SCExAO as a precursor to an ELT exoplanet direct imaging instrument

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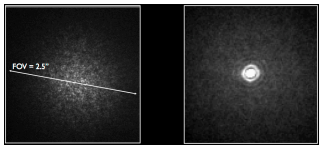
CONTEXT:

The Subaru Coronographic Extreme Adaptive Optics (SCExAO) instrument is a versatile platform for testing the latest high contrast imaging technologies which will pave the way for future extremely large telescope (ELT) instruments. At the heart of the instrument is a 2000 element deformable mirror and a pyramid wavefront sensor allowing for high order wavefront correction at >100 Hz resulting in high strehl ratios (>90%). The workhorse coronagraph is the phase induced amplitude apodization (PIAA) version which allows for an inner working angle of 1 λ/D with very high throughput. Other coronagraphic technologies being tested include the vortex, 4 quadrant, 8 octant and complex mask versions. Making full use of the coronagraph and ExAO system will be the integral field spectrograph CHARIS, which will operate from the y-K bands and offer low resolution spectra to distinguish between planets and speckles. Complementing the coronagraph there is a visible aperture masking, polarimeter known as VAMPIRES allowing for unprecedented spatial and polarization mapping of disks. In addition, a Lucky Fourier imaging instrument allows for diffraction limited imaging in the visible even in poor seeing while the pupil remapper FIRST enables for high fidelity imaging via the robust closure phase observable. Finally we aim to test the feasibility of diffraction limited spectroscopy for high radial velocity precision planet detection around M-dwarfs with the PANDORA instrument. These technologies will one day become indispensible for advanced ELT instruments.

LUCKY FOURIER IMAGING

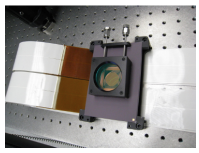
- Consists of a low noise camera and a lens.
- The highest signal to noise ratio Fourier components from a given image are extracted.
- An image is reconstructed from the ensemble of Fourier components.
- The image is diffraction limited regardless of the seeing!
- Operating in the visible (680 nm) offers unprecedented spatial resolution.



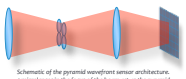
Diffraction limited image of Vega reconstructed from seeing limited images as shown on the left. FWHM is 17 mas despite 2 as seeing! [2]

HIGH ORDER WAVEFRONT CONTROL

- High actuator count deformable mirrors coupled with sensitive wavefront sensors enable high quality wavefront correction. These systems are called extreme adaptive optics (ExAO)
- SCExAO utilizes a Boston MicroMachines deformable mirror with 2000 actuators within the pupil to enable high order correction.
- A non-modulated pyramid wavefront sensor is used to measure the wavefront aberrations in the visible as it operates at the diffraction limit of the telescope rather than the seeing-limit (the case for a Shack-Hartman).



A 2 000 element deformable mirror from Boston Micromachines Coorporation capable of correcting for high order aberrations as well as low. This will be used on the Subaru Coronographic ExAO instrument.

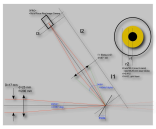


Schematic of the pyramid wavefront sensor architecture. 4 microlenses in the focus of the beam act as the pyramid optic. The pupil is then reimaged onto the detector.

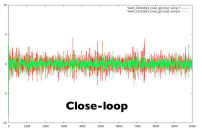
- The ExAO system is set to come online in mid-2013 and will be able to achieve Strehl ratios of 90%.

LOW ORDER WAVEFRONT SENSING

- Low order wavefront sensing is conducted in the near IR where the coronagraph operates (J-H bands).
- The reflected light from the focal plane mask for the coronagraph is used to carefully monitor the fine tip/tilt and other low order aberrations in the system that are non-common to the visible light pyramid wavefront sensor.
- The unique focal plane mask is a binary mask which absorbs the light at the centre of the core and reflects the light at the edges of the core, where the intensity gradient is steepest. This makes it more sensitive to fine tip/tilt errors [1].



