The CHARIS high-contrast integral-field spectrograph

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Many planets have been detected, but largely by non-imaging techniques.
What Makes Imaging Exoplanets Hard

- Separation is not the fundamental limit
- The contrast ratio of Earth is $1 \times 10^{-10}$
- Detection at $1 \times 10^{-5}$ contrast levels is already challenging at low inner working angle

Detecting an Earth-analog, at 1 AU, Orbiting a star 10pc away requires a 2km circular aperture
Effect of Aperture

Classical Round Aperture

Hexagonal Aperture

JWST Aperture

Pupil Plane

Image Plane
Some Direct Imaging Examples

- HR8799 b: 68 AU, ~2,200 M⊕ (2008)
- HR8799 c: 38 AU, ~3,200 M⊕ (2008)
- HR8799 e: ~14.5 AU, ~2,800 M⊕ (2010)
- β pictoris b: 8.5 AU, ~2,500 M⊕ (2008)
- Fomalhaut b: 115 AU, ~1000 M⊕ (2008)
Basics (...again for the 3rd or 4th time) of an IFS
The CHARIS Top Level Design

- Reflective Optics
- Lenslet-based design
- Pinhole Array at Lenslet
  - Woodgate et al. 2006
  - Bonfield et al. 2008
- F/9 Lenslets and relays
- H2RG detector
- Linux and Windows
The Final Hardware

L3 Camera
L3 Collimator
Lenslet
Prisms
Filters
Telescope
Entrance Pupil
Slider Mechanism Locks in Beam

Image Centroids Repeatable to 0.02 pixels through prism changes

High Res

Low Res

Lenslet

L3 Collimato
Zoom-in On Key Optics

- High Res
- Low Res
- Lenslet
- L3 Collimator
Top Level Specs

- Major Science Objective:
  - Spectral characterization
  - Exoplanets
  - Disks
  - Brown dwarfs

- Supports Coronagraph IWA = 3 \( \lambda/D = 90 \) mas
  Current coronagraphs are pushing inside

- 2.07”x2.07” FOV

- R~19, J+H+K Band
  - ~53% Throughput

- R~65-85: J,H, and K Bands
  - ~40% Throughput

CHARIS work was performed under a Grant-in-Aid for Scientific Research on Innovative Areas from MEXT of the Japanese government (Number 23103002) (Hayashi, Kasdin)
The CHARIS IFS

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  - Exoplanets
  - Disks
  - Brown dwarfs
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Technology Contributions: Crosstalk Mitigation, New Dispersion Modes/Materials

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- PISCES work was performed under the Nancy Grace Roman Technology Fellowship (McElwain)
Low vs. High Resolution Mode: Thermal Background

Low Resolution

K-band
~1 Week After SPIE 2016!

First Light On Detector

Extracted Image at ~1550
CHARIS Commissioning Tasks

- Measure CHARIS wavelength calibration
- Determine throughput & zero point
- Measure CHARIS Contrast
- Photometric Calibration
- DM Spot calibration
- Twilight Flats
- Low Resolution operation verification & testing
- High Resolution operation verification & testing
- Circumstellar disk demonstration
- Extended object demonstration
- GPI / CHARIS cross calibration objects
- Astrometric Measurements & Plate Scale
Neptune Broadband Mode – 60 second Exposure
Sensitivity

2 read Saturation Limit in Unocculted Broadband

2 read Saturation Limit in Vortex, Broadband

2 read Saturation Limit in Unocculted H

2 read Saturation Limit in Coronagraphic H

2 read Saturation Limit in Unocculted K

2 read Saturation Limit in Vortex K
Astrometric Calibrators

- Astrometric Calibrator
- GPI Cross Calibrator

Trapezium

M5 Globular Cluster

- Astrometric Calibrator
- Plate Scale & Distortion
Characteristic CHARIS Data

Start

10 min

20 min
51 Eri observations

2 hour time series

Mean subtracted residual
The Quicklook: A Crisp Look At The Data at the Summit
SEEDS Contrast and Goals with CHARIS

SEEDS Contrast Estimate Courtesy Michael McElwain and Tim Brandt and SEEDS team
First Light Contrast Curve

5σ Single Wavelength Raw Contrast (1.6 micron) - 5th magnitude star

Contrast

Radial Distance Arcsec
Thermal Performance

- CHARIS MLI+Cooler performance far exceeds requirement of <80K
- This likely accounts for some of the dispersion discrepancy in the imaging modes
- ~13W of load at 50K in a 291.5K ambient environment
Thermal Stability

- For an IFS, stability is critical to performance
- Spectra begin to drift on detector with differential expansion
L-BBH2 Material Tests

Unknown material properties:
• Cryogenic Index Data
• Thermal Expansion to cryogenic temperatures
• Homogeneity of material
Increase in Abbe ~3%

