Lecture 14

Extreme Adaptive Optics

Claire Max
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Based in part on slides from
Bruce Macintosh and Sandrine Thomas
Outline

• Science parameter space for Exoplanet systems
• Direct imaging of exoplanets with ground-based AO
• Approaches to high-contrast imaging with current telescopes: Angular Differential Imaging
• Coronagraphs to block light from host star
• Gemini Planet Imager: one example of the current state of the art
• Recent scientific results: directly imaged planets and disks
Exoplanets as of 2020

Today 30-40 directly imaged exoplanets
Working requirements for direct imaging

• **Contrast between flux from host star and planet**
  - Depends on wavelength, type of planet, type of star, distance of planet from star, etc.

• **Order of magnitude for sun-like star**
  - Earth: visible $10^{-9}$ to $10^{-10}$
    mid-IR $10^{-7}$
  - Required contrast ratios for gas giants and for M dwarf host starts are not so stringent ($10^{-6}$ ?)

• **Inner Working Angle typically a few $\lambda / D$**
Ground based Instruments: Exoplanet direct imaging instruments

- GPI
- SPHERE
- P1640
- SCExAO

References:
- Macintosh et al, 14
- Beuzit et al, 14
- Hinkley et al, 08
- Guyon et al, 10
Brightness of ExAO targets: Gas Giants

- Hot start
- Normal AO regime
- ExAO regime
- Low-entropy core accretion models

Marley et al 2007
First images of an extrasolar planetary system (Keck and Gemini AO)

Planets Orbiting HR 8799
(Sept. 2008)

Marois et al. 2008 Science Mag
More directly imaged exoplanets

Beta Pic b
VLT NACO

51 Eri b
GPI

PDS 70
SPHERE
Conventional AO limited by scattered light

Strehl ratio $S$

Halo intensity $1 - S$
"Extreme" AO (ExAO)
gain > S/(1-S)
But - this assumes no non-common path errors and no AO artifacts
Keck AO Image of a bright star
Inner part of image - artifacts due to AO optics
Angular Differential Imaging

Image 1

Image 2 (+ 5 minutes)

Subtraction

Marois et al 2006
Image processing to suppress light from host star

Angular Differential Imaging (ADI)

Keck Ks-band | 20s integration

ADI-processed 20s integration

Combined ADI

Total integration time (s) = 20

Marois et al.
Figure 7
Image formation in an ExAO system. (a) Uncorrected atmospheric wavefront. (b) ExAO correction reduces the RMS aberration level from 1186 nm to 141 nm. Without correction, the PSF is an arcsecond-large cloud of speckles (c). The ExAO correction carves out a high-contrast region where telescope diffraction is the main source of flux (d). This diffraction term is removed by adding a coronagraph (e). Abbreviations: AO, adaptive optics; PSF, point spread function; RMS, root mean square.
Coronagraphs

- Invented by Bernard Lyot in 1930 for studying the corona of the sun without waiting for an eclipse
- Block the sun’s light with a circular mask in the focal plane
- Problem: diffraction from the sharp edges of the mask
Cartoon of Lyot Coronagraph

Credit: Subaru website
How can we control diffraction?

PSF = |FT(A)|^2
Lyot coronagraph (Lyot, 1933)
Lyot coronagraph (Lyot, 1933)

Sivaramakrishnan et al 2001 has a nice 1-d analysis of how this works
Large variety of coronagraph ideas

- Lyot family:
  - Basic: Lyot 1939 MNRAS 99, 538; Sivaramakrishnan et al 2001
  - Band-limited: Kuchner & Traub 2003

- Apodizers:

- Interference / wave-optics
  - 4-quadrant phase mask: Rouan et al 2000 PASP 777 1479
  - Nulling interferometer/coronagraphs: Mennesson et al. 2004 Proc. SPIE 4860, 32

- Optical Vortex Coronagraphs

- Most practical coronagraphs only work at > 3-5 λ/D

- Control of phase errors is as important as controlling diffraction
Coronagraph also improves stability

Figure 9
(a) ExAO PSF stability without and with coronagraph (exposure time per PSF = 100 coherence times) and (b) numerical simulation without photon noise. PSF stability is improved by adding a coronagraph to the ExAO system. See Table 3 for simulation details. Abbreviation: PSF, point spread function.

From Olivier Guyon Annual Reviews paper
Shaped-pupil coronagraphs to make dark holes (Kasdin et al. 2003)
Inner working distance
≈ 3-5 \( \lambda / D \)