Schematic of low order wavefront sensor architecture.

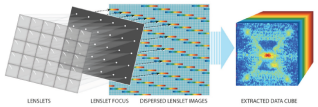


Log of the measured tip/tilt excursion once the low-order wavefront sensor loop was closed on-sky.

- This type of wavefront sensor allows for tip/tilt control of the core down to 0.2 mas!

INTGRAL FIELD SPECTRGRAPH: CHARIS

- CHARIS is an integral field spectrograph that is currently being developed to extend the capabilities of the SCExAO instrument and replace HiCIAO.
- It consists of a micro-lens array which segments the image in the focal plane before it is dispersed and reimaged onto a HAWII 2RG detector [3].



- It will be possible to obtain a data cube of high contrast images as a function of wavelength.
- This will allow for planets to be discriminated from background stars or speckles.
- The low resolving power of the spectrograph will allow for the atmospheres of Jupiter mass and higher companions to be constrained.
- It will be commissioned in 2016.

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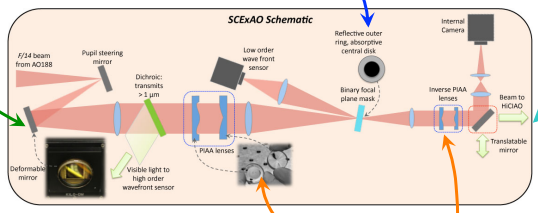
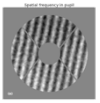
SCExAO Schematic



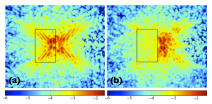
SPECKLE CONTROL AND NULLING

- By applying a sinusoidal modulation to the deformable mirror (which is in the pupil plane), its possible to diffract some light out of the central core and into speckles symmetric about the core.
- The frequency of the sinusoidal modulation, determines the distance from the core (i.e. spatial frequency), the amplitude controls the amount of diffracted light, the position of the sine waves on the DM with respect to the centre determines the phase of the speckle while the direction of the sine waves determines the orientation of the speckles.
- Speckles can be added so that they can be used for contrast calibration when the star is nulled by the coronograph or for astrometry.

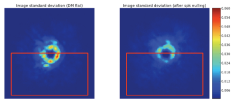


A sine wave applied to the pupil and the corresponding speckles generated in the focal plane.

- Quasi-static speckles due to aberrations and diffraction from the primary and spiders can be nulled out in one portion of an image by applying speckles with the same amplitude and opposite phase to those in the image. This is an active version of differential imaging techniques such as ADI.



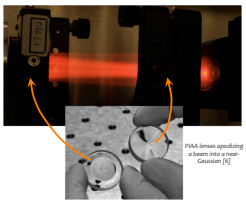
Active speckle nulling in a region of interest in the laboratory. [4]



Active speckle nulling demonstrated on-sky for the first time. Long exposure images reveal a contrast improvement of ~2 and a ~7 times improvement in the standard deviation. These modest results are limited by the dark current, read out noise and limited frame rate of the camera used for speckle nulling. New cameras with better specifications are currently being tested. [5]

CORONAGRAPHS:

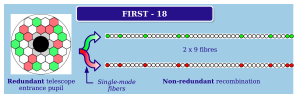
- The workhorse coronagraph is the Phase Induced Amplitude Apodization (PIAA) coronagraph. It allows for the smallest inner working /highest throughput.
- For example the inner working angle, defined as the point of 50% throughput for an off-axis source can be down to 1 λ/D form the stellar target! This greatly enhances the science possible.
- The PIAA coronagraph apodizes the flat topped pupil profile into a prolate spheroid (near Gaussian), greatly reducing the affects of a diffraction from the sharp edges of the pupil and hence making it easier to see a faint companion.
- Other coronagraphs currently being tested on the SCExAO bench include the Vortex, 8 octant and 4 quadrant and complex mask coronagraphs.



