Comparative Exoplanetary Science

A Technical Challenge Now, A Galaxy of Worlds Later!

Ben R. Oppenheimer

Assistant Curator of Astrophysics
American Museum of Natural History

&

Adjunct Assistant Professor of Astronomy
Columbia University
• American Museum of Natural History
• 22 buildings on 16 acres in Manhattan, numerous field stations around the world
• 220 full time researchers in 9 academic departments
• Over 40 million scientific specimens
• Over 300 expeditions per year

• ~5 million visitors per year
• Division of Physical Sciences includes
  1. Earth and Planetary Science
  2. Astrophysics (~5 years old)
QuickTime™ and a Microsoft Video 1 decompressor are needed to see this picture.

B. Abbott, Digital Universe, Hayden Planetarium: see partiview at haydenplanetarium.org
What is a Planet?

- There is no consensus on a scientific definition:
  1. Formation Mechanism
  2. Interior physics classification (fusion reactions)
  3. Wait and see until we have 1000s and classes will be obvious

Surprisingly this is a very controversial issue!

Oppenheimer (2005)
Planets are different from other celestial objects

- **Vogt-Russell Theorem**: “mass and chemical composition are sufficient to completely determine the structure, evolution and outward appearance of a star” (This principle has guided astrophysics theory well beyond stellar structure.)

- Planets have a diversity unmatched in astronomy
Jupiter's Moons
Where does the Vogt-Russell Theorem break down?

- The onset of complexity perhaps begins in the brown dwarf mass range:
- Mass-Composition-Age
- In coolest or lowest mass BDs, more complexity: The chemistry and SEDs are drastically affected by minor changes in composition
A few simple parameters are insufficient to determine a planet’s salient features.

(This is why I am not a theorist, but I will offer a solution to this problem!)
Comparative Exoplanetary Science

• Observe individual planets in great detail
  – atmospheres, internal physics, geology and perhaps biology

• Observe as many planets as possible
  – At different ages, in different environments and with a broad range of parent stars (including pulsars and white dwarfs, giants and subgiants)

• A tiny taste of what we might learn:
  – What do 50 different 1M_J planets have in common?
  – What does a young (or old) Earth mass planet look like?
  – What is a 5 Earth mass planet?
  – Astrolinguistics
How do we do detailed observations?

• We must obtain images and spectra
  – Some very limited techniques can do this now (individual spectral lines for eclipsing systems)
  – Generally requires direct detection: a spatial separation of the planet light from star light

• In the Future:
  – Surface imaging (very high resolution imaging)
  – Manned missions (requires some new physics)
Things you need to know to get into this game:

1. Fourier Analysis (Bracewell, 1986 is excellent)
2. Fourier and Fresnel Optics (numerous books)
3. Rudimentary Atmospheric Science (Kolmogorov)
4. Stellar Structure
5. Planet and Brown Dwarf Structure
6. Astrometry (milliarcsec level)
7. Photometry (AO PSF photometry, very little written)
8. Interferometry (Optical/Near IR and sub-mm/radio)
9. Control Theory
10. Signal Processing (can’t be an astronomer without this)
11. As much electronics as possible
12. As much computer expertise as reasonable (don’t get sucked in)
13. Photodetectors (very broad subject, read everything)
14. Mechanical engineering (basic static and dynamic)
15. Thermal engineering
16. Microelectronics (MEMs)
17. Laser physics and laser technology
18. Wavefront control (heritage from weapons systems)
19. HOW TO WRITE (practice, practice practice)
# Imaging Exoplanets

## Technical Requirements:

1. **Angular Resolution**

<table>
<thead>
<tr>
<th>Distance</th>
<th>10 pc</th>
<th>15 pc</th>
<th>30 pc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Angular Separation: 1 AU orbit</td>
<td>100 mas</td>
<td>67 mas</td>
<td>33.3 mas</td>
</tr>
<tr>
<td>Required Telescope Diameter for observations at $\lambda = 1$ $\mu$m</td>
<td>2.1 m</td>
<td>3.1 m</td>
<td>6.2 m</td>
</tr>
<tr>
<td>Approx. No. Stars Known</td>
<td>325</td>
<td>877</td>
<td>3508</td>
</tr>
</tbody>
</table>
Imaging Exoplanets

