High Contrast Imaging R&D at the Subaru Coronagraphic Extreme Adaptive Optics

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**Adaptive Optics (AO)**

*Atmosphere Turbulence*: Earth’s atmosphere introduces strong and fast optical aberrations.

Aberrations must be continuously **measured** and **corrected** to provide sharp images.

Imaging exoplanets is particularly demanding, as the planet is much fainter than the star it orbits: very little room for error!

→ **AO for exoplanet imaging is referred to as Extreme-AO**

*AO OFF*  
*AO ON*
Imaging exoplanets requires two techniques to be combined:

- Extreme-AO corrects atmospheric turbulence
- A coronagraph masks the light of the bright star

Simulated images below show how Extreme-AO and Coronagraphy deliver high contrast image of a star.

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**Image Descriptions**

- **No AO correction**
- **Extreme-AO correction**
- **Extreme-AO + coronagraph**

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**Technical Notes**

- Monochromatic PSFs, 1.65um
- No photon noise
- 10m/s wind speed, single layer
- 4ms wavefront control lag

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**Legend**

1. ExAO control radius
2. Telescope spider diffraction
3. Diffraction rings
4. Ghost spider diffraction
5. "butterfly" wind effect
6. Coronagraphic leak (low order aberrations)
Subaru Telescope (8.2m diameter) has an exoplanet-imaging instrument (SCExAO)
The instrument team is developing advanced Extreme-AO techniques

Subaru Telescope, Mauna Kea, Hawaii
4200m altitude
Fiber-fed instruments (not visible here):
- RHEA (visible IFU, R=70,000)
- IRD (near-IR spectrograph, R=70,000)
+ experimental photonics spectro
High performance WFS

Low-modulation PyWFS (600-900nm)
14400 sensors → 2000 actuators
loop runs at up to 3.5 kHz

Unmodulated PyWFS demo (H band, SAPHIRA)
14400 sensors → 2000 actuators

NearIR PyWFS correction OFF

NearIR PyWFS correction ON
Neptune imaged with SCExAO doesn’t fit in field of view! (using CHARIS camera)
HR8799
Four planets, orbital periods on the order of 100yr
Each planet 5 to 7 Jupiter Mass

Subaru Telescope/ SCExAO (Currie et. al 2017)
VAMPIRES Update Feb 2018

Key improvement 2017-18: Full Pupil speckle-imaging / PDI mode

- Direct imaging of Mira-variable star omi Cet - clear asymmetry seen.
- Speckle imaging - diffraction-limited

omi Cet

PSF ref (63 Cet)

6 mas / px
FWHM = ~18 mas
λ / D = 19.3 mas

Observed 12/09/2017
Preliminary VAMPIRES science

Circumstellar dust around Red Supergiant μ Cephei

Model-fitting reveals extended, asymmetric dust shell, originating within the outer stellar atmosphere, without a visible cavity. Such low-altitude dust (likely Al$_2$O$_3$) important for unexplained extension of RSG atmospheres.

**Inner radius:** $9.3 \pm 0.2$ mas (which is roughly $R_{\text{star}}$)

**Scattered-light fraction:** $0.081 \pm 0.002$

**PA of major axis:** $28 \pm 3.7^\circ$ • **Aspect ratio:** $1.24 \pm 0.03$

**Left:** model image, shown in polarized intensity. **Middle:** model image shown in four polarisations. **Right:** Model image (intensity), shown with wide field MIR image (from de Wit et al. 2008 - green box shows relative scales. Axis of extension in MIR image aligns with the close-in VAMPIRES image.
Figure 4: Omi Ceti (Mira) polarimetric imaging
Fractional stokes Q (upper left), U (upper right) and I (lower left) images of *omi Cet* and the surrounding mass-loss shell, taken at 750 nm with VAMPIRES. In the polarisation images the mass-loss shell and associated nebulosity is clearly seen, as well as the circumstellar disk around its companion *omi Cet B*. Understanding the mass-loss process relies on properly constraining dust grain size distributions and species (at separate spatially resolved points). This requires observations across a wide set of wavelengths, including Y, J and H band, in addition to R and I as probed by VAMPIRES.
VAMPIRES Update Feb 2018

$H\alpha$ SDI mode implemented with 1st on-sky tests complete

Figure 4: (Top) A view of the entire visible bench of SCExAO. (Bottom left) A zoomed in view of the beam cube switching mechanism. (Bottom right) A zoomed in view of the wheel to switch the filters for differential imaging mode.
Ongoing research / future opportunities
The main specifications of RHEA@Subaru are:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Resolution</td>
<td>8 milli-arcsec</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>R~60,000</td>
</tr>
<tr>
<td>Total Field of View</td>
<td>~4 arcsec</td>
</tr>
<tr>
<td>Instantaneous Field of View</td>
<td>40 milli-arcsec</td>
</tr>
<tr>
<td>IFU Elements</td>
<td>9 (with dithering capability)</td>
</tr>
<tr>
<td>Spectrograph Total Efficiency</td>
<td>40%</td>
</tr>
<tr>
<td>Injection Unit Efficiency</td>
<td>Strehl × 0.6</td>
</tr>
</tbody>
</table>

RHEA first light @ Subaru: Eps Vir (detail)  
Feb 2016
Simultaneous spectroscopy of planet and background speckles

Spectroscopic characterization of exoplanets
Exoplanet search using high spectral resolution signatures as differential signal

- H-band is most useful for self-luminous planets.
- J-band is less useful for the self-luminous one although it's very important for habitable planets.
- Y-band exhibits worse contrast in general, and it's just important for UV absorbers (TiO & VO) in hot planets (>~2000K).

