Topics in Observational Astrophysics

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Lecture 21
Exoplanets - 3

- Direct imaging and high contrast imaging continued
- The P1640 HCI system
  - AO system
  - Coronagraph
  - Integral Field Spectrometer
- Speckle suppression to create a dark hole around the bright star

Project 1640 schematic

- On the 5-m Hale telescope at Palomar Observatory.
- Broadly similar to GPI on Gemini-S (8m) and SPHERE on the VLT (8m)
- Has a 3388 Actuator deformable mirror (DM) in the AO system, a Cal System and a H2RG detector system.

IFS = integral field spectrograph: gives a spectrum for every spatial pixel in the field of view (see earlier lecture).
PALM3000 AO system

P1640 replaces PHARO

Low-Order DM (349 act.)
Tip/Tilt Mirror
High-order DM (3388 act.)

High-Order WFS
Low-Order WFS

+ Wavefront Processor Computer
+ Supervisory Software & User Interface
Infrared Tip/Tilt Sensor

Fig from Bouchez et al SPIE 2008

Coronagraph

Telescope Pupil
Evenly Illuminated

Image is made (top)
And occulted (bottom)

Pupil is reimaged (top)
And partially blocked (bottom)

The Final image after Coronagraph has only 0.5% of the original Starlight.

Credit: Hinkley, Oppenheimer and Sivaramakrishnan

Occulting Spot

Lyot Stop
The light that goes to the Cal system is used to correct non-common path errors. These are wavefront errors that are due to optics downstream of the WFS of the AO system. They are corrected by applying extra terms to the DM.
Apodizer

Figure 75. Detail of the Jenoptik microdot apodizing pupil mask. The astrometric grid is evident in the upper left panel.

Grid later removed

Credit: Sasha Hinkley
Built in the American Museum of Natural History in New York

Credit: Sasha Hinkley

Micro-lens array

Detector

IFS
Integral Field Spectrograph

- Microlens based design
- No moving internal parts
- Entirely cryogenic (77K)
- Filter permits simultaneous observation over 995-1795 nm
- Field of View: 3840x3840 mas
- Lenslet Plate Scale: 19.3 mas/lens
- ~40,000 spectra per image
- Spectral resolution: 31-58
- 1.45s to 1500s exposures

Hinkley et al. 2011 PASP, 123, 74

Spectrograph Internals

- Array of 270 x 270 microlenses with 75μm pitch. Two powered faces.
- Teledyne H2RG 2048 x 2048 pixel HgCdTe array
Scanning through a cube

Each frame in the movie is a single wavelength slice in the data cube.

The speckle pattern expands as the wavelength increases.

Companions do not move radially like the speckles do.

Wavelength goes from 1.1 - 1.8μm

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S4 Speckle Suppression
(Fergus et al. 2014, 794, 161 and Veicht et al. 2015)

S4 computer software uses principle component analysis (PCA) to model the speckle background in the absence of companions.
Speckle suppression in a dark hole using a deformable mirror

- It is possible to use a deformable mirror to correct for speckles due to peaks and valleys (imperfections) in the surface of the primary mirror.
- The DM simply retards or advances the wavefront to flatten it.
- If the DM has $N \times N$ actuators with $N$ across the pupil the shortest period wavefront error we can fit (i.e. correct for) has $N/2$ periods in one dimension.
- Longer period errors can also be corrected so there are $N/2$ correctable modes in one dimension.
- So in the full aperture the number of modes $M$ is given by
  $$M = \pi \left( \frac{N}{2} \right)$$
  (area of circle)/(area of square) = $\pi/4$
- Let the average mode amplitude be $h_0$, so the speckle produced by this mode has a relative intensity given by
  $$I(\text{typ. speckle})/I_{\text{stot}} \approx a^2/4 = \left( \frac{\pi h_0}{\lambda} \right)^2$$
- To get this we used ($a$ is the phase amplitude delay)
  $$a = 2\pi h_0 / \lambda \quad \text{and} \quad A_{\text{spec}} = A_{\text{star}} \left( \frac{a}{2} \right)$$

