Survey of high contrast imaging instrument concepts

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SPHERE Paranal instrument scientist

Sagan Summer workshop, 2014-07-21

Content

• High contrast imaging is the richest technique for exoplanet science

• The mother of high contrast imagers: HST

• Basics of high contrast imagers:
  • Building blocks
  • The order matters

• Highlights of 1st generation high contrast AO imagers

• 2nd generation high contrast XAO imagers are here!

• The future:
  • On the ground: ELTs
  • In space: JWST, AFTA-WFIRST & EXO-C/S
High contrast imaging is the richest technique
High contrast imaging is the richest technique

\[ f(t) \]

LU16: Crossfield et al. 2013

... and the most difficult one (contrast, IWA)
## 1st generation medium-high contrast imagers

For ground-based near-infrared instruments, the first acronym is usually for the adaptive optics system, while the second one is for the camera. The type of coronagraph is given in the last column, when available. Note that the contrast performance of these instruments varies a lot, depending on the instrument design itself and on the observing strategy. Instruments marked with a † are no longer available. SH stands for Shack-Hartmann WFS. CF for curvature WFS.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Telescope</th>
<th>AO</th>
<th>Wavelength (µm)</th>
<th>Ang. res. (mas)</th>
<th>Coronagraph</th>
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<td>WFPC2†</td>
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<td>1.1–3.5</td>
<td>30–90</td>
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<td>Clio/PISCES</td>
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<td>30–70</td>
<td>APP</td>
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<td>1.1–2.5</td>
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</table>
The mother of all high contrast imagers
High contrast imaging in space enabled by **stability**

HST only had classical Lyot unoptimized coronagraphs, but its unmatched stability benefited, and still benefits all of its imagers: WFC2/3 (nc), STIS (bars), NICMOS (hole), ACS (proper masks)

...so much so that archival data mining is producing wealth of results

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**Figure 1:** HST images of the circumstellar disk around the Herbig Ae star HD 141569a. All of the images have been subtracted using images of reference PSF stars. The upper left image shows a non-coronagraphic image taken with ACS, and the others are coronagraphic images. The disk is ~7 arcsec across, and the total disk flux is about 0.02% of the total stellar flux. Subtractions by the author.

**REFERENCES**


**Figure 2:** Robust visual detection limits for a point source near a star in the ACS in V band, with and without the coronagraph and with and without subtraction of the stellar light (roll subtraction). Also plotted is the corresponding brightness of Jupiter as it would appear at various radii from a star located 1 parsec away.

ACS V-Band Point Source Detection Limits

- Direct (unsubtracted)
- Direct (subtracted)
- Coronagraph (unsubtracted)
- Coronagraph (subtracted)

**ACS**

Krist et al. 2006
Its secret: 3 fine guidance sensors (FGS)

~1 mas pointing accuracy over > 10 min
70’ FoV, R < 17
ALICE: an overwhelming harvest
Soummer, Pueyo, Perrin, Choquet, et al

Figure 7. GUI used to for the analysis of a target (TWA 6 - ROSAT116 in this example).

Figure 10. Five debris disks newly revealed in scattered light from NICMOS coronagraphic archive (filter F110W) with image from [26].

Figure 11. Six companion candidates discovered in the NICMOS coronagraphic archive with the ALICE pipeline and reprocessed with the final version of the pipeline and the final products will be delivered to the MAST archive.
Lessons learned applied to new programs

Schneider et al. 2014 (STIS)
Not a level-playing field!

High contrast imaging through this requires some well thought out architecture!
Building blocks of direct imaging instruments

- Telescope
- Coronagraph(s)
- Deformable mirror(s)
- Wavefront sensor(s)
- Camera(s)
- INS Control Software / UI
- Real-time computer
- Motors and controllers
- Spectrograph/ Polarimeter
- Calibration sources
- DFS: pipeline/archive
- Tip-tilt mirrors
- Dichroic/splitters
- High quality optical relays
- ADC
- Derotators
Architecture: order matters

- All high contrast imagers are based on a variant of the following
- Devil is the details of their respective implementation
VLT: NAOS-CONICA
10 years of AO at the VLT
Subaru: AO188 - HiCIAO
Keck: AO-NIRC2
Transitioning to a new regime
Gemini: NICI

SDI built in!
Palomar WCS
Serabyn et al. 2007

- Keep pupil location at DM
- Magnify pupil (by $f_1/f_2$)
- Center sub-pupil on DM
- Maintain F# to AO system \( \Rightarrow \) post-AO optics unchanged

Result: >90% Strehl Ratio (how close the PSF is to the theoretical one for the perfect system)
1st gen untapped potential: L’ band imaging

- Technical advantage:
  - Untapped potential: free high Strehl
  - Vortex coronagraph to compensate for loss in resolution

Morley et al. 2012

Hanot & Absil 2010
Mid-IR vortex at Paranal


8 years of R&D

@ Paranal observatory


N band (Feb 2012) L band (Sep 2012)

4.6 µm 1.4 µm 4.7 µm
Fig. 3. Two different disc reductions: cADI-disc (top) and PCA-disc (bottom). The black arrow shows the apparent midplane, has a position angle of 29\degree (equal to that of the main disc) and a total length of 6.400. The color scale is identical for both images but not linear (square root). The green square marks the position of the star and the green circle has a radius of 0.400.

Fig. 5. PCA-disc image where each vertical profile has been normalized by the maximum spine brightness to enhance the vertical position of the spine. The two green circles have a radius of 0.400 and 2.000 respectively. The PA of the main disc (29\degree) as measured from (Lagrange et al. 2012a) is indicated by a plain red line, whereas the best fit PA of 30\degree.8 and 211\degree.0 (NE) and 211\degree.0 (SW) as measured from the L’ images are shown with dashed lines.

The surface brightness distribution (SBD) appears smooth between 0.500 and 3.800, compatible with a single power-law dependence of the SBD with separation. The inflection seen in the visible at 200 by Golimowski et al. (2006) is not detected in our data. A linear regression to the NE and SW extensions between 0.500 to 3.700 yields slopes of 2.77 ± 0.18 and 2.57 ± 0.16 respectively. The linear fit is shown in dotted line in Fig. 8.