<table>
<thead>
<tr>
<th>band</th>
<th>molecules</th>
</tr>
</thead>
<tbody>
<tr>
<td>y</td>
<td>TiO, VO, FeH, H2O</td>
</tr>
<tr>
<td>J</td>
<td>CH4(weak), H2O, FeH, Fe(5-6 lines), K(4 lines), Na(2 lines)</td>
</tr>
<tr>
<td>H</td>
<td>CH4, C2H2, CO2, NH3, CO(weak), H2O, FeH</td>
</tr>
</tbody>
</table>

Table 1. Important molecules in Y, J, and, H bands

Figure 1. HITRAN Line Intensity (T=1000K)

- Optical beam path 1
- Fiber ports
- Optical beam path 2
- Fiber positioning mechanisms
FIRST visible light interferometer (stellar physics mostly)

1 frame of fringes on η Peg ($R_{\text{mag}} = 2.3$) - Subaru - 2013.07.25

X² map (closure phase fitting)

- $\lambda/D$ at 800nm: 15mas
- $\lambda/D$ at 600nm: 20mas

Separation: 44mas ± 4mas
Median flux ratio: 0.033
Predictions: sep=50mas, flux ratio at 800nm: 0.036
GLINT: Guided Light Interferometric Nulling Technology (funded - PI: Tuthill)

Near-IR photonic nuller chip

Figure 1: Dust density (Left panel) and simulated 10 μm near-IR image (Right panel) for an exozodiacal disk containing a 5 Earth-mass planet in a 1 AU orbit. The dust shepherding of the dust by orbital resonances is clearly visible, and presents a significantly more prominent marker to a remote observer than the planet itself.

Figure 2: Upper panels illustrate a star (yellow dot) lying centered within the pattern of a 2-beam nuller where its light is suppressed, while hypothetical planets (red, blue) traverse the interferometer fringes as the instrument is rotated. Lower panels show the resultant planetary transmission signals produced at the output.
Coronagraphy

Coronagraphs:
- Vortex
- Lyot
- PIAACMC
- 8QPM
- Shaped Pupil
- vAPP
Speckle Control

Speckle nulling, in the lab and on-sky (no XAO).

Experience limited by detector readout noise and speed.

KERNEL project: C-RED-ONE camera.

From:
- 114 e- RON
- 170 Hz frame rate

To:
- 0.8 e- RON
- 3500 Hz frame rate

Expect some updates
MKIDS camera (built by UCSB for SCExAO)

Photon-counting, wavelength resolving 140x140 pixel camera

Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

Delivery to SCExAO in jan 2018
Fast DM modulation

Coherent Differential Imaging

Speckle Sensing

Uncalibrated image

Calibrated image (incoherent planet light)

Fast focal plane images

Square modulus

Coherent intensity

Non-linear solver

Speckle field (coherent)

Compute DM(s) solution to cancel coherent light

Apply to DM(s)

Speckle Control
Subaru team is co-leading the development of cacao, a high-performance toolkit for AO control, which is gaining wider adoption (Subaru, Magellan, Keck + ESO?)

**We will provide software integration to this new standard.**

**Approach:**

Build AO control loop as a finite set of CPU-managed processes. Processes can manage computations on GPGPU(s)

*Interprocess communication (IPC) is contained in data:* cacao streams are held in shared memory and contain semaphores

→ Complexities of IPC are handled by compiler and Kernel (semaphores, shared memory)

Semaphore-based IPC has μs-level latency
End-to-end Timing Jitter
RMS < 5 us, max delay ~50us

End-to-end timing jitter measured by monitoring completion time of last real-time stream: modal pseudo-open loop coefficients.

Jitter includes following components:
- Hardware synchronization (PyWFS tip-tilt mirror)
- Camera readout
- Data transfer over TCP link
- All real-time computations, CPU and GPU
- Time measurement errors
End-to-end Timing Jitter
Histogram, measured @ 2kHz

- Delay > 40 us: 0.005%
- Delay > 20 us: 0.15%
- Delay > 10 us: 0.645%
- Delay > 5 us: 9.01%
- 80% within +/- 3.92 us

10% of loop iteration @ 2 kHz
Hardware Latency measured on SCExAO

Time between DM command issued and corresponding WFS signal observed
(Camera readout + TCP transfer + processing + DM electronics)

Measurement noise
+/- 25 us lines

Sum squared difference between two WFS frames
Open loop reconstruction
Comparison between gain values