Technical Requirements:

2. Contrast

For exact analog of the solar system at 10 pc,
- Jupiter: \( > 10^8 \times \) fainter than Sun, 0.5 arcsec away
- Earth: \( > 10^{10} \times \) fainter, 0.1 arcsec away

100 x better than current imaging technology in any field
More Sophisticated Contrasts Needs

Burrows et al. (2004)

1 Mₜ planet orbiting a G2V star at 4 AU
An Earth-like planet will be $10^{10}$ to $10^{12}$ times fainter than the star it orbits and fractions of an arcsecond away from it.
Solar System Analog at 10 pc?

Simulated
99.9999% Strehl Image in H Band
8 m Telescope

Saturn
Jupiter
(22.5 m)

Sun, suppressed at $10^{-6}$ total luminosity
Reality: a Star from the Palomar 5-m

Reality

Perfection

.039 arcsec image width

2.5 Arcseconds

I-band (.8\(\mu\)m)
Image Quality

Strehl Ratio: \( S = \frac{\text{Peak intensity of real image of a point source}}{\text{Peak intensity of a perfect image}} \)

Uncorrected image: \( S \sim 0.5\% \)

\( S = 80\% \) means \( \sigma \sim 1/14 \) rms WFE
How Do We Do This?

Achieve extremely high image quality

Block the star optically

Null the star with interferometry
Adaptive Optics

Real K band data from Palomar AO System

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

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

Integrated images
Low-Order AO
High-Order AO

Image

Corrected Image (S ~ 96%)
AO Point Spread Functions
Take a Break from listening to me

1. What is the general expression for the radius out to which an AO system can correct a PSF? Use telescope diameter $D$, linear number of actuators across aperture $N_{\text{act}}$, and $\lambda$

2. What is the wave front error in nm in the H-Band (1.6 microns) for 96% and 99.99% Strehl?

You have 10 minutes
Lyot Coronagraphy

Bernard Lyot, 1939, Pic du Midi
Quantitative theory: Sivaramakrishnan et al. (2001)
Lyot Coronagraphy

Pupil

Occulting Spot

Lyot Stop
Lyot Coronagraphy

Occulting Spot

Lyot Stop
Lyot Coronagraphy

Occulting Spot

Lyot Stop
Lyot Coronagraphy

99%
Of starlight rejected

But only 30-50% throughput

Occulting Spot

Lyot Stop
Adaptive Optics Coronagraphy

$N_{\text{act}} = 64$

Grey: uncorrected
Dotted: AO corrected
White: AO + Coronagraph
What Contrast does this get you?

Contrast error budget current AO - red: calibratable yellow: noise
CfAO EXAO team (2005)
Speckles are *The* dominant source of noise!
Think Fourier

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

First order
Pupil: \( \exp(i\phi) \sim 1 + i\phi + \ldots \)
Image: \( \delta(0) + \text{FT(sin)} + \ldots \)

Higher order
The \ldots terms create higher frequency harmonics

<table>
<thead>
<tr>
<th>Strehl 99%</th>
<th>Strehl 97%</th>
<th>Strehl 90%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Strehl 70%</th>
<th>Strehl 60%</th>
<th>Strehl few%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
THE STRUCTURE OF HIGH STREHL RATIO POINT-SPREAD FUNCTIONS

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ABSTRACT

We describe the symmetries present in the point-spread function (PSF) of an optical system either located in space or corrected by an adaptive optics (AO) system to Strehl ratios of about 70% and higher. We present a formalism for expanding the PSF to arbitrary order in terms of powers of the Fourier transform of the residual phase error over an arbitrarily shaped and apodized entrance aperture. For traditional unapodized apertures at high Strehl ratios, bright speckles pinned to the bright Airy rings are part of an antisymmetric structure. In a PSF of a spatially extended source, the bright speckle is rich in structure with a core.
Speckle theory - approach