The steeper slope of the NE extension explains why it appears slightly fainter beyond 1.500. The error bar shown in Fig. 8 only includes the measurement error. Although the image was corrected for self-subtraction by applying the iteration technique described in section 3.1, significant self-subtraction could still occur below 0.800 therefore the brightness below 0.800 should be considered as a lower bound. To overcome this difficulty we performed forward modeling with an innovative approach.

4. Forward modeling

4.1. Modelling philosophy

We used scattered light disc models to interpret the observed features and to disentangle ADI artifacts from real features. The disc models were generated with the GRaTeR code (Augereau et al. 1999). For each of the seven individual cubes of frames, the disc model is rotated to the appropriate parallactic angles of the initial frames and subtracted. The resulting cubes are re-reduced using the same PCA algorithm as described previously. The six reduced images are then combined together to obtain one single disc-subtracted image. These steps are repeated iteratively by varying the free parameters of the disc model, until a merit function is minimized. The minimization algorithm is a downhill simplex method or amoeba.

For each minimization, three different sets of initial conditions were explored, all representing physically acceptable conditions, to reduce the risk of finding local minima. We found that all sets agreed within less than 5%. The merit function is a reduced chi squared com-
Science highlights from 1st generation

Keck-NIRC2: HR8799, 4-planet system (Marois et al. 2008-10)

NACO: 1st “exoplanet” imaged (Chauvin et al. 2004)

HD95086 with NACO (L')
Rameau et al. 2013
Science highlights from 1st generation

- **GJ758** (~10-30M\(_J\) at 30AU) - (Thalmann et al. 2009)
- **HiCIAO results**
  - k And (~52AU, Carson+12)
  - SAO206462 (Muto+12, 100AU)
  - PDS 70 (Hashimoto+12, 140AU)
- **HD 19467**
  - 1" x 30.9 AU
- **Keck-NIRCam: brown dwarf companion**
  - (Crepp et al. 2014)
- **NICI: HR4796 debris disk**
  - (Wahhaj et al. 2014)
2nd generation high contrast imaging instruments
2nd generation = 1st generation on steroids

- Extreme AO, $C = (1-S) / N^2$ (Serabyn et al. 2007):
  - High density DM
  - High density, low noise, faster WFS
  - Better optics => excellent wavefront quality
  - Optimized for stability => slow thermal & mechanical drifts
  - Speckle control strategies are fully built in!

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Telescope</th>
<th>AO</th>
<th>Wavelength ($\mu$m)</th>
<th>Ang. res. (mas)</th>
<th>Coronagraph</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3K-P1640/SDC</td>
<td>Hale 200”</td>
<td>64-SH</td>
<td>1.1–2.4</td>
<td>45–90</td>
<td>APLC/VC</td>
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<td>VLT</td>
<td>40-SH</td>
<td>0.5–2.4</td>
<td>15–55</td>
<td>Lyot/APLC/FQPM</td>
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<td>Gemini South</td>
<td>48-SH</td>
<td>0.9–2.4</td>
<td>23–55</td>
<td>APLC</td>
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<td>Subaru</td>
<td>14-C &amp; 48-P</td>
<td>0.55–2.4</td>
<td>15–55</td>
<td>PIAA/SP/VC</td>
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<td>Magellan</td>
<td>25-Pyramid</td>
<td>0.55–5</td>
<td>18–160</td>
<td>Lyot(+APP)</td>
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<td>LMIRCAM</td>
<td>LBT’</td>
<td>30-Pyramid</td>
<td>2–5</td>
<td>60–120</td>
<td>APP+VC</td>
</tr>
</tbody>
</table>
2nd generation: deal with speckle headaches

Red pill: image plane wavefront sensing

Blue pill: differential imaging

I’ll have both!
Similar architecture + a few (critical) tweaks

SAME ARCHITECTURE FOR NEXTGEN SPACE-BASED CORONAGRAPHS!
# Configuration - environment - telescope interaction

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Location</th>
<th>Focus</th>
<th>Note</th>
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<td>P3K</td>
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<td>CA</td>
<td>Cassegrain, Equatorial mount</td>
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<td>LBT</td>
<td>AZ</td>
<td>Combined, ASM</td>
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<td>Magellan</td>
<td>Chile</td>
<td>Nasmyth, ASM, Rotating</td>
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<tr>
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<td>Subaru</td>
<td>Hawaii</td>
<td>Nasmyth, Modular</td>
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<tr>
<td>GPI</td>
<td>Gemini S</td>
<td>Chile</td>
<td>Cassegrain, Small, light weight</td>
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<tr>
<td>SPHERE</td>
<td>VLT</td>
<td>Chile</td>
<td>Nasmyth, Heavy, stable (damped)</td>
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</table>
After two years of intensive test in labs at Grenoble, the SPHERE instrument and its SAXO AO system has been shipped to Paranal Observatory in February 2014, reintegrated and fully retested in the VLT integration hall (in March and April 2014) on the bottom of the mountain and finally installed on the telescope the ten last days of April. SPHERE has seen its first on-sky photon the 4th of May and the AO loop has been closed less than 20 min after the beginning of operation.

The three first week of May have been dedicated to functional tests and very first performance analysis. We present here the very first results obtained on-sky, knowing that, they are deduced from the very first data during the early days of the instrument commissioning. Exhaustive analysis and full performance assessment will be provided in the coming months after the various SPHERE commissioning run (from July to October 2014).

5.1 Classical images

Let start with classical PSF images (without coronagraph).

**Figure 13**

- [Left] Nice photo of SPHERE on UT3
- [Right] The first SPHERE H-band PSF. Image and circular profile.

The AO spatial cut off frequency is clearly visible at 840 mas (as expected). Several regime (see text for details) have been identified on the image.

**Figure 14**

Illustration of image and coronagraphic PSF stability.

From Left to Right. Two saturated images acquired with a 20 min interval. Intensity difference (absolute value). All the data are plotted in log scale.
Wild weather conditions!
J. O’Neal, ESO

+ monsoon, wildfires (+ strikes, bbq)
Coronagraphs are allergic to dust...
Earthquakes!
Wind shake - Vibrations - M2 control
Sauvage & Fusco et al.