Credit: Traub and Oppenheimer, 2010
Speckle suppression in a dark hole

- At each point in the pupil the net amplitude will be the sum of $M$ complex vectors of average length $h_0$ but with random phases. This is exactly the random walk problem in two dimensions. Therefore the expected average amplitude will be

$$h_{\text{rms}} \approx M^{1/2} h_0 \quad \text{or} \quad h_{\text{rms}} = \frac{\sqrt{\pi Nh_0}}{4}$$

- So from equation [*] and defining the average contrast as

$$C = \frac{I(\text{ave. speckle})}{I(\text{star})} = \left( \frac{\pi h_0}{\lambda} \right)^2$$

we get

$$C = \frac{4h_{\text{rms}}^2}{N\lambda}$$

Speckle suppression in a dark hole

- This says that to achieve a contrast $C$, with an otherwise perfect coronagraph, we need to control the $N \times N$ element DM with an accuracy such that the reflected wavefront has an RMS error of $h_{\text{rms}}$ or better.
- The DM must be controlled to a surface error of $h_{\text{rms}}/2$, of course.
- Rearranging gives

$$h_{\text{rms}} = \frac{N\lambda \sqrt{C}}{4\sqrt{\pi}}$$

- For example, if we desire $C = 10^{-10}$, and we have $N = 64$, then $h_{\text{rms}}$ must be about $\lambda/10,000$. Thus the wavefront must be 100 times better than a typically “excellent” $\lambda/100$ wavefront.
- $C = 10^{-10}$ corresponds to the speckles having the same brightness as an Earth clone.
- For $C = 10^{-7}$ and $N = 64$ then $h_{\text{rms}} = \lambda/350$. 
Speckle suppression in a dark hole

- At 500nm with $C = 10^{-10}$ the DM must control the reflected wavefront to an accuracy of $h_{\text{rms}} = 0.5 \, \text{Å}$. This may seem impossible, given that this is about half the radius of a Si or O atom; however, a typical (0.1 to 1.0 mm) DM element averages over many such atoms, and it is the average surface that counts here.
- In addition, we know from experiment (e.g., Trauger and Traub, 2007) that this is perfectly feasible.
- At 500nm with $C = 10^{-7}$ the DM must control the reflected wavefront to an accuracy of $h_{\text{rms}} = 14 \, \text{Å} = 1.4\text{nm}$.
- There are data processing techniques which can recover a good SNR for a faint companion like an exoplanet even when it is 100 – 1000 times fainter than the average speckle. For example, cross-correlation with a molecular spectrum template (requires high spectral resolution) or advanced speckle subtraction software such as P1640’s S4 code.

Speckle suppression in a dark hole

- Can think of the DM as a grating device that can be commanded to generate a surface ripple that can diffract starlight to a specific target point in the focal plane. The phase of the controlled scatter can be adjusted by shifting the wave pattern on the DM from sine to cosine, for example.
- The DM can be used to steer starlight to points in the focal plane, with the desired amplitude and phase so as to cancel starlight that arrived by other means. The DM is thus an extremely powerful device.
- Note that this only works for light from the star itself; light from an exoplanet is not coherent with starlight, so the DM cannot use starlight to cancel an exoplanet.
Inner and outer working angles

- The inner working angle is set by the occulter.
- The outer working angle is sometimes defined as the size of the dark hole and is set by the spacing between the DM actuators, L, in the telescope pupil plane.
- For example, if $D_{tel} = 8m$ and there are 64 actuators in the DM across the diameter of the pupil (i.e. a $64 \times 64$ actuator DM) then $L=125$ mm.
- The angular radius of the dark hole, $\theta$, is the maximum angle to which the highest-frequency spatial period of the DM can redirect light.

![Diagram showing inner and outer working angles](image)

Path difference $A$ to $B = \lambda$

- Can think of the DM as a diffraction grating.
- The angle $\theta$ is $\lambda$ divided by two actuator-spacings of the DM, or $D/(N/2)$, giving the angular radius as

$$\theta(\text{dark hole}) = \pm \frac{N\lambda}{2D} = \pm \frac{\lambda}{2L}$$

- Thus the maximum size of the dark hole is a square of angular size $N\lambda/D$, which is a length of $N$ resolution elements of the pupil. This square is centered on the star.