also polarization methods
  - Mask excludes zero-POAM light on-axis, transmits it off-axis
  - Lyot stop traps excluded light ➔ this is a Lyot coronagraph but Lyot mask throughput is almost 100%

- Recent demos on binary stars
  - Great strength is IWA ~2λ/D
  - Still achieving modest contrast

- 2nd-tier technology maturity
External Coronagraphs

- Large occulting mask between star and telescope
  - Typically 50-80m diam and 50-100 Mm from telescope
    - Mm = 1000 km
  - Size driven by small IWA and diffraction
- Compatible with any telescope: obscured, segmented, etc.
- Only need telescope to be diffraction limited
- Petal is tapered to suppress diffraction into shadow
- 2+–week slews
  - Lots of astrophysics time
  - Limited agility for exoplanet studies
- Telescope must carry instruments and inter-spacecraft telemetry to help maintain alignment
- Most petal tolerances > cm, some ~0.1mm, a few ~0.01mm
- 2nd-tier maturity, with all issues on occulter
Other issues

UV coated optics

- Internal coronagraphs have 15-25 mirrors to the exoplanet FPA
  ➔ If throughput is low, we don’t want to lose another 50% of exoplanet light to aluminum/MgFl coatings

- Occulter system could have only 4-5 mirrors to the exoplanet FPA ➔ can afford more loss at UV-coated mirrors
  ➔ might allow UV observations of exoplanets

Instrument volume

- Internal coronagraphs require multiple relay mirrors
  - Volume for folded coronagraph instruments
  - Multiple spectral & polarization channels
  - Competes with wide-field imaging instruments

- Occulter only needs camera with filters, spectrometer with modest spectral resolution
## Summary

<table>
<thead>
<tr>
<th>Obscuration</th>
<th>Lyot or OVC</th>
<th>PIAA</th>
<th>VNC</th>
<th>Occulter</th>
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<table>
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<th>PIAA</th>
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<tbody>
<tr>
<td>&lt;~3 pm 1-10 hr</td>
<td>&lt;~3 pm/1-10 hr</td>
<td>&lt;~3 pm/0.1 sec</td>
<td>&lt;40 nm</td>
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<td>≤ 2</td>
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<td>≤ 2</td>
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<td>10-15%</td>
<td>60-80%</td>
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<td>50%</td>
<td>70-80%</td>
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**Flowdown from exoplanet science to telescope properties**

**Starting assumption:** we must have 60 mas IWA to find enough TXPs

- 4m diam coronagraph ➔ very aggressive 2.4 $\lambda/D$ instrument
  ➔ monolithic unobscured, few-picometer wavefront stability
  if Lyot ➔ severe cut in throughput, much longer integration times
- 8m diam coronagraph ➔ comparatively modest 4.5 $\lambda/D$ instrument
  ➔ monolithic unobscured, 0.5-0.8 nm wavefront stability
  if Lyot ➔ ~40-60% cut in throughput, longer integration times
- Any size with occulter ➔ all tough requirements on occulter
  ➔ any diffraction-limited telescope, 20-40 nm wavefront stability

### Controlled WF accuracy and stability

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<td>Focus</td>
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<td>Astigmatism</td>
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<td>Coma</td>
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