Searching for Other Worlds
Next Generation Extreme Adaptive Optics
on Ground-Based Telescopes
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But we’ve already found many…

- Doppler surveys have cataloged >200 planets
  - Indirect searches are limited by Kepler’s third law: $a = P^{2/3}$
    - $P_{\text{Jupiter}} = 11$ years
    - $P_{\text{Neptune}} = 165$ years
  - Exo-Jupiters remain undetected
  - A survey of outer regions ($a > 10 \text{ AU}; P > 31.6 \text{ yr}$) is impractical using indirect methods
Doppler planets

- Only 5% of stars have known Doppler planets
  - Why isn’t it 15 to 50%?
- A diversity of exoplanets…
  - ≤20% of the Solar System’s orbital phase space explored
  - Is the Solar System typical?
- Do A & early F stars have planets?
  - What about M dwarfs?
- How do planets form?
  - Core accretion vs. gravitational collapse
- New questions
  - What is the origin of dynamical diversity?
Why high contrast imaging?

Broad scientific application

– Exoplanet detection
  • Direct methods explore beyond 5 AU
  • Direct methods give all 6 orbital parameters
  • Indirect methods give only $a$, $M \sin i$, & $e$

– Circumstellar disks
  • Proto-planetary & debris disks

– Fundamental stellar astrophysics
  • Large mass range main sequence binaries
    – Brown dwarfs & white dwarfs

– Mass transfer & loss
  • Cataclysmic variables, symbiotic stars & supergiants

– Solar system: Jovian/Kronian moons, asteroids
Do it from space?

- **Space:** expensive high quality optics, stable PSF
  - Low billions of $, 10 year timescales
  - Terrestrial Planet Finder (TPF) waiting behind James Webb Space Telescope (JWST) in NASA queue
  - ESA Darwin nulling interferometer
  - For resolution go short wave (terrestrial planets)
  - Lower contrast for self-luminous jovians (JWST mid-IR)

- **Ground:**
  - Low 10’s of millions of $, 5 year timescales
  - Atmospheric transparency windows
  - Adaptive optics SNR
    - Better wavefront correction at longer $\lambda$ (J=1.2, H=1.6, K= 2.2 microns)
    - At K and longer, thermal background rises
  - Residual speckles on all timescales
Adaptive Optics (AO) Schematic

Adaptive Optics removes effects of turbulent mixing of layers of air at different temperatures.

Claire Max, CfAO
Wavefront slope data

YUV420 codec decompressor are needed to see this picture.

Shack-Hartmann subaperture slope data
Deformable mirror

- Glass face-plate
- Reflective coating
- Light
- Cables leading to mirror’s power supply (where voltage is applied)
- PZT or PMN actuators: get longer and shorter as voltage is changed
- Claire Max
AO - data

QuickTime™ and a Animation decompressor are needed to see this picture.

PalAO - 241 actuators
Strehl ratio ~70%, K band
\( \lambda / D = 0.1 \)
Paschen alpha
Soummer & Lloyd
Spatially filtered wavefront sensing

- 5-layer 14.5 cm r0 atmosphere
- 5560 K star, 700-900 nm WFS (25 nm resolution), no atmospheric dispersion
- H-band APLC, no atmospheric dispersion, (1.47, 1.52, 1.57, 1.625 (optimized) 1.78 microns)
- Optimized-gain Fourier control on I_mag=6, 2 kHz

Poyneer & Macintosh
Solar system seen from 10 parsec

Simulated image almost perfect, infrared (H Band 1.65 micron) 8 m Telescope

Star’s speckle & photon noise overwhelms planet signal

Saturn (22.5")

Spectrum - atmospheric composition, surface temperature, maybe gravity

Sun, suppressed by a million Planets not extinguished

Cujam omega Her
Direct methods

- Interferometry - work mostly in pupil plane
  - Null out central star, see planet
    - Small field of view, narrow spectral bandpass
    - Closure phase and non-redundant masking

- Coronagraphy - work mostly in first image plane
  - Attenuate or cancel central star, see planet


USAF Advanced Electro-Optical System (AEOS) 3.6m 1000-actuator AO system on telescope on Maui, H band (1.6 micron) image with Lyot Project coronagraph
Detection of cooling planets

- Contrast required to detect an exo-Jupiter in a 5 AU orbit in the visible is $2 \times 10^{-9}$
- Near-IR contrast is 2-3 orders of magnitude more favorable
  - Radiation escapes in gaps in the CH$_4$ and H$_2$O opacity at Y, J, H, & K

Exoplanet atmospheres

- Exoplanets occupy a unique location in (surface gravity, effective temperature) phase space
  - Over 5 Gyr a Jovian mass exoplanet traverses the locus of H₂O & NH₃ cloud condensation
- “Last frontier” of classical stellar atmospheres

Galileo

![NH₃](image)

