Subaru Coronagraphic Extreme Adaptive Optics

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Subaru Coronagraphic Extreme-AO (SCExAO)

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SCExAO is a central part of Exoplanet instrumentation at Subaru Telescope.

Together with its modules and IRD, it provides Subaru Telescope with unique and broad exoplanet discovery and characterization capabilities.

We are preparing SCExAO to be visitor instrument on TMT.

OPTIMIZED FOR SMALL IWA (<0.1 arcsec)
→ reflected light giant planets on Subaru
→ Earths around M-type stars on TMT
Subaru Coronagraphic Extreme Adaptive Optics
**Wavefront sensing:**
- Non-modulated pyramid WFS (VIS)
- Coronagraphic low order wavefront sensor (IR) for non-common tip/tilt errors
- Near-IR speckle control

2k MEMS DM

Numerous coronagraphs – PIAA, Vector Vortex, 4QPM, 8OPM, shaped pupil (IR)

Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetary Signatures (VAMPIRES) (VIS)

Fibered Imager for a Single Telescope (FIRST) (VIS)
Fourier Lucky imaging (VIS)

Broadband diffraction limited internal cal. Source + phase turbulence simulator
Coronagraphs

Deformable mirror
Extreme-AO loop

2000 actuators MEMs DM running at 3.6 kHz (fastest ExAO system)
depth depletion EMCCD → very sensitive

Now reaching 80% SR in H under challenging conditions (m=7 star,
50mph wind)

Recent upgrade allows 3.6kHz loop operation with zonal and modal
reconstruction
→ low-latency control
→ modal reconstruction for predictive /
LQG control (under development)

SCExAO uses 25,000 cores
running >1GHz
How SCExAO achieves high contrast

(1) Small IWA, high throughput Coronagraphy
→ removes diffraction (Airy rings), transmits \( r > 1 \) l/D region

(2) Extreme-AO with fast diffraction-limited WFS
→ removes wavefront errors

(3) Near-IR LOWFS
→ keeps star centered on coronagraph and controls Focus, Astig, etc..
→ records residual WF errors to help process data

(4) Fast Near-IR Speckle control
→ modulates, removes and calibrates residual speckles

*Requires fast low-noise detectors*
Coronagraphs

Jovanovic et al.

Table 8. Details of SCExAO coronagraphs.

<table>
<thead>
<tr>
<th>Coronagraph type</th>
<th>Inner working angle (λ/D)</th>
<th>Waveband(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIIA</td>
<td>1.5</td>
<td>y-K</td>
</tr>
<tr>
<td>PIIACMC</td>
<td>0.8</td>
<td>y-K</td>
</tr>
<tr>
<td>Vortex</td>
<td>2</td>
<td>H</td>
</tr>
<tr>
<td>MPIIA + Vortex</td>
<td>1</td>
<td>H</td>
</tr>
<tr>
<td>MPIIA + 8 Octant</td>
<td>2</td>
<td>H</td>
</tr>
<tr>
<td>4 quadrant</td>
<td>2</td>
<td>H</td>
</tr>
<tr>
<td>Shaped pupil</td>
<td>3</td>
<td>y-K</td>
</tr>
</tbody>
</table>
SCExAO: wavefront control loop

**Extreme-AO LOOP**
- Facility Adaptive Optics system
- Sharpens image
- 2000 actuator Deformable mirror
- High speed pyramid wavefront sensor
  - Measures aberrations
- 3.7 kHz

**CORONAGRAPHIC LOW ORDER LOOP**
- Near-IR camera
  - Measures low-order aberrations
- 800 – 1350 nm
- 10-200 Hz
- Removes starlight

**SPECKLE CONTROL LOOP**
- CHARIS spectrograph
  - Exoplanet spectra
  - Slow speckle calibration
- 1350 – 2500 nm
- ~0.5 Hz
- ~2 kHz
- 800 – 2500 nm (rejected by coronagraph)

**MKIDs camera**
- Measures residual starlight
- 800 – 1350 nm
- ~2 kHz

**SCExAO: wavefront control loop**
- ~0.5 Hz
LLOWFS closing loop on first ten Zernike modes with Vortex on SCExAO instrument (March 2015)

Ref: Singh et al. 2015
Systematically removing speckles

Presence of static & slow-varying aberrations in the path of science camera sets contrast limit at present
Speckle nulling results on-sky (June 2014)

Single frames: 50 us

Meta data:
- Date: 2nd or June
- Target: RX Boo (also repeated on Vega)
- Seeing: <0.6"
- AO correction: 0.06" post-AO corrected in H-band (0.04" is diffraction-limit)
- Coronagraph: None (used Vortex on Vega)

Martinache, F. et al.
Coherent Speckle Differential Imaging
8m: Pyramid-based system + nearIR Speckle Control → 1e-8 contrast