Preliminary
Figure 1. PALM-3000 optical layout, viewed from beneath the Cassegrain in cage. Light passing through the PALM-3000 optical bench is folded by path-reducing fold mirrors, FM1 and FM2, to the collimating parabola, OAP1. In collimated space, the beam is folded by FM3 to the active tip-tilt mirror, TTM, followed by the low-order (LODM) and high-order (HODM) deformable mirrors, the latter of which resides conjugate to the entrance pupil (the telescope primary is the aperture stop). A fourth fold, FM4, sends light directly to a matched, re-imaging OAP2. In converging space, wavefront sensing light is split by an exchangeable dichroic/beam-splitter in reflection at the SSM1 star selection mirror, making a periscope pair with the complementary SSM2, before entering the focusable wavefront sensor, WFS, and acquisition camera assembly, ACam. Science light proceeds in transmission from SSM1 into the science instrument volume, where each back-end science instrument implements additional optics as necessary.
Project 1640  
Oppenheimer et al.
Adaptive Secondary Mirror (ASM; 585 actuators)

Pyramid WFS 378 modes controlled at 1KHz

1KHz AO loop

NAS ring

Mag AO
Close et al. 2014
LBT(I)
Hinz et al.

Incoming Light
Visible Light
Left Wavefront Sensor

Fast (1 kHz) Corrector (Piston, Tip-Tilt)

Beamcombiner

IR Light

Slow Corrector (Piston, Tip-Tilt)

Incoming Light
Visible Light
Right Wavefront Sensor

Nulling and Imaging Camera (NIC)

2-2.4 and 8-13 um light

Imager

Nulling Interferometer

LMIRCam (3-5 um)

Phase Sensor (2-2.4 um)

NOMIC (8-13 um)
LBT and Mag AO ASM

Excellent for mid-IR imaging (minimize # of optical surfaces)
Fig. 1.—System level flow diagram of the SCExAO instrument. Thick purple and blue lines depict optical paths while thin red arrowed lines signify communication channels. Dashed lines indicate that a connection does not currently exist but there are discussions to establish it in future.

Fig. 2.—Image of SCExAO mounted at the Nasmyth IR platform at Subaru Telescope. To the left is AO188 which injects the light into SCExAO and at the right, HiCIAO. The FIRST recombination bench can be seen in the foreground.
Fig. 3.— Schematic diagram of the SCExAO instrument. Top image: shows the layout of the portable calibration source. Middle image: shows the layout of the visible optical bench which is mounted on top of the IR bench. Bottom image: shows the layout of the IR bench. Dual head green arrows indicate that a given optic can be translated in/out of the beam.
Gemini planet imager
Macintosh et al.
Global concept of the SPHERE instrument, indicating the four subsystems and the main functionalities within the Common Path and Infrastructure (CPI) that receives the telescope light and feeds the 3 science subsystems, with the Common Path including pupil optics (tip-tilt-mirror) and wavefront sensor, and near infrared (NIR) coronagraphic devices in order to feed the AO system through the use of additional devices in the AO concept to meet the requirements (and hopefully the goal) in terms of detection (AD3) the proposed design of SPHERE (see AD1) is divided into four subsystems, namely, the AO system, a coronagraphic device to cancel the planet when observing directly the star, and so on. This ultimate control will also be partially ensured by the AO system through the use of additional devices in the AO concept to meet the requirements (and hopefully the goal) in terms of detection (AD3) the proposed design of SPHERE (see AD1) is divided into four subsystems, namely, the AO system, a coronagraphic device to cancel the planet when observing directly the star, and so on. This ultimate control will also be partially ensured by an adaptive correction of the wavefront sensor, and near infrared (NIR) coronagraphic devices in order to feed the AO system through the use of additional devices in the AO concept to meet the requirements (and hopefully the goal) in terms of detection.

This correction of the wavefront sensor is therefore led to the following improvements in system performance: a reduction of the static speckle (through the reduction of airy pattern intensity due to the coronagraph optimization), a reduction of the photon and flat field noises (i.e., a gain in Signal to Noise Ratio for a given integration time) and a control of system internal defects (non-common path aberrations (NCPAs), optical axis decentering, vibrations, etc.). This control will be achieved mainly by reducing the static speckle, which is the main limiting factor for the detection of faint objects. The SPHERE system aims at detecting extremely faint sources (giant extrasolar planets) in the vicinity of bright stars. The concept behind this very challenging instrument is illustrated in Figure 1, where the common NIR optical path is indicated in red, and the exclusively Vis beam is indicated in blue. The infrared dual spectropolarimeter (ZIMPOL) is indicated in blue, and the infrared dual spectrometer (IFS) is indicated in red. The main components of the SPHERE instrument are indicated in the figure, including the beam deflection mirror (DM), the adaptive optics (AO) system, the coronagraph and imaging system, and the wavefront sensor. The figure also shows the four eight meter telescopes of the Very Large Telescope (VLT) and the location of the SPHERE instrument on the Nasmyth platform. The SPHERE instrument is the first part, from the entrance of the telescope light to the second focus (FP2), where the light is split into two beams, one for the infrared dual spectropolarimeter (ZIMPOL) and one for the infrared dual spectrometer (IFS). The three science subsystems, with the Common Path systems ZIMPOL (in blue), IRDIS and IFS (in red), are shown in the figure. The main components of the SPHERE instrument are indicated in the figure, including the beam deflection mirror (DM), the adaptive optics (AO) system, the coronagraph and imaging system, and the wavefront sensor. The figure also shows the four eight meter telescopes of the Very Large Telescope (VLT) and the location of the SPHERE instrument on the Nasmyth platform.
# Wavefront sensing

<table>
<thead>
<tr>
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<th>Pyramid</th>
<th>Modulation</th>
<th>Curvature</th>
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<td>x</td>
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<td>x</td>
<td>x</td>
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<td>AO188</td>
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<tr>
<td><strong>GPI</strong></td>
<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td><strong>SPHERE</strong></td>
<td>x</td>
<td></td>
<td>x(*)</td>
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</table>
**Shack-Hartmann vs Pyramid WFS**

Ragazzoni & Farinato 1999

![Diagram of Shack-Hartmann vs Pyramid WFS](image)

In the context of wavefront sensing, the Shack-Hartmann WFS and Pyramid WFS are compared for their performance in adaptive optics systems. The Shack-Hartmann WFS uses lenslets to capture wavefront information, while the Pyramid WFS employs a pyramid structure to achieve similar results with a different approach.

