Exoplanet Imaging with CHARIS and Future Synergies with WFIRST CGI

Tyler D. Groff

SCExAO+CHARIS Team: Jeffrey Chilcote, Timothy Brandt, Jeremy Kasdin, Julien Lozi, Thayne Currie, Nem Jovanovic, Ananya Sahoo, Sebastian Vievard, Olivier Guyon


LUVOIR Team: Thanks especially to Laurent Pueyo, Qian Gong, Matt Bolcar
SCExAO and CHARIS: Takeaways toward CGI

1. Block starlight: Coronagraph
2. Fix Aberrations: Wavefront Control
3. Get a spectrum of the image plane: Integral Field Spectrographs
4. Data Post-Processing for speckle subtraction: Necessary on the ground and in space

Our primary goal is to take spectra of the planets we discover.

HR8799 data processing by Tim Brandt from CHARIS Engineering Data
Integral Field Spectroscopy - Concept

Lenslet Array: Forms Sparse Image

Primary Image From Telescope

at Lenslet Array

Collimator

Disperser

Dispersed Spectra: One Spectrum Per Lenslet

Camera

Extraction Algorithm

at Detector Array

Data Cube
CHARIS First detections

HR8799 ADI only

HR8799 ADI + SDI

HD32297 Roll Subtracted

ADI+SDI detection of HR8799 c,d,e at SNR of 50, 35, and 15 respectively (~2-3 x 10^{-5})

HR8799 preliminary data processing by Tim Brandt, HD32297 Processing by Thayne Currie
CHARIS Science Highlights - kappa And b and HR8799

Kappa And b (Currie et al. 2018, AJ, 156, 291)

HR8799 (Currie)

Shaped Pupil Testing on HR8799 and Kappa And b (Currie+ 2018)
More CHARIS Science Highlights - HR8799

J. Wang et al., in prep

- Planet spectra based upon 2 full nights of CHARIS
- Possible planet variability seen with CHARIS
- CHARIS is the only instrument currently capable of making these precise observations
New Wollaston Spectro-polarimetry mode for CHARIS

- CGI has a Wollaston mode as well, contributed by JAXA.
WFIRST is the next NASA flagship mission (launch 2025)
- Primary Instrument: Wide Field Instrument (WFI)
- Technology Demonstration: CoronaGraph Instrument (CGI)
- CGI is the first **full system demonstration** in space for future missions that must reach $10^{-10}$ contrast detection limits
- Ground state of the art is $\sim 5 \times 10^{-6}$
- Paving the way for future missions capable of taking spectra of Earth analogs, furthering the search for life in the Universe
- Along the way, CGI will do **groundbreaking science** in direct imaging and **spectroscopy** of exoplanets and protoplanetary disks
- Goddard is building the spectroscopy modes for CGI

IFS is now rescoped to a direct imaging prism+slit

*Slot available for accommodation, prism would be an added capability funded by starshade
Spectral Characterization of Exoplanets

Self-luminous, young super Jupiters: atm. properties

Mature Jupiter analogues in reflected light: mass & atm. properties

Credit: M. Marley (Ames)
All lens surfaces are spherical.

The spectral dispersion is achieved with a prism and a compensator.
Example Observational Overlap

M5 Globular Cluster

HR8799 w/Post-Processing

Published CGI FOV overlaid onto a CHARIS image from the Subaru telescope

10 $\lambda / D$ ($\sim 0.5''$) Coronagraph outer working angle

3 $\lambda / D$ radial inner working angle

Angular separation where requirements are set
New Dispersion Mode: Zero Optical Deviation Prism

Baseline Filter Bands

<table>
<thead>
<tr>
<th></th>
<th>Center</th>
<th>Cut-on</th>
<th>Cut-off</th>
<th>Bandwidth %</th>
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</thead>
<tbody>
<tr>
<td>CGI Band 2 (Shaped Pupil)</td>
<td>660</td>
<td>610</td>
<td>710</td>
<td>15.2</td>
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<tr>
<td>CGI Band 3 (Shaped Pupil)</td>
<td>730</td>
<td>675</td>
<td>785</td>
<td>15.1</td>
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<tr>
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<td>656</td>
<td>800</td>
<td>19.8</td>
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<tr>
<td>Starshade Band 2</td>
<td>887</td>
<td>799</td>
<td>975</td>
<td>19.8</td>
</tr>
</tbody>
</table>