300Hz speckle control loop (~1kHz frame rate) is optimal

Residual speckle at ~5e-5 contrast and fast → good averaging to detection limit at few 1e-7
SAPHIRA Infrared APD array

HgCdTe avalanche photodiode manufactured by Selex

Specifications
320 x 256 x 24μm
32 outputs
5 MHz/Pix

50 frame average
MKIDS camera (built by UCSB for SCEXAO)

Photon-counting, wavelength resolving 100x200 pixel camera

Pixels are microwave resonators at ~100mK photon hits → resonator frequency changes

Deliver to SCEXAO in CY2016
Electron-injector nearIR camera
(Northwestern Univ / Keck foundation)

3 μm Electron-injection speckle imaging camera

1 μm Electron-injection low-order wavefront sensing (pointing) camera
Fig. 3.— (a) Image of PSF. PSF with 2 sets of artificial speckles at 10 $\lambda/D$ (400 mas) from the PSF, (b) incoherent speckles, (c) coherent speckles. PSF subtracted image (d) with incoherent speckles (e) with coherent speckles. A square-root stretch was applied and the minimum and maximum of each image adjusted for maximum contrast. Data taken on Beta Leo on the 1st of April, 2015.
SCExAO high contrast imaging capabilities: expected schedule for capabilities offered to observers

**NearIR planet detection at moderate contrast**
- 2014: VAMPIRES
- 2015: PyWFS
- 2016: SAPHIRA

**Phase 1 operation**
- LOWFS + slow speckle control
- Moderate contrast improvement over HiCIAO
- Small IWA (~2 l/D) coronagraphy

**NearIR planet imaging at high contrast**
- 2016: RHEA
- 2017: FIRST

**Phase 2 operation**
- Significant contrast improvement over HiCIAO thanks to ExAO
- High SR (~0.9)
- More robust performance for coronagraph and LOWFS systems
- Smaller IWA (~1 l/D)

**Full system (CHARIS+MKIDS)**
- MKIDs camera → faster speckle control and better calibration → significantly higher contrast at small separation (~1e-8)
- Spectroscopy: CHARIS + MKIDS provide spectroscopy from ~0.8 um to 2.7um

**Visible light interferometry, polarimetry**
- (disks, stellar physics)

**Near-IR spectroscopic characterization**
- Ultra-High contrast → reflected light
- Strong visible light capabilities
SCExAO near-IR bench, End 2016

SAPHIRA

HiCIAO or MKIDS

CHARIS

Near-IR InGaAs cameras → to be replaced with EI technology

SAPHIRA
**Fig. 5.**— Calibration data for the APF-WFS acquired by the SCExAO science camera. Top left: the reference PSF, acquired with the system in its starting state. From left to right and top to bottom: the PSF after the corresponding Zernike mode has been applied. A non-linear scale is used to better show the impact of a 30 nm RMS DM modulation.

**Fig. 6.**— Experimentally recovered Zernike modes. Save for the spherical aberration, one will observe that the modes extracted from the analysis of the images of Fig. 5 do reproduce the features expected after looking at the theoretical reconstructed modes presented in Fig. 4.
HiCIAO + SCExAO: Kappa Andromedae (Currie et. al, in prep)

HiCIAO
HiCIAO + SCExAO: Substellar companion (sub-arcsec separation)


Also detected with GPI (similar SNR)
SCExAO data used to better constrain the object's temperature, gravity, and mass.
Direct Imaging Search for Companion Giant Planets and Brown Dwarfs to Sun-like Stars with Radial Velocity Drifts using Subaru/SCExAO

Elodie/Sophie radial velocity drift over 12 years

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Direct detection of the companions at the origin of the drift

First result in press: Hébrard et al. 2016
SCExAO visible images
FWHM 17mas
Resolves some stars

Beta Delph – 239 mas sep
(0.7”x0.7”, 8.56 mas/pix)

Resolved image of Betelgeuse

\[ \lambda = 680 \text{ nm} \]
Figure 1. A schematic diagram of VAMPIRES as configured on-sky in 2013 July, with all items relevant to the VAMPIRES beam train shown. Operation of each sub-system is described in the text. Abbreviations: M - Mirror; L - Lens; OAP - Off Axis Parabola; DM - Deformable Mirror; Dicr.M - Dichroic Mirror; HWP - Half-wave plate; BRT - Beam Reducing Telescope; LCVR - Liquid-Crystal Variable Retarder; LCC - LCVR Controller; TC - Temperature Controller; Cam - Camera; QWP - Quarter-Wave Plate; Depolz - Depolarizer; OAP col. - OAP Collimator; Lin polz - Linear polarizer. In an alternative configuration, the HWP can be replaced with a pair of QWP to allow birefringence to be corrected as needed.
Non-polarised mode and results

- VAMPIRES can also operate as a conventional (non-polarimetric) non-redundant masking instrument.