$G=0.000 \rightarrow$ over-estimates OL values
All $G>0.0$ reconstructions match at \(\%\)-level

$G=0.000$ test relies entirely on WF residuals for OL estimation
$G>0.000$ tests rely mostly on DM values for OL estimation

*Test shown here uses full speed RM acquisition which underestimates RM by \(~15\%) due to DM time-of-motion → reconstructed WFs from WFS are over-estimated by \(~15\%)*
Conventional Lyot Coronagraph, Broadband light: 0.9-1.7 um (62% wide band)

Average raw contrast [15-20 I/D] = 2.3e-6

Average raw contrast stability [15-20 I/D] = 5.5e-8

Average raw contrast stability [11-34 I/D] = 1.1e-8 (averaged value within white box)
Fast RM acquisition (4000 Hadamard pokes in 2s @ 2 kHz) + Removing temporal DM response from response matrix by using two poke sequences

Temporal bleeding from previous poke pattern (should be removed from RM)

Camera readout RF coupling between pixels
~1% electronic ghosts at 2kHz frame rate
Needs to be kept in RM

RM assembled from single poke sequence:
+- + - + -

RM assembled from average of two poke sequences:
+- + - + -
+- + - + -

RMs reconstructed from Hadamard pokes, 2kHz modulation (DM moves during EMCCD frame transfer)
Multi-channel DM virtualization & timing knowledge/stability → on-sky response matrix acquisition, while ExAO loop running

Left: WFS reference
Right: Response to single actuator poke (one of 2000)

RM measurement @ 2kHz takes 4000 pokes = 2 sec
Multiple RMs averaged to increase SNR
Removing Hysteresis and DM-induced vibrations from response matrix calibration (piezo curvature DM)
Predictive Control

The main fundamental limit to Extreme-AO correction are that:

1. **FLUX**
   The star used for measuring aberrations has limited flux → measurements are noisy

2. **SPEED**
   Turbulence is moving fast, and it’s very difficult to catch up.
   Note: There are also unavoidable latencies in the hardware

In conventional AO systems, we can average the last few measurements to reduce noise → this adds latency, so this is not a viable solution for Extreme-AO

**SOLUTION:** Predictive control optimally uses the last few measurements to predict the aberrations at the time of correction

**CHALLENGE:** The temporal relationships between past and future aberrations are not known in advance and change continuously (depends on wind speeds and many other things) → we must learn them in real-time: machine learning
The Machine Learning challenge

Need to derive 100s of millions of control matrix (CM) values within minutes, using billions of samples...

Example:
SCExAO, 3 kHz, 10-step predictive control, 100 sec training
Input: $14,400 \times 3,000 \times 100 = 4.32e9$ measurements
Output: $14,400 \times 2000 \times 10 = 288e6$ CM coefficients

Solution:
We deploy linear **Machine Learning** technique on a modal control space (smaller # of dimensions).
We use GPU cores (35,000 cores @ 1.6 GHz in SCExAO main RTC).
The Machine Learning challenge

One of two GPU chassis

SCExAO uses 30,000 cores running @1.3GHz
Re-thinking adaptive optics

The machine learning approach to predictive control is part of a wider machine learning approach to adaptive optics.

Conventional adaptive optics (pre-2018):
Off-sky calibration are performed to write a static control law. The control law is captured in a control matrix (CM) linking the last measurement to a correction.

Machine learning based AO:
The control law is continuously optimized based on analysis of real-time measurements. The control law includes predictive control and can also include sensor fusion if multiple sensors are deployed.
**Conventional AO:**

We measure RM/CM.

**Advanced AO control:**

We want to use past measurements (predictive control) and other measurements (sensor fusion) → control matrix is very big, and usually impossible to measure.

We derive CM from WFS(s) telemetry.
On-sky predictive control matrix
(modal representation, 100 modes shown)

Conventional AO would have control matrix
100 x 100 elements
Identity matrix

Optimal control adds elements outside of diagonal

Predictive control adds these blocks to control matrix

WFS measurement
Last WFS measurement

Step -1
WFS measurement

Step -2
WFS measurement

Step -3
WFS measurement

2kHz, target #1

1kHz, faint source

2kHz, target #2
First on-sky results (2 kHz, 50 sec update) → 2.5x raw contrast improvement

OFF (integrator, gain=0.2)  ON

Average of 54 consecutives 0.5s images (26 sec exposure), 3 mn apart
Same star, same exposure time, same intensity scale
New detectors

Photon-counting, wavelength resolving 140x140 pixel camera

Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

In operation @ Palomar
Delivered SCExAO March 2018
Giant Magellan Telescope
European Extremely Large Telescope
Towards Habitable Planets Imaging

Tools tested on current large telescopes will enable habitable planet imaging on 30-m class telescopes currently in development.

Significant challenges in real-time data processing algorithms to extract signal from noise... at multiple kHz with multiple sensors.

Habitable planets are stars cooler than Sun will be the easiest to image with large ground-based telescopes (cooler star → more moderate contrast).