R(λ) for 730nm band

R(λ) for 660nm band
Example Observational Overlap: Amended to a Deployable Slit

M5 Globular Cluster

Published CGI FOV overlaid onto a CHARIS image from the Subaru telescope

HR8799 w/Post-Processing

10 $\lambda/D$ (~0.5") Coronagraph outer working angle

3 $\lambda/D$ radial inner working angle

Angular separation where requirements are set
- The slit size is a function of PSF core
- Shaped Pupil FWHM is asymmetric
  - Nyquist sampled at 500nm
- R=50 is **minimum** at onset of methane feature in that band.
- Core = 1.9 x 0.8 FWHM area in $\lambda/D$
  - 5 pixels / FWHM in X direction @ 660nm

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**Slice of PSF Core**

![Graph showing the Normalized PSF with different labels and markers,Courtesy A.J. Eldorado Riggs](image-url)
- Slits are integrated into the upstream field stop mechanism
- Several slits per mode
  - No slit
  - Different slit widths
  - Perhaps clever apertures for better speckle statistics
- After planet is detected
  - Slit deployed over the planet
  - Prism is engaged
**Simulating the Slit Spectroscopy Mode**

- **OS6 SPC model (2018) by John Krist**
- The slit mask is oriented perpendicular to the bowtie
- Two cases simulated:
  - Requirements performance
    - Optical MUFs applied
    - Fiducial $5 \times 10^{-8}$ flux ratio @ $4 \lambda/D$
  - Science performance case
    - $5 \times 10^{-9}$ flux ratio planet
    - Optical MUFs turned off

Simulation by Neil Zimmerman
Simulating the Slit Spectroscopy Mode: 730nm band

Assumes:
- Perfect Registration
- No image drift on detector

Albedo spectrum model by Nikole Lewis
Simulation by Neil Zimmerman
Simulating the Slit Spectroscopy Mode: 660nm band

Albedo spectrum model by Nikole Lewis
Simulation by Neil Zimmerman
Requirements: All About Stability

- **Ground-to-Orbit Stability**: The final focal plane must stay within tolerance
- **Jitter Stability**: Alignment disturbance from observatory structural dynamics (~100 seconds)
- **Thermal Stability**: Alignment disturbance from observatory thermal drift (~10 hours)
- Limited by telescope pointing and time between opportunities to recalibrate the IFS
- These periods drive stability requirements on:
  A. The stellar point spread function (PSF) on the lenslet array
  B. The lenslet PSFs (PSFlet) reimaged on the detector
Wavelength Accuracy of the Slit Spectroscopy Mode
Post-processing and Data Calibration

- Post-processing the CGI prism/slit data requires subtracting speckles via Reference Differential Imaging (RDI)
- Difference in the stars’ spectra complicate this procedure
- CHARIS relies on advanced speckle subtraction techniques, ADI/SDI/KLIP/LOCI etc.
- Time domain and speckle statistics is a new hot topic
- As we move forward, we should consider how our post-processing advancements on the ground will translate to CGI and future missions such as LUVOIR/HabEx
Beyond CGI: An Example for LUVIOR

- Example design by Neil Zimmerman for LUVIOR Architecture A

- Not only looking at diffraction limited performance...have to handle resolved sources!

- Now we are at the point of systems level optimizations of coronagraph, wavefront control, and telescope

The Problem: Aberrations

Normalized PSF from Ripple3

Aberrated PSF from Ripple3

Graph showing aberrations with annotations.
Instrument overview

SPIE Conference, Optics and Photonics, 2019

Credit: Matt Bolcar and Laurent Pueyo
Trades for back end spectrograph

- IFS: more mature concept, more efficient to identify planets, hard to obtain “high resolution” and necessary field of view (limited pixel real estate).
- Fiber fed and Slit Spectroscopy: less mature and efficient, however provides the precious high resolution in the near-IR.
Conclusions

- **Science**
  - CHARIS and SCExAO lend interesting precursor observations
  - Advances in science driven post-processing will directly benefit

- **Technology**
  - Data cube extraction and retrievals flowed directly from CHARIS
  - Requirements, Implementation, Lessons Learned
  - Setting the stage for future missions
CHARIS Performance/Operation/Hardware Status

- Regular Maintenance Items
  - Cryomech
    - Molecular Sieve Adsorber replacement every 15,000 hours
    - Last replacement was at 19,571 hours in August 2018
    - ~10,500 hours of run time since then
    - New part must be ordered and next replacement in ~200 days
  - Hard Disks
    - Data offload management ~once/year