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

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

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

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

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

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


A, a are FT pairs  \( \Phi, \phi \) are FT pairs  star is convolution

\[
P_{AO} = p_0 + p_1 + p_2 \\
= aa^* \\
- i[a(a^* \ast \Phi^*) - a^*(a \ast \Phi)] \\
+ (a \ast \Phi)(a^* \ast \Phi^*) \\
- \frac{1}{2}[a(a^* \ast \Phi^* \ast \Phi^*) + a^*(a \ast \Phi \ast \Phi)],
\]

\[
p_1 = -i[a(a^* \ast \Phi^*) - a^*(a \ast \Phi)] = 2\text{Im}[(a(a^* \ast \Phi^*))],
\]

\[
p_2 = (a \ast \Phi)(a^* \ast \Phi^*) - \frac{1}{2}[a(a^* \ast \Phi^* \ast \Phi^*) + a^*(a \ast \Phi \ast \Phi)].
\]

First order pinned speckle, second order halo, second order Strehl term
Enables analytical proof that “Speckle Decorrelation” idea does not work
Speckle theory - pictures

Speckle theory - infinite order expansion


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

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

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

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

\[ p_n = i^n \sum_{k=0}^{n} \frac{(-1)^{n-k}}{k!(n-k)!}(a \ast^k \Phi)(a^* \ast^{n-k} \Phi^*), \]

no net power is contained in any term except the zero-order perfect PSF term

Shows why pupil apodization reduces speckle noise (think Fourier space! Outer edges of aperture=high freq. In pupil plane--- p_2 Halo), and ‘shaped pupil’ approaches are extra-sensitive to aberrations
Speckle Theory: $\lambda$ Dependence

Data Cube Movie
Across an astronomical filter

10 nm Steps
$S \sim 90\%$
$\lambda = 1.6 \mu m \ (1.0 \ at \ left)$

QuickTime™ and a Animation decompressor are needed to see this picture.
Apodized Pupil Lyot Coronagraph

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

99.9% Of starlight rejected

60-80% throughput

Soummer (2005)
### Types of Coronagraphs

<table>
<thead>
<tr>
<th>Type</th>
<th>PSF at 0.4'' (0 nm WFE)</th>
<th>Alignment Tolerance</th>
<th>Manufacturable</th>
<th>Proven Technique?</th>
<th>Observing Efficiency</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyot</td>
<td>$10^{-6}$</td>
<td>Easy</td>
<td>Yes</td>
<td>Yes</td>
<td>40-50%</td>
<td>Excludes most science goals</td>
</tr>
<tr>
<td>Apodized Lyot</td>
<td>$10^{-7}$</td>
<td>Easy 2% of pupil</td>
<td>Yes in visible (1950) Medium-risk</td>
<td>AP no LC yes</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>Band limited, infinite for a given $\lambda$</td>
<td>In theory, infinite for a given $\lambda$</td>
<td>Easy</td>
<td>No in IR High-Risk</td>
<td>Yes in visible No in IR</td>
<td>10% within $10\lambda/D$ 50% outside</td>
<td>Throughput is poor</td>
</tr>
<tr>
<td>Shaped Pupil</td>
<td>$10^{-7}$</td>
<td>Easy</td>
<td>&lt;10 nm precision</td>
<td>Proven only at extremely high SR</td>
<td>10%</td>
<td>Excludes most science goals</td>
</tr>
<tr>
<td>Phase Mask</td>
<td>$10^{-7}$</td>
<td>Tilt must be &lt; 30 $\mu$as</td>
<td>Prototype exists but high risk</td>
<td>Yes at $10^{-4}$ at $4\lambda/D$</td>
<td>80%</td>
<td>Vibration sensitivity</td>
</tr>
<tr>
<td>Pupil mapping</td>
<td>$10^{-7}$</td>
<td>Very Hard</td>
<td>Expensive High-Risk</td>
<td>Low performance prototype</td>
<td>100%</td>
<td>Excludes most science goals without reversing PR</td>
</tr>
<tr>
<td>Pupil nulling</td>
<td>$10^{-7}$</td>
<td>Hard</td>
<td>Probably but High-risk</td>
<td>Yes at $10^{-4}$ in visible in lab</td>
<td>20-50%</td>
<td>Excludes some science goals</td>
</tr>
</tbody>
</table>
Extreme AO + APLC

