Exoplanet High Contrast Imaging Technologies
Ground

KISS Short Course:
The Hows and Whys of Exoplanet Imaging

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Telescope Diameter (Bigger is Better)

- Diameter:
  - Collecting area goes as $D^2$ -> more photons
  - Spatial resolution goes as $1/D$ -> sharper images (closer planets)

- Rule of thumb: it is easier to build large telescopes on the ground than to build them in space
Ground Based Telescopes

- Magellan Clay 6.5 m
- Subaru 8 m
- Gemini-S 8 m
- VLT 8 m (4)
- Keck 10 m (2)
- LBT 8x22 m
Ground Based Telescopes

- GMT 24.5 m
- TMT 30 m
- E-ELT 39 m

The future is under construction . . .
Turbulence

- There's a catch . . .

- Light must propagate through the Earth's atmosphere to reach a telescope on the ground.

- Temperature variations in the atmosphere cause index of refraction variations

- The characteristic scale of these variations, r0, is less than telescope diameter D (for large telescopes).

- Result: the wavefront reaching the telescope is no longer flat
  - This is why stars twinkle
Flat Wavefronts

Pupil Plane

Focal Plane
Turbulence Degraded Wavefronts

Pupil Plane

Focal Plane
Adaptive Optics

- AO systems measure and correct the OPD caused by turbulence

- Key components
  - Wavefront sensor
  - Deformable mirror
  - Real time control system

- Limited by:
  - Speed of components
  - Number of actuators (DOF)
  - Brightness of stars

Courtesy of Claire Max
AO for Exoplanet Imaging

Generic AO System

Gemini Planet Imager (GPI)

See Macintosh+ (2014), Poyneer+ (2016)
AO for Exoplanet Imaging

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Generic AO System

Gemini Planet Imager (GPI)

Coronagraph
Low-Order WFS
Integral Field Spectrograph

See Macintosh+ (2014), Poyneer+ (2016)
Facility Adaptive Optics system
- Sharpens image

2000 actuator Deformable mirror
- Removes starlight

CORONAGRAPHIC LOW ORDER LOOP
- Near-IR camera
  - Measures low-order aberrations
  - Measures residual starlight
  - 800 – 2500 nm (rejected by coronagraph)

SPECKLE CONTROL LOOP
- MKIDs camera
  - Measures residual starlight
  - 800 – 1350 nm
  - ~2 kHz

Extreme-AO LOOP
- High speed pyramid wavefront sensor
  - Measures aberrations
  - 3.5 kHz

CHARIS spectrograph
- Exoplanet spectra
  - Slow speckle calibration

Block diagram of SCExAO
Courtesy of Olivier Guyon and Nemanja Jovanovic
See Jovanovic et al, 2015.
Ground Exoplanet Imagers Today

- MagAO
  - 6.5 m Magellan Clay, 0.5 um (VisAO) to 5 um (Clio)
- LBTI
  - 8x22 m LBT, 1-13 um imaging, IFS, nulling & Fizeau interferometry
- P1640
  - 5 m Palomar, 0.9-1.78 um IFS
- GPI
  - 8 m Gemini-S, 0.9-2.4 um IFS, polarimetry
- SPHERE
  - 8 m VLT, 0.5-2.32 um imaging, IFS, polarimetry
- SCExAO
  - 8 m Subaru, 0.5 – 2 um, many modes of observation
MagAO and LBTI

Adaptive secondary mirrors

- Minimum new optical surfaces, optimal for thermal-IR
- 8x22 m Large Binocular Telescope, Mt. Graham, AZ
- 6.5 m Magellan Clay Telescope, Las Campanas Obs., Chile

See Esposito+ (2011); Close+ (2012); Hinz+ (2013)

Steph Sallum (LBTI+NRM) and Kate Follette (MagAO+VisAO) [Sallum et al, Nature, 2015]

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See Esposito+ (2011); Close+ (2012); Hinz+ (2013)
• Spectro-Polarimetric High-contrast Exoplanet Research
• At 8 m VLT (ESO)
• For more, see https://www.eso.org/sci/facilities/paranal/instruments/sphere/overview.html
Gemini Planet Imager (GPI) on Gemini South (Chile)
See also Poyneer+ (2016), and http://planetimager.org/
Introducing MagAO-X

- A new Extreme-AO system for Magellan
- 2000 actuators, 3.6 kHz
- Goal: 1 λ/D coronagraphy in the visible (see Males+, SPIE, 2016)
- Status: recommended for funding by NSF-AST (MRI), in preliminary design phase.

