High-Contrast Imaging of Binary Stars with Starshades

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Starshade SIP Meeting
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Overview

1. Motivation for Binary Star Direct Imaging
2. Direct Imaging of Binaries with Starshades

Hubble Image of Alpha Centauri A & B
Why Binaries? Nearby FGK Targets for Roman

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Nearest 20 Stars:
13 Multi-Stars
4/7 Multi-Star Hab.
Zones w/in Roman FOV

Legend:
BOLD – Binaries
Color – Hab.Zone w/in Roman FOV
Green – Companion can be ignored
Red – Companion must be suppressed
Multi-Star Systems increase **quantity**
Of direct imaging targets

Plotting hypothetical exo-Earth contrast for all stars within 20 pc (based on Guyon 2019)

~1/2 of all FGK stars are in binary systems
- 41/67 in 10 pc
- 259/519 in 20 pc

Alpha Centauri A & B is a special science case:
- 3x closer than any other star system
- 3x better spatial/spectral resolution
Multi-Star systems increases **quality** of direct imaging targets

Roman CGI *may* be able to image Earth twins

- Due to unusual proximity, breaks common-wisdom assumptions about what Roman can do:
  1. At gibbous phase, an Earth-like planet around Alpha Cen B may be within CGI’s sensitivity limits (depending on final performance)
  2. For a Roman Starshade Rendezvous, completeness is significantly improved and an Earth-like planet around Alpha Cen A or B would be within sensitivity limits
  3. Optical imaging could detect structure in exozodi due to spatial resolution for aCen

Alpha Cen enables ~3x better IWA and resolution

- Based on Bailey 2019

Roman Starshade Rendezvous Limit

Instrument curves are 5σ post-processed detection limits.
Direct Imaging Challenges with Binary Stars

Challenges due to binary:
- Off-axis leakage from the binary companion creates a contrast floor
- Depth of the contrast floor is a function of the binary separation and brightness fraction
- A coronagraph for the off-axis companion is insufficient as contrast would be limited by its speckles!
Light Leakage from Binary Companions (10 pc)

Roman PSD characteristics
(provided by J. Krist)
- $D = 2.4m$
- $\lambda = 650nm$
- 20 nm RMS with $f^{-2.5}$ power spectrum
- 48x48 DM

Note: Contrast floor for an on-axis starshade due to unsuppressed off-axis companion star

Required companion suppression:
- 31/41 have leakage $> 1e-10$
Habex PSD characteristics
(provided by J. Krist)
- $D = 4.0\text{m}$
- $\lambda = 650\text{nm}$
- 20 nm RMS with $f^{-2.5}$ power spectrum
- 64x64 DM

Note: Contrast floor for an on-axis coronagraph/starshade due to
unsuppressed off-axis companion star

Required companion suppression:
- 193/259 have leakage $> 1\text{e-10}$
Overview

1. Motivation for Binary Star Direct Imaging
2. Direct Imaging of Binaries with Starshades

Hubble Image of Alpha Centauri A & B
<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>WC SOLUTIONS</th>
<th>Notes</th>
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<td><strong>On-axis blocker</strong></td>
<td><strong>Off-axis blocker</strong></td>
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<td>MSWC-0</td>
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<td>2nd Starshade</td>
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<td>Starshade</td>
<td>Coronagraph (i.e. standard WC)</td>
<td>SSWC (i.e. standard WC)</td>
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**SSWC**=Single Star Wavefront Control (WC), **SNWC**=Super-Nyquist WC, **MSWC-0** = Multi-Star WC (0\textsuperscript{th} order, or sub-Nyquist) **MSWC-s** = Multi-Star WC (super-Nyquist)
An on-axis and off-axis starshade can effectively suppress both stars operating in wide bandwidths. Requires operation of two starshades simultaneously.
An off-axis starshade removes leakage from Alpha Cen B turning the binary star problem into a single-star problem that can be controlled using the CGI. Performance set by CGI PSF + WC.
An on-axis starshade blocks Alpha Cen A achieving deep contrast and wide bandwidths, while off-axis speckles from Alpha Cen B are blocked using SNWC.
(3) SNWC with Roman Starshade

**Super-Nyquist Wavefront Control**
Mean Contrast: 2.76e-11

**Observation Strategy:**
(a) Create a larger $10 \, \lambda/D \times 10 \, \lambda/D$ discovery region with 10% bandwidth
(b) Create a smaller $2 \, \lambda/D \times 2 \, \lambda/D$ characterization region with 20% bandwidth

**Characterization Dark Hole**

**Diffraction Pupil** (Bendek 2016, Riggs 2020)
Roman Starshade Multi-Star Imaging Scenarios

(1) Dual Starshade Option

Pros:
- Wide characterization bandwidth
- Relaxed tolerance for off-axis starshade

Cons:
- Two starshades required
- Cannot slew while observing binaries

(2) CGI + Starshade Option

Pros:
- Uses existing CGI and WFC system
- Relaxed tolerance for off-axis starshade

Cons:
- On-axis CGI contrast floor at $10^{-9}$

(3) Starshade + SNWC Option

Pros:
- Achieves $10^{-10}$ contrast
- Uses existing WFC system

Cons:
- May require open slot in SPC wheel for diffraction grating to enable wide binaries
SNWC with Habex Starshade

Simulation parameter summary:
- 10% bandwidth about 650 nm
- 2-DMs [64x64]
- Boston MEMS Quilting
- On-axis star behind focal plane mask
- Off-axis star located 200 $\lambda/D$
- Initial contrast: 3e-8
- Final contrast: 1.2e-10

Data Source:
Boston Micromachines
Conclusions

**Methods:**
- Starshades can be used as the on-axis or off-axis blocker for multi-star imaging:
  1. Dual starshade option for both on-axis and off-axis stars
  2. Off-axis starshade with CGI on-axis
  3. On-axis starshade with SNWC for off-axis leakage control is possibly the most promising option (can reach $10^{-10}$ contrast and uses existing WFC)
- Demonstrated $1e-10$ in simulation for both Roman and Habex starshade scenarios
- **Discussion question:** can we maintain compatibility of hybrid operation between starshade imaging mode with coronagraph’s WFC to enable binary star imaging?

**Science:**
- Starshade + SNWC would enable imaging & characterization of Earth-like planets with Roman
- Multi-star imaging improves quality & quantity of target stars:
  - Alpha Centauri A & B have ~3x better SNR or spatial/spectral resolution
  - Other notable nearby target stars: 61 Cyg A&B, Eta Cass A&B, Mu Her A, Mu Cass A