PAOLA AO simulation by Jolissaint (2005)
Spatially-Filtered Wavefront Sensing AO by Poyneer & Macintosh (JOSA 2004)
Extreme AO + APLC + IFU

Control Radius Carved Out

IFU provides Speckle removal
PSF components - ExAO + APLC

Contrast error budget ExAO - red: calibratable yellow: noise
CfAO EXAOC team(2005)
PSF components - ExAO + IFU

Contrast error budget for ExAO with Multi-wavelength Imaging
I=7 one hour exposure 5-sigma detection
CfAO EXAO team (2005)
Summary: Qualitative

- Control your Wave Front Errors
- Get rid of as much starlight as practical
- For residual wave front errors, get as much information as possible so you can remove them in post processing
Summary: Quantitative

• Starlight Removal:
  – Lyot Coronagraph removes 99% of starlight
  – Modified Lyot can remove 99.95% (apodizers)
  – Novel designs do better but require Strehl ratios near 99% (not obviously achievable on ground, perhaps in space)
Summary: Quantitative

- Residual Wave Front Errors must be less than about 1 nm for $10^{-8}$ contrast without differential image subtraction or spectral information on speckles.
- Spectral imaging can improve contrast by up to a factor of 100 (infinite signal to noise, see Sparks and Ford 02)
Summary: Space vs. Ground

• Space is not a perfect solution to these problems
• Wave front errors persist and must be controlled, but are much slower
• May be possible to control wave fronts at angstrom level or better with modest advances in technology. Needed for $10^{-10}$-$10^{-12}$ contrast (TPF)
Coming up after the break: What is it like to do this for a living?
The Lyot Project

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AMNH

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James P. Lloyd
Cornell University

Jeffrey R. Kuhn
University of Hawaii

Lewis C. Roberts, Jr.
The Boeing Company

http://lyot.org
Air Force Maui Optical Site

Atop Haleakala, Maui

10,000 ft Observatory
Since early 1950s

Leader in AO Development
US Air Force Advanced Electro-Optical System (AEOS)

- 3.6 m telescope
- Atop Haleakela (Maui)

- StratCom’s Space Surveillance Program

- 941 actuator deformable mirror
  \( N_{\text{act}} = 32 \) (highest in world)

- 30% Strehl at I-Band
- 80-90% at H-Band
AEOS

- Tracking speed 17 degrees/sec

QuickTime™ and a H.263 decompressor are needed to see this picture.
Known but unseen exoplanets (Marcy et al. 2003)
Protoplanetary Disks

HD 141569
10 Myr
A Star
100 pc

Hubble ACS image

Lyot Project
Field of View

Clampin et al. 2003
Lyot Project Coronagraph
Kermit IR Camera

Built by UH/UC Team Members

First light in April 03
The AMNH Astrophysics Lab

Class 10000 Clean Room

Zygo GPI-xHR

Expanding Now: Class 1000 CR CMM
Initial Assembly

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.
In Lab Performance

Total Wave Front Error: 61 nm (8 optics)

96% Strehl at H band (1.6 microns)
Prototype Mask

334 microns

Microscope Image by Jacob Mey and Charlie Mandeville (AMNH EPS Microprobe Lab)
Science Grade Mask

334 microns

Microscope Image by Jacob Mey and Charlie Mandeville (AMNH EPS Microprobe Lab)
245 um mask
Pure Nickel with
Gold Coating

Confocal Microscopy

SiC may be
A better solution
Welcome to Sunny Maui!