Outer working distance
≈ \( N \lambda / D \)
Random intensity of all the Fourier components produces speckles
As speckles average out ($\tau \sim D/v_{\text{wind}}$) planets can be detected
Must get rid of static errors as well
ExAO 0 nm static errors, 5 MJ/500 MYr planet, 15 minute integration
ExAO 1 nm static errors, 5 MJ/500 MYr planet, 15 minute integration
ExAO 2 nm static errors, 5 MJ/500 MYr planet, 15 minute integration
ExAO 5 nm static errors, 5 MJ/500 MYr planet, 15 minute integration
Table 2 Main instruments benefiting from AO and high-contrast imaging capabilities. This non exhaustive list groups the instruments by generation.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Telescope</th>
<th>Wavelength (μm)</th>
<th>Operations$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADONIS</td>
<td>La Silla 3.6</td>
<td>1-5</td>
<td>1996-?</td>
</tr>
<tr>
<td>PUEO</td>
<td>CFHT</td>
<td>0.7-2.5</td>
<td>1996-2013</td>
</tr>
<tr>
<td>NaCo</td>
<td>VLT</td>
<td>1-5</td>
<td>2002</td>
</tr>
<tr>
<td>Lyot Project</td>
<td>AEOS</td>
<td>0.8-2.5</td>
<td>2003-2007</td>
</tr>
<tr>
<td>ALTAIR-NIRI</td>
<td>Gemini N.</td>
<td>1.1-2.5</td>
<td>2003</td>
</tr>
<tr>
<td>NIRC2</td>
<td>Keck</td>
<td>1-5</td>
<td>2004</td>
</tr>
<tr>
<td>NICI</td>
<td>Gemini S.</td>
<td>1.1-2.5</td>
<td>2007</td>
</tr>
<tr>
<td>HiCIAO</td>
<td>Subaru</td>
<td>1.1-2.5</td>
<td>2009</td>
</tr>
<tr>
<td>PALM-3000/P1640</td>
<td>Palomar 200''</td>
<td>1.1-1.65</td>
<td>2009</td>
</tr>
<tr>
<td>FLAO/LMIRCam</td>
<td>LBT</td>
<td>3-5</td>
<td>2012</td>
</tr>
<tr>
<td>GPI</td>
<td>Gemini S.</td>
<td>1.0-2.3</td>
<td>2013</td>
</tr>
<tr>
<td>MagAO/VisAO</td>
<td>Clay</td>
<td>0.5-5</td>
<td>2014</td>
</tr>
<tr>
<td>SPHERE</td>
<td>VLT</td>
<td>0.5-2.3</td>
<td>2014</td>
</tr>
<tr>
<td>SCExAO</td>
<td>Subaru</td>
<td>0.5-2.2</td>
<td>2015</td>
</tr>
</tbody>
</table>

$^a$ Instruments without end date are still in operation.
## Extreme AO Systems today

**Table 4  ExAO systems: Primary ExAO wavefront control characteristics**

<table>
<thead>
<tr>
<th></th>
<th>Status</th>
<th>DM&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Primary WFS(s)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palm3000+P1640, Palomar (5 m)</td>
<td>Operation 2012–2017</td>
<td>66</td>
<td>SHWFS, 2 kHz</td>
</tr>
<tr>
<td>GPI, Gemini (8.2 m)</td>
<td>Operation 2014–present</td>
<td>50</td>
<td>SHWFS, 1 kHz</td>
</tr>
<tr>
<td>SPHERE, VLT (8.2 m)</td>
<td>Operation 2014–present</td>
<td>50</td>
<td>SHWFS, 1.2 kHz</td>
</tr>
<tr>
<td>SCExAO, Subaru (8.3 m)</td>
<td>Operation + development</td>
<td>48</td>
<td>Pyramid, 3.6 kHz</td>
</tr>
<tr>
<td>MagAO-X, Magellan (6.5 m)</td>
<td>Development</td>
<td>48</td>
<td>Pyramid, 3.6 kHz</td>
</tr>
</tbody>
</table>

<sup>a</sup>Number of actuators across the beam diameter.

<sup>b</sup>Highest speed supported by hardware and real-time computer. Systems can run slower on fainter stars to optimize correction. SCExAO’s max speed (3.6 kHz) offers marginal performance gain over 2-kHz speed. Abbreviations: DM, deformable mirror; WFS, wavefront sensor; SHWFS, Shack–Hartmann wavefront sensor.

From Olivier Guyon Annual Reviews paper
Schematic of Gemini Planet Imager
## Comparison of original Keck AO and GPI AO parameters

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Deformable mirror</strong></td>
<td>349 actuators</td>
<td>4096 actuators</td>
</tr>
<tr>
<td></td>
<td>(240 active)</td>
<td>(1809 active)</td>
</tr>
<tr>
<td><strong>Subaperture</strong></td>
<td>56 cm</td>
<td>18 cm</td>
</tr>
<tr>
<td><strong>Control rate</strong></td>
<td>670 Hz</td>
<td>2000 Hz</td>
</tr>
<tr>
<td><strong>Wavefront sensor</strong></td>
<td>Shack-Hartmann</td>
<td>Spatially-filtered Shack-Hartmann</td>
</tr>
<tr>
<td></td>
<td>400 – 1000 nm</td>
<td>700-900 nm</td>
</tr>
<tr>
<td><strong>Strehl @ 1.65 µm</strong></td>
<td>40%</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td><strong>Guide star mag (NGS only)</strong></td>
<td>$R &lt; 13.5$ mag.</td>
<td>$I &lt; 9$ mag. ( $V &lt; 11$)</td>
</tr>
</tbody>
</table>
Data pipeline assembles cubes: image of planet as function of wavelength
For Class Projects, how to calculate contrast ratio?

- Not a simple expression, as it depends on removing internal wavefront errors as well as atmospheric ones, coronagraph performance, etc.

- One very rough guess (from Milli et al. 2017):

\[
Contrast \approx \frac{1 - \text{Strehl}}{N_{\text{actuators}}}
\]

- In real systems this is an under-estimate of the contrast.

- For ExAO, want very high Strehl (>90%).
References, part 1


LaFreniere, D., et al., “A new algorithm for point-spread function subtraction for high-contrast imaging”


Poyneer, L., Macintosh, B., and Veran, J-P., “Fourier transform wavefront control with adaptive prediction of the atmosphere”, 2007 JOSA A 24, 2645