Images at Hα (656 nm)
Limits of Ground Based AO

- Technology keeps getting better
  - Fast, high order DMs are readily available
  - Low (near zero) noise, fast detectors are becoming ubiquitous
    - From visible (EMCCD) to IR (APD arrays)
    - With energy resolution (MKIDS)

- Fundamental limit: photon noise
  - Stars are only so bright
  - Limits number of actuators: can not correct all errors
  - Limits system speed: always behind the wind
  - Overall limit on image quality achievable from ground

- Key metric (for exoplanets): Contrast
  - Ratio of detectable planet brightness to star brightness
Discussing Contrast Limits

- Space and Ground people sometimes mean different things

- Typical usage:
  - Space: raw post-coronagraph & WFC contrast
    - No dependence on integration time, etc.
  - Ground: final contrast, after post-processing
    - Includes hours of integration, weeks/months/years of post-processing work

- Result: space people tend to think that ground people are crazy
The Extremely Large Telescopes will change the game
  - Diameters of 25, 30, and 39 m dramatically improve IWA

ELTs will image smaller planets than we can today
  - And spectroscopically characterize them

ELTs should be able to probe the HZs of nearby M-dwarfs
Ground-based Contrast Limits

Assumptions:

- $I_{\text{mag}} = 8$ (WFS > 100 targets)
- $H_{\text{mag}} = 6$ (Science)
- Noiseless detector
- 1.3 I/D IWA coronagraph
- 30% system efficiency
- 40% bandwidth in both WFS and science
- Time lag = 1.5 WFS frames
- Mauna Kea “median” atmosphere

Analysis for 30 m TMT by Olivier Guyon (See Guyon, 2005, 2012)
Ground-based Contrast Limits

Macintosh et al, 2006
Ground-based Contrast Limits

Bonavita et al. 2012

Smaller IWA
Higher contrast

2014, 8-m
VLT/SPHERE

2030, 40-m
EELT/PCS

Courtesy of Markus Kasper
Exoplanet Imaging Regimes

Log10 Contrast

Angular separation (log10 arcsec)

1 Re rocky planets in HZ for stars within 30pc (6041 stars)
c/o O. Guyon, see Guyon+, SPIE 2012
Exoplanet Imaging Regimes

Angular separation (log₁₀ arcsec)

Log₁₀ Contrast

Space

Earth-like planets @ Sun-like stars

IWA limited by D

10⁻¹⁰ contrast achievable

1 Re rocky planets in HZ for stars within 30pc (6041 stars)
c/o O. Guyon, see Guyon+, SPIE 2012
Exoplanet Imaging Regimes

Larger D Atmosphere will limit us to $\sim 10^{-8}$ at IWA.

"Earth-like" (?) planets @ M stars

1 Re rocky planets in HZ for stars within 30pc (6041 stars)
c/o O. Guyon, see Guyon+, SPIE 2012
High Contrast Imaging on the Ground

- We have built, and are building, large telescopes on the ground
  - Current generation, 5-10 m, with AO, studying exoplanets right now
  - Next generation, 25-39 m, probing the HZs of nearby stars in the next 10-15 years.
- Atmospheric turbulence is the big challenge on the ground
  - Adapative optics
- Post-AO ground exoplanet imagers are similar to space-based
  - Similar coronagraphy problem
  - Post-coronagraphic wavefront control
  - Post-processing
- Ground and Space are not really in competition
  - Different strengths, different weaknesses
  - Will study complimentary planet populations