One Crate Missing!
Unocculted Images

S ~ 90%

Composite
Log Scale

Core: .2 s
Wing: 2 s

2.5"

unocculted H band image of delta Hercules (V = 3 mag. A3IV, 25 pc)

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

Real Coronagraphic Pupil

Real data!

Best Unocculted Image
Lyot Project first light: 85-90% Strehl

Oppenheimer, Digby, Perrin, Roberts, Sivaramakrishnan, Soummer & Makidon (2005)

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

Coronagraphic image of 55 Cnc
Residual speckles dominate noise
• Speckle pinning
• Speckle amplification
• Symmetric halo speckle
• Chromaticity of speckles

55 Cnc
<table>
<thead>
<tr>
<th>Calibration Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 min</td>
</tr>
<tr>
<td>Total Int.</td>
</tr>
<tr>
<td>Time</td>
</tr>
<tr>
<td>H-Band</td>
</tr>
</tbody>
</table>
Delta Herculis

H band
5" FOV
150 20 sec images

Scintillation ~10% (I)

\[ \Delta H = 11 \text{ mag at } .3" \]
in single exposure

14 in 20 minutes

QuickTime™ and a Animation decompressor are needed to see this picture.
## Lyot Project Data in Perspective

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Telescope Size</th>
<th>Band</th>
<th>Year</th>
<th>Star Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palomar 60” Coronagraph</td>
<td>60”</td>
<td>I band</td>
<td>1994</td>
<td>Gliese 105AC</td>
</tr>
<tr>
<td>Hubble WFPC2 I band</td>
<td></td>
<td></td>
<td>1995</td>
<td>Gliese 105AC</td>
</tr>
<tr>
<td>AO Coronagraph K-Band</td>
<td>200”</td>
<td></td>
<td>1999</td>
<td>Gliese 105AC</td>
</tr>
<tr>
<td>Lyot Project H-band</td>
<td></td>
<td></td>
<td>2004</td>
<td>55 Cancri</td>
</tr>
</tbody>
</table>

![Image of Lyot Project Data](image.png)
Dual Mode Imaging for Polarimetry: Derivation of Q and U Stokes Parameters

$P_0$ Fully Functional May 2005 $P_{90}$

Set of 4 acquired for each observation ($P_0P_{90}$, $P_{90}P_0$, $P_{45}P_{135}$, $P_{135}P_{45}$)
Simultaneous Multiwavelength Data

J  H  K
An IFU for the Lyot Project!
Other Projects

Gemini Extreme AO Coronagraph
   Led by Bruce Macintosh (exaoc.ucolick.org) with AMNH
   building the coronagraphic optics (funding pending)

VLT Planet Finder
   Led by Jean-Luc Beuzit (funding pending)

New High-Order CIAO on Subaru?
   Led by Motohide Tamura

TPF-Coronagraph Mission
   Science goals being defined now (STDT and
   see M. Turnbull’s poster)

I haven’t even mentioned any of the interferometry projects!
<table>
<thead>
<tr>
<th>Pixel Diameter</th>
<th>Pixel size @ planet (km)</th>
<th>Image</th>
<th>Interferometer Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1276</td>
<td>IR Visible</td>
<td>64 m² 120 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>576 m²</td>
</tr>
<tr>
<td>25</td>
<td>510</td>
<td>IR Visible</td>
<td>1,024 m² 6,000 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9,216 m²</td>
</tr>
<tr>
<td>100</td>
<td>128</td>
<td>IR Visible</td>
<td>0.64 km² 24,000 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.76 km²</td>
</tr>
<tr>
<td>400</td>
<td>32</td>
<td>IR Visible</td>
<td>144 km² 100,000 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,296 km²</td>
</tr>
</tbody>
</table>

**Resolving Earth**
QuickTime™ and a YUV420 codec decompressor are needed to see this picture.