### Shack-Hartmann WFS

- **Lenslet Array**: The wavefront is sampled using lenslets, which divide the wavefront into small segments. Each lenslet captures a small portion of the wavefront, allowing for detailed analysis.

### Pyramid WFS

- **Pyramid Structure**: The wavefront is sampled using a pyramid structure, which is a more compact arrangement compared to the lenslet array. This design can reduce the number of elements needed for the same level of performance.

### Performance Comparison

- **Limiting Magnitude Gain Estimate**: The limiting magnitude gain is a measure of the system's ability to detect faint objects. The gain at the largest modes is generally unchanged with respect to the Shack-Hartmann WFS, but there is a gain in sensitivity, especially for large telescopes.

- **Pyramid WFS**: The pyramid WFS offers a way to comply with the different behaviors of the two WFS, particularly in cases where the geometrical approximation is not accurate. Hence, no speculations are made about the specific Zernike polynomial for a given radial order.

### Graphs

- **Maximum Radial Order vs. Magnitude Gain**: The graphs illustrate the magnitude gain as a function of the maximum radial order for both the Shack-Hartmann (SH) and Pyramid (Pyr) WFS. The Pyramid WFS shows a much higher gain in sensitivity, especially for large radial orders.

- **Peak to Valley Signal**: In Fig. 2, the normalized Peak to Valley signal vs. specific Zernike polynomials is plotted for both the Shack-Hartmann and Pyramid WFS. The Pyramid WFS is shown to perform better in this comparison.

- **Strehl Ratio**: The recombination of the whole pupil at the scientific focal plane is limited by the telescope's physical constraints, such as the size of the pupil and the effects of diffraction. The graphs help in estimating the performance of the WFS in these scenarios.

- **Pyramid WFS Performance**: The geometrical approximation is crucial for the Pyramid WFS, as it relies on the proper sampling of the pupil. The graphs show how the Pyramid WFS performs under different conditions, providing insights into its effectiveness in various astronomical settings.
Spatial filtering for SH WFS
Poyneer & Macintosh 2006

Observing a astrometric field in ADI mode (with pupil stabilization) has allowed us to demonstrated that non-atmospheric speckle (static) are really stable and can be accurately removed by the ADI procedure. The AO corrected area is shown with the green circle. Focal plane residue does not show any speckle like features.

5.3 Impact of the SH spatial filter

Now, let’s go back to the spatially filtered SH. The goal of this device is to remove the aliasing effects in the WFS measurements [7], [8]. Figure 17 shows the very nice behavior of coronagraphic images (i.e. the increase of AO correction and ultimate performance) as a function of the spatial filter size. The gain brought by the Spatially filtered SH is up to a factor 3. We have managed to go down to 1.1 λ/d which is close to the theoretical limit and which allows us to have a real aliasing free WFS.

SOME NICE IMAGES … AND MORE TO COME

A detailed description of SPHERE overall performance (in terms of final contrasts and detectivity aspects) will be found in [4]. In this section we only show some nice images obtained during the first commissioning. They have been post processing (either using ADI or deconvolution processes). The final results show the very good AO efficiency and, more importantly, its extremely good stability with time.

Figure 17 Evolution of the coronagraphic images as a function of the spatial filter size.

Fusco et al. 2014

SPHERE SF-SH on sky!

Fusco et al. 2014
Spatial filtering is critical for high contrast

Fusco et al. 2014

H  J  Y
Low-noise cameras

- EMCCD allows for very low readout noise
- Super-sensitive WFS

**Figure 11** SR ratio as a function of GS magnitude (R band) for various SPHERE wavelengths (and thus SPHERE configuration in terms of beam splitting between WFS and scientific paths)

4.3 SAXO performance in poor (large seeing and wind speed) conditions

In this section, the performance (as well as the robustness) of the system is studied in the poor condition regime, i.e. a seeing of 1.12 arcsec and two wind speed values of 12.5 and 30 m/s. These measurements have been performed in good T°C conditions (< 17°C) so that the DM had a relatively good shape at rest. First of all, despite some actuators in saturation (well handled by the anti-wind up and Garbage Collector processes), the loop was stable and robust during all the acquisition process (a few tens of minutes).

**Figure 12**

- Seeing = 1.2, wind speed = 12.5 m/s
- Seeing = 1.2, wind speed = 30 m/s

**SPHERE** (verified on sky, closed loop on R~15.9)
# DM technology

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<td>PZT, CILAS (97)</td>
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<td>SPHERE</td>
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<td>PZT, CILAS (1.6k)</td>
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</table>
Stacked array electrostrictive effect (PMN, PZT)

Bimorph lateral electrostrictive

MEMS (electro/magneto)

Voice coil Magnetic
Dead actuators are contrast killers
## Coronagraph choices

### Table

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<th>APLC</th>
<th>SP</th>
<th>4QPM/8OPM</th>
<th>(RA)VC</th>
<th>PIAA(*)</th>
<th>APP (*)</th>
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</tbody>
</table>

### Diagram

- **Amplitude**
  - Lyot
  - HBLC
  - APLC
  - SP
  - PIAA(*)/RAVC
  - SPPM

- **Phase**
  - VC, 4QPM, 8OPM
  - APP

- **Focal Plane**
  - Lyot
  - HBL C
  - APLC
  - PIAA(*)/RAVC
  - SP

- **Pupil Plane**
  - VC, 4QPM, 8OPM
  - APP
CoronAgraphs
2nd order coronagraphs (very small IWA):
VC2 / 4QPM / PIAA

4th order coronagraphs:
BL4 / VC4 / PIAA*

Topological charge 2 – IWA = 0.9λ, id

Topological charge 4 – IWA = 1.7λ, id

Mawet et al. 2010

APLC

Sivaramakrishnan et al.