Debris disks

• Gravitationally sculpted disks provide key evidence for exoplanets
  – Morphology of dust trapped in libration points provides key to masses an eccentricities of exoplanets
  – Surface brightness, color, phase function, and polarization indicates quantity composition and grain size distribution

• Fomalhaut debris disk F606W + F814W HST/ACS coronagraph
  – $\mu \approx 20$ mag arc sec$^{-2}$
  – $\mu/\mu_0 \approx 10^{-10}$
  – High-mass exoplanet in a low eccentricity orbit

• Synergy with ALMA
  – Probe disjoint dust grain populations
Monte Carlo of GPI on 8-m
GEMINI PLANET IMAGER

• GPI
  – AO
    • \( r_0 = 100 \) cm
    • 2.5 kHz update rate
    • 13 cm subapertures
      – \( R = 7 \) mag. limit
  – Coronagraph
    • Ideal apodization
  – Science camera
    • Broad band \( H \)
    • No speckle suppression

• Target sample
  – \( R < 7 \) mag.
  – 1703 field stars (< 50 pc)

• Results
  – 110 exoplanets (6.5 % detection rate)
  – Semimajor axis distribution is complementary to Doppler exoplanets
Complementarity with indirect surveys

- **Adaptive Optics**
  - $r_0 = 100$ cm
  - 2.5 kHz update rate
  - 13 cm subapertures
    - $R = 7$ mag. limit
- **Coronagraph**
  - Ideal apodization
- **Science camera**
  - Broad band $H$
  - No speckle suppression
- **Target sample**
  - $R < 7$ mag.
  - 1703 field stars ($< 50$ pc)

- **Results**
  - 110 exoplanets (6.5 % detection rate)
  - Semimajor axis distribution is complementary to Doppler exoplanets
What is needed to get there?

- **Adaptive Optics**
  - Faster, better
  - Fewer **speckles**

- **Coronagraph**
  - Better suppression of central star
  - Less **speckle** amplification

- **Science camera**
  - Integral Field Spectrograph
  - Better **speckle** identification

- **Data analysis**
  - Better **speckle** subtraction
Multi-wavelength imaging (MWI)

$\lambda = 1.2 - 0.8$ microns  SR $\sim 85\%$ at H-band (simulation)

QuickTime™ and a Animation decompressor are needed to see this picture.
Coronagraphic train

Suppress unaberrated light from the on-axis star

- Entrance pupil or aperture of telescope
- First image plane - “direct image”
- Opaque stop or transmissive but phase-changing stop “focal plane mask” (FPM)
Coronagraphic train

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Occulted image after FPM
Re-imaged pupil: “Lyot pupil”

Lyot stop: smaller than aperture for opaque FPM or the same size for phase mask coronagraphy
‘Stopped down’ Lyot pupil
Coronagraphic train
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  - ‘Stopped down’ Lyot pupil
- Final coronagraphic image

Basic coronagraphic theory, mask optimization, Gemini ExAO simulation
Focal plane mask

transmission: \( m(\theta) = 1 - w(\theta) \)

Aperture \( \Pi(x/D) \)

Graded mask

Masked Image
\( (1 - w(D/\lambda) \sin(\theta/2)) \)
93% Power Blocked

The Second Pupil Field
\( \Pi(x/D) \ast \{ 0(x) - \frac{\pi}{D} W(x/D) \} \)

Lytot Stop
Transmission Function
\( \Pi(x/D) \)

On-Axis Throughput
\( \Pi(x/D) \ast \{ 0(x) - \frac{\pi}{D} W(x/D) \} \)

Final Image
98% Power Blocked
Occulted image

\[ \text{Opaque mask} \]

\[ \Pi(x/D) + \delta(x) - \frac{\pi}{D} W(\pi x/D) \]

Lyot Stop
Transmission Function
\[ \Pi(x/D) \]

On-Axis Throughput
\[ \Pi(x/D) \cdot \left( \Pi(x/D) + \delta(x) - \frac{\pi}{D} W(\pi x/D) \right) \]

\[ \text{FT} \]

Final Image
98% Power Blocked

Brookhaven National Lab July 18 2007
Lyot pupil

Aperture
\[ \Pi(x/D) \]

FT

Image
\[ \text{sinc}(x/D) \]
Total Power: 100%

Occulting Mask

Transmission Function

Original pupil

A

A – A*W

Lyot pupil

D/s

Final Image
98\% Power Blocked
Lyot field construction


Gaussian occulting stop
5 \( \lambda/D \) FWHM

Entrance aperture function: \( A(x) \)

FT of image plane occulting spot’s density profile: \( W(x) \)

\[ A(x) \ast W(x) \]

Lyot pupil field
\[ A(x) - A(x) \ast W(x) \]

Jean Baptiste Joseph Fourier: if \( w, W \) are transform pairs, the product of their equivalent widths is unity, or \( EW(W) = 1/EW(w) \)
Optimized masks

Reflective focal plane masks
Guiding done behind hole

Reflective Lyot stop masks
Pupil monitored continuously
Focal plane mask quality

How do small imperfections affect performance?