Data for design down to 110K
Extrapolations down to 77K
Expecting the curve to flatten out at below 110K
Subsequent index measurements change below the curve profile

Goddard CHARMS test data

n(T) at 2.38 μm. Quad $\Delta n(77K) = 1.0118e-05$
Fits to As-built Spectral Resolution

<table>
<thead>
<tr>
<th>Mode</th>
<th>As-built</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>75.2</td>
<td>82</td>
</tr>
<tr>
<td>H</td>
<td>65.2</td>
<td>69</td>
</tr>
<tr>
<td>K</td>
<td>77.1</td>
<td>82</td>
</tr>
<tr>
<td>Broadband</td>
<td>18.4</td>
<td>19</td>
</tr>
</tbody>
</table>

As-Built vs. Design Spectral Resolution

Fits Computed by Tim Brandt for Pipeline
Repeatability

- Test Methodology:
  - Move prisms in and out several times
  - Measure root-mean-square scatter of lenslet spot positions at 1150, 1800 nm

Based on Fits Computed by Tim Brandt on Monochromatic PSFs. Fits have high residuals at corners of field.
Mitigating Crosstalk

- Array of field stops ("pinholes")
- Clips diffractive contamination lenslets

Impose Ensquared Energy requirements to capture Design, Alignment, Geometric distortion

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>Ensquared Energy (180 x 180 um)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated from Measured Data</td>
</tr>
<tr>
<td>1150</td>
<td>0.980</td>
</tr>
<tr>
<td>1650</td>
<td>0.968</td>
</tr>
<tr>
<td>2400</td>
<td>0.950</td>
</tr>
</tbody>
</table>

\[ \varepsilon = 0.1\% \quad 0.5\% \quad 0.8\% \quad 1\% \]

Min. EE 99.6% 98.2% 97.2% 96.5%
PSFs sampled with H2RG

K-band Flat Field Through Lenslet

2370 nm PSF through Lenslet Array
Crosstalk Performance

1. Adjacent spectra contaminate each other’s spectra
2. Variance in target spectrum makes the problem worse
3. Careful control of wavefront+pinhole array mitigates crosstalk

Integrated crosstalk in CHARIS estimated to be <4%
Even better after PSF fits are accounted for in extraction

This result is entirely due to diligence in tolerances and requirements through entire optical train.

1) Lenslet Pitch
Dispersed Distance

2) Spiegel&Burrows Warm Start Models

50 Myr, R=15

8 M_J, Clear
8 M_J, Cloudy
10 M_J, Clear
10 M_J, Cloudy

Transmitted \( A_F \) [arbitrary units]
Solution:

- Use many lenslets to build oversampled lenslet PSFs
- Lenslet PSFs vary over the field, but in a smooth, measureable, and reproducible way
- Bottom line: *We can measure our lenslet PSFs extremely well even with some undersampling.*
Telecentric Correction of Pinhole Positions
Alignment and Imaging of Lenslet Output

- Collimation using fiber array and custom pinhole arrays in visible light
- Tip-Tilt and Focus are locked to maximize stability
- Pinhole throughput checked in visible light

Final Lenslet Array

Pinholes imaged through lenslets

PSFlets at 635 nm
CHARIS First Detections and Analysis by the Team

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)

HR4796A - ADI only

HR4796A – ADI+SDI

HD91312 K-band Slice

HR8799 preliminary data processing by Tim Brandt, HD32297 Processing by Thayne Currie, Quick HR4796A and HD91312 analysis by M. Rizzo et al.
The Science: 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
The Power of Low Resolution in Post-Processing

HR8799 c – 40 sigma detection
HR8799 d – 25 sigma detection
HR8799 e – 5 sigma detection
Define power spectral density requirements of wavefront for wavefront control

Window 2
S1: $\lambda/23.9246$ PV, 5.4586nm RMS

Spatial Frequency [cycles/ aperture], $d = 24.1$ mm

Contrast With Non–Common Path

Average Contrast

$10^{-6}$
CHARIS: Impact of Image Registration

Update

No Update

Error
CHARIS Arrived in Hilo!
Rebuilding at Subaru
Data Workshops
2.5 days
- Theory on ramps and cube extraction
- Everyone installed and tested cube extraction
  - Built calibrations
  - Extracted data cubes from archived data
- Calibration procedures
- Short ADI/SDI tutorial
- 17 on-site participants
- 4 remote participants
- Ran on Linux, Mac, and Windows
Thank You
CHARIS Images and Contrast Goals

Thanks to my team members Tim Brandt, Jeff Chilcote, and Maxime Rizzo for Processing these Images

SEEDS Contrast Estimate Courtesy Michael McElwain and Tim Brandt and SEEDS team