SP and APP insensitive to tip-tilt

Spec: 10^{-2} \lambda
Goal: 10^{-3} \lambda
Low Order Wavefront Sensor (LOWFS)

- P3K: CAL (P1640) + pseudo-SCC (SDC) — 3
- GPI: CAL — 2’-3
- SCExAO: CLOWFS, LSOLOWFS — 2’ and 3
- SPHERE: DTTS, PTTS — 1
- LBT/MAgAO: NA
The instrument called Differential Tip-tilt Sensor (DTTS) is a specific tool developed inside SAXO to ensure that the star is always well centered on the coronagraph. A global estimation of thermal drift is also inserted inside the cryostat to minimize the IR background.

2.1. Specifications

For the instrument performance, this can be divided in the two axis with a required precision better than 0.14 mas/hour/axis. For the residual uncorrected tip-tilt fluctuations at very high frequency (considered here as a noise), the studies on instrument called Differential Tip Tilt Plate (DTTP) have led to the choice of an auxiliary sensor located as close as possible to the coronagraph focal plane device. This has been chosen so that the residual uncorrected tip-tilt fluctuations at very high frequency (considered here as a noise) is lower than 2 mas instantaneously, assuming a 1 kHz frame rate for the angular velocity evolution. Considering all the possible parameters involved, we believe that a solution based on an open loop model of each part of the mechanical structure holding the optical fiber is shown in Figure 2.

DM +TT mirrors

Visible WFS

Differential Tip-Tilt Plate

RT

Coronagraph (IR)

IR

98 %

2 %

DTTS (IR)

Optical fiber

Crystal Window + IR filter

Detector mechanics

Liquid LN2 line

Precise positioning and repositioning of the image on the coronagraph is crucial for the fine absolute position performance. As an example, a 10 % error on the average image position (or optical axis position) on the coronagraphic mask is a main specification for the SPHERE instrument. Indeed, the precise positioning and repositioning of the image on the coronagraph is crucial for the fine absolute position performance. For a period of 18 days, we collected a large set of data with maximum temperature variation of 10°C. We tested 3 different orientations of the mechanical structure. The impact of orientation is small compared to the data dispersion and we will process the data of all orientations the same way in all the following sections. The typical Detector integration times (DIT) were DIT=90 ms and the number of DIT (NDIT) was chosen so that the DIT.NDIT was 30 s long. Each DIT consists of a 2 s integration time, which holds the fiber, a pinhole of 165 μm diameter has been cemented to keep the size of the light beam on the detector because the centre of the detector is too noisy for a precise centroid measurement. This off-axis position is very useful because it allows us to rotate the test apparatus to verify its sensitivity to temperature variation and confirm that it is not due to the test source.

A cold stop received by the detector and leaves an unvignetted field of view of 4.2 arcseconds on the F/40 beam delivered by SPHERE.

The differential refraction effect (between visible and IR wavelengths). Such an effect can been estimated to 0.16 m/m per km for each 0.031 mas per second (linear evolution with time). The differential evolution will not be accurate enough to fulfill SPHERE requirements in terms of absolute position performance. As an example, a 10 % error on the average image position (or optical axis position) on the coronagraphic mask is a main specification for the SPHERE instrument. Indeed, the precise positioning and repositioning of the image on the coronagraph is crucial for the fine absolute position performance. For a period of 18 days, we collected a large set of data with maximum temperature variation of 10°C. We tested 3 different orientations of the mechanical structure. The impact of orientation is small compared to the data dispersion and we will process the data of all orientations the same way in all the following sections. The typical Detector integration times (DIT) were DIT=90 ms and the number of DIT (NDIT) was chosen so that the DIT.NDIT was 30 s long. Each DIT consists of a 2 s integration time, which holds the fiber, a pinhole of 165 μm diameter has been cemented to keep the size of the light beam on the detector because the centre of the detector is too noisy for a precise centroid measurement. This off-axis position is very useful because it allows us to rotate the test apparatus to verify its sensitivity to temperature variation and confirm that it is not due to the test source.
P1640 CAL system
Vasisht et al.

P1640 Optical Setup

LOWFS  IFS  CAL Camera

From P3K

Ap

Mod

T/T

FPM

BS

MBS

P1640 T/T
10 Hz

CAL-HOWFS

LOWFS

Fixed Low Order Phase map

High Order Phase map
0.01 Hz

AO WFE
~140 nm rms

P3k SH
P3K Recon

Centroid offset targets

LODM / HODM

PALM 3000

NCP WFE

Phase to Centroid Offsets

CAL SYSTEM
P1640 CAL system in action
Vasisht et al.

P-mode sequence

No Adaptive Optics  AO on, star unocculted, short exp.  AO on, star occulted, long exp.

AO on, star occulted, Calibration system on, long exp.

All systems on, Long exposure, Companion to SW
We can detect companions about 10,000x fainter than this one
P1640 CAL system doing E-field correction
Vasisht et al.
GPI CAL system
Wallace et al.

The GPI CAL system is shown in the diagram above. The system includes an apodized pupil, a reflective pinhole, phase-shifting elements, and low-order wavefront sensors (LOWFS). The LOWFS is located in the blue dashed box and is used to measure the wavefront aberrations of the light passing through the telescope and adaptive optics system. The measured centroid motions at each of the quad cells are transformed into the corresponding phase map in the input pupil via a matrix multiply with the reconstructor. The reconstructor was generated using a detailed simulation that took into account the effects of the apodized pupil, the finite size of the focal plane mask, and the coarse sampling of the lenslet array.

### 1.2 Cal low-order wavefront sensor (LOWFS)

As illustrated in Fig. 1, light that passes through the hole in the focal plane mask is re-collimated and forms a real image of the pupil. Our optics then relay this pupil image to another image at the location of the lenslet array just before the infrared sensor. There are seven lenslets that span the pupil, the subsequent spots are then sampled by a quad cell of 2x2 pixels. The measured centroid motions at each of the quad cells are transformed into the corresponding phase map in the input pupil via a matrix multiply with our reconstructor. The reconstructor was generated using a detailed simulation that took into account the effects of the apodized pupil, the finite size of the focal plane mask, and the coarse sampling of the lenslet array.

### 2.2 LOWFS absolute accuracy

Validation of the LOWFS absolute accuracy consisted of first measuring a transparent phase aberration with a Zygo (we used a microscope slide), and then measuring the same slide with the LOWFS in the final Calibration instrument. The Cal instrument reconstructs the first 16 Zernike coefficients. The requirement for this absolute agreement is 5 nm, rms, and we measured an agreement of 3.8 nm, rms.