Microscope Image by Jacob Mey and Charlie Mandeville
(AMNH EPS Microprobe Lab, Lyot Project)

334 microns
Effects of tip-tilt

QuickTime™ and a Animation decompressor are needed to see this picture.

Movie of 50 minutes of Lyot Project H-band data (2004)
Effects of tip-tilt

Digby et al. (2006)

Guessing game: Where is the central star?

Prizes for a fast answer include:
  Shorter survey length (ground)
  Shorter mission duration (space)
Effects of tip-tilt

Lyot Project first light

941-channel AO on 3.6m AEOS telescope
FPM 0.35” in H-band (4 λ/D)

Coronagraphic image of 55 Cnc  March 2004
• Suppress light from the central star
• Residual speckles dominate noise (Racine et al. 1999)
What is a speckle?

Think Fourier

\[ \sin(x) \leftrightarrow 2 \delta \text{’s} \]

First order

Pupil: \( \exp(i\phi) \sim 1 + i\phi + \ldots \)

Set \( \phi = \epsilon \sin(2n\pi x/D) \)

Image: \( \delta(0) + \epsilon \text{FT}sin + \ldots \)

Higher order

The … terms create higher frequency harmonics

Strehl 99%  Strehl 97%  Strehl 90%

Strehl 70%  Strehl 60%  Strehl few%
Speckle theory - approach


Aperture $A(x,y)$: real function

Phase $\phi(x,y)$: real function

Electric field over aperture: $A \exp(i \phi) = A A_f$

For $\phi < 1$ truncate expansion of $\exp(i \phi)$ at second order in $\phi$:

$$A_{AO} = AA_{\phi} = A(1 + i\phi - \phi^2/2 + ...).$$

FT this to get image plane electric field
Speckle theory - results


A, a are FT pairs    F, f are FT pairs    star is convolution

\[
\begin{align*}
P_{AO} &= p_0 + p_1 + p_2 \\
&= aa^* \\
&= -i[a(a^* \Phi^*) - a^*(a \Phi)] + (a \Phi)(a^* \Phi^*) \\
&- \frac{1}{2}[a(a^* \Phi^* \Phi^*) + a^*(a \Phi \Phi^*)], \\
p_1 &= -i[a(a^* \Phi^*) - a^*(a \Phi)] = 2\text{Im}[(a(a^* \Phi^*))], \\
p_2 &= (a \Phi)(a^* \Phi^*) - \frac{1}{2}[a(a^* \Phi^* \Phi^*) + a^*(a \Phi \Phi^*)].
\end{align*}
\]

First order pinned speckle (Bloemhof ApJL 2000)
Second order halo, second order Strehl term

Enables analytical proof that “Speckle Decorrelation” (Angel 1994) idea does not work
Speckle theory - pictures

Speckle theory - infinite order expansion


\[ A_{AO} = AA_{\phi} = A(1 + i\phi - \phi^2/2 + \ldots). \]

\[ a_{ao} = \sum_{k=0}^{\infty} \frac{i^k}{k!} (a \star^k \Phi), \]

\[ p_{AO} = \sum_{k=0}^{\infty} \sum_{j=0}^{\infty} \frac{i^k}{k!} (a \star^k \Phi) \frac{(-i)^j}{j!} (a^* \star^j \Phi^*). \]

\[ p_{AO} = \sum_{n=0}^{\infty} \sum_{k=0}^{n} \frac{i^k (-i)^{n-k}}{k!(n-k)!} (a \star^k \Phi)(a^* \star^{n-k} \Phi^*). \]

\[ p_n = i^n \sum_{k=0}^{n} \frac{(-1)^{n-k}}{k!(n-k)!} (a \star^k \Phi)(a^* \star^{n-k} \Phi^*), \]
Speckle theory - up to 5th order

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Apodized pupil Lyot coronagraph

At Lyot pupil no under-sizing required. Increased throughput and resolution

Soummer (2005)
ExAO Apodized pupil Lyot coronagraph

Apodize (shade) entrance pupil -
Reduce “ringing” due to hard edges
and improve dynamic range
Reduces speckle amplitudes
‘bagel’

Direct image
PSF

Classical Lyot coronagraph
PSF

Apodized pupil
Lyot coronagraph
PSF

PAOLA AO simulation by Jolissaint (2005)
Spatially-Filtered Wavefront Sensing AO by Poyneer & Macintosh (JOSA 2004)
Lyot Project first light

Coronagraphic image of 55 Cnc
Residual speckles dominate noise

- Speckle pinning
- Speckle amplification
- Symmetric halo speckle
- Chromaticity of speckles
- Apodized pupil coronagraph
- Spider suppression
- Astrometric techniques

941-channel AO
3.6m AEOS telescope
FPM 0.35” in H-band (4 λ/D)
March 2004

Gemini GPI
European Southern Observatory VLT SPHERE
Subaru HiCIAO

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