**Observed S-type star chi Cyg**

\[ V \sim 8 \text{ at time of observation} \]

- \[ \text{VAMPIRES UD Diameter} \]
  - \[ 32.2 \pm 0.1 \text{ mas (750 nm)} \]
- c.f. CHARM Catalogue, Richichi et al. 2005:
  - \[ \text{UD} = 32.8 \pm 4.1 \text{ mas (V band)} \]

**Observed close binary eta Peg**

- Detection confidence (MC) > 99.9%
- \[ \text{Separation} 48.9 \pm 0.6 \text{ mas} \]
- c.f. orb. params. Hummel+ 1998 → 49.9 mas
- \[ \text{Contrast} 3.55 \pm 0.06 \text{ mag} \]
- c.f. Hummel+ 1998: 3.61 ± 0.05 mag

Chi Cyg Power spectrum (log scale)
Note fall-off in power at longer BLs, since object is resolved.
Preliminary VAMPIRES science – in preparation

*Circumstellar dust around Red Supergiant μ Cephei*

- Observed with annulus mask at 775 nm
- Raw differential polarized visibilities show distinctive sinusoidal signature of circumstellar dust shell, with clear asymmetry *(right)*
- Dust scattering model fitted via synthetic differential visibilities *(below)*
Preliminary VAMPIRES science – in preparation

_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 ± 0.2 mas (which is roughly $R_{\text{star}}$)

Scattered-light fraction: 0.081 ± 0.002

PA of major axis: 28 ± 3.7 ° • Aspect ratio: 1.24 ± 0.03

**Left:** model image, shown in polarized intensity. **Middle:** model image show 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.
RHEA: Replicable High-resolution Exoplanet & Asteroseismology (PI: Michael Ireland, ANU)

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 $\times$ 0.6</td>
</tr>
</tbody>
</table>

RHEA first light @ Subaru: Eps Vir (detail) Feb 2016
FIRST visible light interferometer

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

\lambda/D at 800nm: 
- 20\text{mas}
- 15\text{mas}

\lambda/D at 600nm:
- 20\text{mas}

Separation: 44\text{mas} \pm 4\text{mas}
Median flux ratio: 0.033
Predictions: sep = 50\text{mas}
flux ratio at 800nm: 0.036
Near future developments
GLINT: Guided Light Interferometric Nulling Technology (proposed - PI: Tuthill)

Near-IR photonic nuller chip

Figure 1: Dust density (Left panel) and simulated 10 µm near-IR image (Right panel) for an exozodacal disk containing a 5 Earth-mass planet in a 1 AU orbit. Shredding 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.
SCExAO feeding IRD
Jovanovic, Kawahara, Kotani, Guyon

- 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>

Simultaneous spectroscopy of planet and background speckles

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

AO upgrade

Near-IR closed loop PyWFS with SAPHIRA

Replace AO188 with optimized AO correction
Would include near-IR Pyramid WFS
→ high throughput feeding to IRD
→ more flexibility / Wavelength coverage for visible light modules
→ higher high contrast imaging performance
→ path to TMT instrument
The ongoing fight against vibrations

5-30 Hz telescope vibrations
Due mostly to telescope Alt encoders

Short-term solutions:
- Install accelerometers on telescope
- Feed-forward loop to AO188 TT
- LQG control

Long-term:
Change encoders
SCExAO uniquely expands exoplanetary system characterization capabilities at Subaru

Central star:
Diameter, shape, pulsations, limb darkening (FIRST, IRD, RHEA)
Binarity → masses, constrain RV measurements (FIRST/VAMPIRES/IRD, RHEA)
Chemical composition (IRD, RHEA)

Planet mass and orbit from RV (IRD) + imaging

Reflected visible light spectra from post-coronagraph fiber-fed spectroscopy (SCExAO + IRD)

Near-IR spectroscopy (CHARIS + MKIDs)

Hot inner dust (thermal emission):
visible spectroimaging (FIRST, RHEA)
nearIR spectroimaging (CHARIS+MKIDs)

Reflected light dust:
visible spectroimaging (FIRST)
polarimetric imaging (VAMPIRES)
near-IR imaging+spectroscopy (CHARIS+MKIDs)
Where would habitable planets be in contrast/separation?

- **2 \( \lambda/D \)**
  - \( \lambda = 500 \text{nm} \)
  - \( D = 16 \text{m} \)
  - \( D = 2 \text{m} \)

1 Re rocky planets in HZ for stars within 30pc (6041 stars)

- **M-type stars**
- **K-type stars**
- **G-type stars**
- **F-type stars**

Angular separation (log10 arcsec) vs. log10 contrast.