### 2.3 LOWFS tip/tilt precision

A key requirement of our instrument is to act as the bore site for GPI. It’s critical that it maintain good tip/tilt performance for different stellar magnitudes. In this test, we measured the tip/tilt noise in the LOWFS for different flux levels corresponding to the magnitudes shown below (Fig. 5). Our system can achieve pointing knowledge at the ~ two milliarcsec level in 20 secs at 8th magnitude.

Only this part is currently being used
HOWFS to be commissioned
SCExAO LOWFS, option I
Guyon et al. 2009

Note: reflection from the spot can be used from any reflective masks
SCExAO LOWFS, option II
Singh et al. 2014

The configuration of LLOWFS that we will discuss in this paper is shown in Figure 1. LLOWFS is a low-order wavefront sensor (LSWFS) that is based on a reflective Lyot stop (RLS) and an annulus in the focal plane mask. The RLS reflects the unused starlight towards a detector which is used for low-order sensing. The LLOWFS is designed to measure the low-order aberrations of the telescope, such as tip-tilt and focus, with a high accuracy.

In contrast, GPI uses the starlight that passes through the focal plane mask to perform high-contrast imaging. The GPI's pupil plane image is presented in Guyon et al. (2009). As we operate with a slight defocus the flux density is reduced, and the low order modes such as focus and the astigmatisms apart from tip-tilt sensing for phase mask coronagraphs such as the Vortex, the Hartmann wavefront sensor in its calibration unit. GPI's pupil plane image is on a single side of the focus at all times. A phase-induced amplitude apodization with a variable focal plane mask and re-images the pupil on a Shack-Hartmann wavefront sensor in its calibration unit. GPI's pupil plane image is presented in Guyon et al. (2009).

For the accurate detection of the focus aberration, a Hartmann wavefront sensor in its calibration unit. GPI's pupil plane image is presented in Guyon et al. (2009). As we operate with a slight defocus the flux density is reduced, and the low order modes such as focus and the astigmatisms apart from tip-tilt sensing for phase mask coronagraphs such as the Vortex, the Hartmann wavefront sensor in its calibration unit. GPI's pupil plane image is presented in Guyon et al. (2009).

SCExAO LOWFS, option II
Singh et al. 2014

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Differential imaging techniques and corresponding data reduction methods

DI all about modulating/demodulating

θ, ADI

λ, SDI

t, RDI

<table>
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</table>
Performance and early science results
10 years of progress pioneered at Palomar
P3K-P1640, the first XAO - IFS on sky
Oppenheimer et al.

No Post Processing

After S4 Speckle suppression
LBT: L’ high contrast imaging at its best
Skemer et al. 2012, 2014
L’-band vortex at LBT
Defrere et al. 2014

The Large Binocular Telescope Interferometer (LBTI) is a NASA-funded nulling and imaging instrument designed to coherently combine the beams from the two primary mirrors of the LBT for high-sensitivity, high-contrast, and high-resolution infrared imaging (1.5-13 μm). It is equipped with two scientific cameras: LMIRCam (the L and M bands) and Nulling Optimized Mid-Infrared Camera (NOMIA) covering respectively the 3-5 μm and 8-13 μm wavelength ranges. In addition, the near-infrared light (H and K bands) can be sent to a fringe tracker for high-angular resolution interferometric observations.

Since the discovery of a fourth planet in 2010, the community of planet hunters has speculated about the presence of a fifth planet located closer in and shaping the inner debris disk. Several attempts at imaging the inner planets are shown for comparison (magnitude from the discovery papers). The detection limits at short angular separations are improved by installing an L’-band AGPM vortex coronagraph to the position of the mean motion resonance 2:1 with d, which is one of the possible stable configuration. In order to reach a rejection factor of 100 next time by doing a better adjustment of focus in the AGPM plane.

The rejection ratio is defined here as the ratio between the maximum intensity in the direct image and the maximum intensity in the coronagraphic image.

Figure 1. Left, scanning electron microscope (SEM) image of the center of an annular groove phase mask (AGPM). Right, SEM picture of the cleaved subwavelength grating, from which the geometric parameters of the AGPM-L4 profile are deduced: line width of 0.58 μm, and 10, 23 cases. The AGPM vector vortex coronagraph is among the most promising solutions in that context, as it enables imaging down to 2.5-3.8 μm.

In this paper, we have presented the first observations obtained with the AGPM vortex coronagraph recently installed at LBTI/LMIRCam. The goal of these observations was to demonstrate the exquisite inner working angle (IWA) of the AGPM and assess its relevance for the ongoing LBTI planet survey (LEECH, LBTI Exozodi Exoplanet Imaging Campaign, LEXI).

Figure 4. Current 5-σ L’-band contrast vs. linear separation (AU). The dotted line represents the raw contrast curve (without considering self-subtraction). The four known planets are shown for comparison (magnitude from the discovery papers). The attenuation of the PCA algorithm was estimated by introducing fake companions directly in the data cube, separated by a few arcseconds from each other and placed on three radial branches separated by 120° in azimuth. The fake companions were injected at 0.55 AU (4.7 AU) and 5.5 AU (9 AU). This distance corresponds to the IWA of the AGPM and assess its relevance for the ongoing LBTI planet survey (LEECH, LBTI Exozodi Exoplanet Imaging Campaign, LEXI).

Each deformable mirror uses 672 actuators that are controlled by the Adaptive Optics System to correct atmospheric turbulence at 1 kHz. The overall LBTI system architecture and performance are presented elsewhere in these proceedings.
Mag AO: visible AO!
Claus, Males, Morzinski et al.

example of high contrast in the visible: Beta Pic b


GPI also on beta Pic

(SDI/TLOCI 30min) H band

MagAO KLIP noise floor
Mag AO: Hα SDI

ADI reduced Continuum (643 nm) image. Detect weak point source 9.65 mag fainter at 83 mas PA=130.

ADI reduced Halpha filter (656.3 nm). Detected H alpha point source 295% Continuum.

ASDI reduction: (Continuum PSF subtracted from each Halpha image) then SDI frames ADI processed. HD142527B remains the same.

The Green circle is the location of a faint source found by NIR.