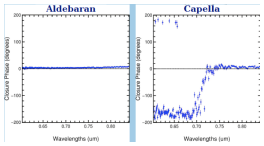
PIAA lenses apodizing a beam into a near-Gaussian [6]

PUPIL REMAPPING INTERFEROMETER: FIRST

- Pupil remapping is a photonic analogue of aperture masking but allows for all the light in the pupil to be used.
- This means increased information through greater Fourier coverage and hence a more accurate reconstruction of the stellar target. This also allows for a fainter companion to detected.
- FIRST has had 2 years of commissioning at the Lick observatory (Shane Telescope) and demonstrated good performance thus far.
- It will allow for high fidelity, diffraction limited images of binaries and post AGB stars to be taken. With improvements in performance it may even be capable of imaging Jupiter's in reflected light as well.



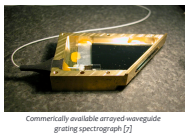
18 fibers used across the pupil currently and the chosen non-redundant remapping.



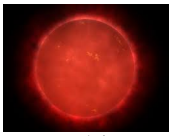
Data from commissioning of the FIRST instrument at the Lick observatory. The flat closure phase signal as a function of wavelength is typical for a single unresolved object. The step function for Capella reflects the presence of a binary. [5]

EXAO FED DIFFRACTION LIMITED SPECTRGRAPH: PANDORA

- By exploiting the 90% strehl ratio, low residual tip/tilt error (0.2 mas) and the PIAA lenses it is possible to couple light into a single-mode fiber with a theoretical efficiency of ~100% in the near-IR (H-band).
- A single-mode fiber forms the ideal slit for a spectrograph as it is temporally invariant to changes at the input eliminating modal noise and allows for the spectrograph to compact.
- PANDORA will harness photonic technologies including an Arrayed Waveguide Grating spectrograph [6] as well as a Fiber Fabry-Perot interferometer in order to achieve m/s radial velocity precision!
- Further absolute wavelength referencing will push this to the sub m/s level.
- **An Earth-sized planet within the habitable zone of an M-dwarf can orbit in only a few days and generate a redial velocity signature of ~1 m/s, which will be detectable by our instrument.**



Commercially available arrayed waveguide grating spectrograph [7]



An M-dwarf

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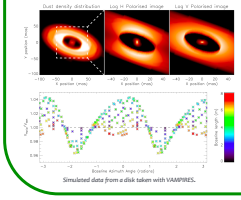
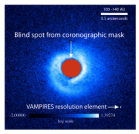
APERTURE MASKING POLARIMETER: VAMPIRES

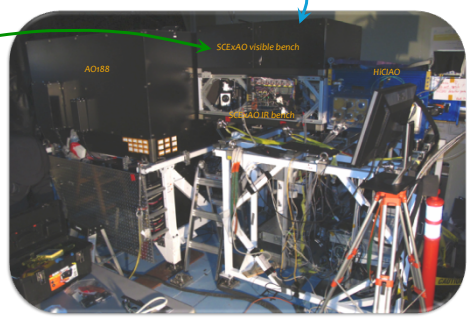
- VAMPIRES is a visible aperture masking interferometer with polarimeter capabilities.
- It will operate from 600-1000 nm and allow for sub-diffraction limited imaging of post AGB stars and disks with full polarimetric information.
- The instrument is undergoing testing at Subaru and will become operational from 2014.
- It will compliment the polarimetric mode of HiCIAO and enable imaging of the inner portion of disks as well as resolving dust grain models for post AGB star shells.



Simulated data from a disk taken with VAMPIRES.



MWC758 disk imaged with the polarimetric mode of HiCIAO and the resolution of VAMPIRES [8].



SUMMARY:

- SCExAO supports many novel modules and technologies which will be very powerful for high contrast imaging.
- These technologies will be indispensible to future ELT instruments and the direct imaging of planets.
- ExAO systems can also be used for precise radial velocity measurements via diffraction limited spectrograph, yet another way in which they contribute to exoplanetary science.

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