Close et al. 2014
GPI early exoplanet science
Macintosh et al. 2014; Chilcote et al. 2014

Fig. 2.— Left: 30-minute GPI image of Beta Pictoris. The spectral data has been subtracted using angular and spectral differential techniques. Beta Pictoris b is detected at a 5-sigma contrast level (mK e c s e q u e n c ei sa l s os h o w o n . ( O t h e r

Fig. 3.— Contrast vs. angular separation at 1.5–1.8 µm for a PSF-subtracted 30-minute GPI exposure. Contrast is shown for PSF subtraction based on either a flat spectrum similar to a L dwarf or a methane-dominated spectrum (which allows more e

Fig. 4.— Posterior distribution of the orbital elements of Beta Pictoris b using both November and December 2013 observations from GPI. Both spectra are in agreement.

0.4''

0.0 0.2 0.4 0.6 0.8 1.0 1.2

Radius (arcseconds)

10^7 10^8 10^9 10^10 10^11 10^12

5-sigma contrast

1.2 1.1 1.0 0.9 0.8 0.7

1.50 1.55 1.60 1.65 1.70 1.75 1.80

Wavelength (µm)

November 2013
December 2013

0.4 0.6 0.8 1.0

F_ν (normalized)

1.0 1.1 1.2


Date [year]

Offset [arcsec]
GPI early exoplanet science
Perrin et al. 2014

One individual 60 s exposure

Combined total intensity

Polarized intensity

The overplotted circles indicate the coronagraphic occulting spot size.

Note the very uniform and dark background indicating that the stellar PSF has been suppressed to low levels below the noise floor, in this case set by the instrument.

The image is displayed in the same angular scale in all panels, and the left two have the same brightness display color scale.

Figure 7 shows the results for the March 2014 dataset, the disk is easily seen without any PSF subtraction. Near the corners can be seen the 4 satellite spots used for astrometric and photometric reference to the occulted star, plus four more di spots due to uncorrected "wavefront error." The excess to the right is dominated by unsubtracted background emission seen only away from zenith it was not strictly apodization limited PSF. The excess peaks (Hinkley et al. 2009). On the eastern side of the belt has been thought to be the side closer to observers on Earth. The near-infrared polarimetry interpretation.

The 2013 December 12 UT observations occurred just before dawn in good seeing conditions. We obtained seeing peaks of 0.64 mas in the H-band, 15 mas in the K-band and 25 mas in the I-band. The target was acquired via standard GPI acquisition and coronagraph alignment processes (Dunn et al. 2014; Savransky et al. 2014) since the atmospheric dispersion compensation was small (et al. 2014; Hartung et al. 2014). The waveplate was rotated by 60 degrees to mitigate their induced vibrations. Modifications to the IFS cryocoolers were throttled down to reduce their induced vibrations. The one significant change is that the ADC was by the end of the observations as a commissioning test, even though at air mass above 1.5. The observation procedures and total integration time were similar to those in December, in- cluding the acquisition of skies immediately afterwards.

All observations were reduced using the methods in 
Perrin et al. 2014 to get the polarization of the star, at least on the western side. In fact the polarized intensity is brightest at the smallest separations. In polarized light the ansae are not particularly brighter than the adjacent portion of the ring to the west, contrary to the interpretation.

On 2014 March 25th dataset. The disk is easily seen without any PSF subtraction. Near the corners can be seen the 4 satellite spots used for astrometric and photometric reference to the occulted star, plus four more di spots due to uncorrected "wavefront error." The excess to the right is dominated by unsubtracted background emission seen only away from zenith it was not strictly apodization limited PSF. The excess peaks (Hinkley et al. 2009). On the eastern side of the belt has been thought to be the side closer to observers on Earth. The near-infrared polarimetry interpretation.

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On 2014 March 25th dataset. The disk is easily seen without any PSF subtraction. Near the corners can be seen the 4 satellite spots used for astrometric and photometric reference to the occulted star, plus four more di spots due to uncorrected "wavefront error." The excess to the right is dominated by unsubtracted background emission seen only away from zenith it was not strictly apodization limited PSF. The excess peaks (Hinkley et al. 2009). On the eastern side of the belt has been thought to be the side closer to observers on Earth. The near-infrared polarimetry interpretation.

The 2013 December 12 UT observations occurred just before dawn in good seeing conditions. We obtained seeing peaks of 0.64 mas in the H-band, 15 mas in the K-band and 25 mas in the I-band. The target was acquired via standard GPI acquisition and coronagraph alignment processes (Dunn et al. 2014; Savransky et al. 2014) since the atmospheric dispersion compensation was small (et al. 2014; Hartung et al. 2014). The waveplate was rotated by 60 degrees to mitigate their induced vibrations. Modifications to the IFS cryocoolers were throttled down to reduce their induced vibrations. The one significant change is that the ADC was by the end of the observations as a commissioning test, even though at air mass above 1.5. The observation procedures and total integration time were similar to those in December, in- cluding the acquisition of skies immediately afterwards.

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SPHERE first light!

**SPHERE**

- **SPHERE image in H2**
- **deconvolved image using MISTRAL [9]**
- **Synthetic image from CASSINI data [10]**

**CONCLUSION**

**SPHERE - SAXO** is a 12 years project involving 12 institutes in Europe and more than 2500 Full Time Equivalents. The system design has barely evolved from the early sketches (2012) to the final telescope implementation. At the end, the AO system gathers state of the art components (detectors, deformable mirror and real time computer) and some of its innovative features allow to have performance which has exceeded the original specifications. Even though we have experimented some problems with our high order deformable mirror, solutions have been proposed by the consortium to mitigate the effects and to be able to work with the current device. Nevertheless, DM remains, for the moment, the main risk of failure for the whole system. Back-up, long-term, solutions are now under investigation between ESO, CILAS and the SPHERE consortium to deal with this particular point.

Extensive laboratory tests have fully demonstrated both the performance, the reliability and the stability of the AO loops (and of SAXO and SPHERE as a whole). The first on-skylight commissioning has confirmed laboratory tests by providing unprecedented images and coronagraphic data on the VLT. The system stability has been re-demonstrated on-sky and the first performance assessment, even though Strehl ratio is slightly smaller than expected due to bad weather conditions and residual high frequencies on the telescope M2, are more than encouraging. The principal feature of SAXO have already been successfully tested from a functional point of view and fine tuning of the AO system as well as of the telescope control should allow to reach, in the coming months, the full system performance.

Commissioning on-going
SPHERE early contrast performance

- Com1, improved since!
- M2 control issue solved => 92% Strehl at H
- tip-tilt rms within specs (3 mas)
## Summary

<table>
<thead>
<tr>
<th>Telescope/Platform</th>
<th>WFS</th>
<th>DM</th>
<th>Coronagraph</th>
<th>LOWFS</th>
<th>DI</th>
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</thead>
<tbody>
<tr>
<td>P3K/P1640/SDC/PHARO</td>
<td>SH</td>
<td>LODM/HODM (Xinetics)</td>
<td>APLC/RAVC/VC</td>
<td>CAL + SH</td>
<td>SDI/RDI</td>
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<td>LBT(I)</td>
<td>Pyramid</td>
<td>ASM</td>
<td>APP/VC (LMIRCAM)</td>
<td>N/A</td>
<td>ADI/RDI</td>
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<tr>
<td>MagAO</td>
<td>Pyramid</td>
<td>ASM</td>
<td>APP (Clio2)</td>
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<td>ADI/RDI/SDI</td>
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<tr>
<td>SCExAO</td>
<td>Curvature (AO188) / Pyramid</td>
<td>LODM/HODM (CILAS(*)/BMC)</td>
<td>PIAA/VC</td>
<td>CLOWFS/LSLOWFS</td>
<td>ADI/SDI/RDI</td>
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<td>SFSH</td>
<td>LODM/HODM (CILAS/BMC)</td>
<td>APLC</td>
<td>CAL + SH</td>
<td>ADI/SDI/PDI</td>
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<tr>
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<td>SFSH (EMCCD)</td>
<td>HODM (CILAS)</td>
<td>APLC/4QPM/CLC</td>
<td>DTTS</td>
<td>ADI/SDI/PDI</td>
</tr>
</tbody>
</table>
Future of high contrast imaging from the ground and from space
Huge parameter space to explore, a single machine cannot do it all!

Habitable planets around nearest M stars
2020-2030 horizon

Challenge: diffraction and wavefront control over large, segmented and/or heavily obscured apertures
# In space: JWST

<table>
<thead>
<tr>
<th>Mode</th>
<th>Instrument</th>
<th>Wavelength (microns)</th>
<th>Pixel Scale (arcsec)</th>
<th>Field of View</th>
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<tbody>
<tr>
<td>Coronography</td>
<td>NIRCam</td>
<td>0.6 – 2.3</td>
<td>0.032</td>
<td>20 x 20”</td>
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<tr>
<td>Coronography</td>
<td>NIRCam</td>
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<td>MIRI</td>
<td>10.65</td>
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<tr>
<td>Coronography</td>
<td>MIRI</td>
<td>11.4</td>
<td>0.11</td>
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<td>Coronography</td>
<td>MIRI</td>
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<tr>
<td>Coronography</td>
<td>MIRI</td>
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<td>0.11</td>
<td>30 x 30”</td>
</tr>
</tbody>
</table>

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**Krist et al. 2007**

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**Marshall’s talk on Friday**

“Coronagraphy with JWST”
WFIRST - AFTA

Challenges: pupil geometry, pupil geometry, pupil geometry! + optical aberrations, polarization, telescope time/availability

some say it could be our only/best shot
at a space-based coronagraph for the foreseeable future
EXO-C: backup to WFIRST-AFTA

Challenges: 1.4-m aperture, budget
EXO-Starshade
Zooming in: synergy and complementarity!
Spergel et al 2013, WFIRST-AFTA

The RV technique, for example with longer periods, eventually reveals planets with Doppler signals associated with large systems that are beyond the current reach of RV systems. Methane is a strong absorber of red light because methane is a strong absorber of red light. The planet system is characterized by a certain metallicity of Doppler signals. The known small planets include a large number of heavy elements compared to the sun or protosolar nebula. This is a strong absorber of red light.

Experience from Kepler says that multiple examples like Earth and several times larger are observed. The metallicity of Doppler signals is sensitive to planet composition, size, and type. The known small planets include a large number of heavy elements compared to the sun or protosolar nebula. This is a strong absorber of red light.

Direct imaging of exoplanets provides a new and powerful discriminator between different planet types. Simple photometry can provide clues about exoplanets. Spectra can distinguish between different parts of the solar system, produced rocky planets that formed them, gradually building up the outer gassy envelope. This same mechanism, in a different formation scenario, the giant planets are significantly enhanced in heavy elements compared to the sun or protosolar nebula. This is a strong absorber of red light.

Measuring brightness at different wavelengths, say green and red, will allow the inclination of the orbit to be measured, presently not known. If we measure brightness at different wavelengths, the radius of Jupiter, for about 200 of the nearest stars within 30 pc. Color indicates if the coronagraph is equipped with polarizing filters that the known small planets include a large number of heavy elements compared to the sun or protosolar nebula. This is a strong absorber of red light.

Figure 21. Figure 21: This figure is a snapshot in time of contrast and separation for model planets, ranging in size from 0.1 to 10 or 200 of the nearest stars within 30 pc. Brightness (contrast) changes before and after maximum elongation will tell us about clouds and gas in the atmosphere. Spectra can distinguish between different parts of the solar system, produced rocky planets that formed them, gradually building up the outer gassy envelope. This same mechanism, in a different formation scenario, the giant planets are significantly enhanced in heavy elements compared to the sun or protosolar nebula.

Zooming in: synergy and complementarity!
High contrast imaging with ELTs: still a lot to be done, invented, combined, optimized

- E-ELT: building on EPICS studies, Planetary Camera and Spectrograph (PCS) R&D roadmap written by ESO and made public to European Institutions

- TMT: Planet Finder Instrument (PFI) study from 2006 concluded VNC is the optimal way to deal with segments, not true anymore

- GMT: build on LBT experience, PIAA
Synergistic developments

Remapping techniques

Apodizers

Small IWA coronagraphs

MKIDS

Post-coronagraphic WFS

Post-processing advances

Statistical significance
That’s all folks! Have fun out there!

SPHERE commissioning pics (J. Girard)