Direct imaging of habitable planets from ground and space

Olivier Guyon (Subaru Telescope & University of Arizona)

Direct imaging of habitable exoplanets with space telescopes
  – New technologies: coronagraphy, wavefront control
  – Scientific opportunities – what size telescope?
  – The case for a multi-purpose mission
    Wide field imaging, coronagraphy and astrometry?

Direct imaging of habitable exoplanets with ELTs
  Why M dwarfs?
  Why ELTs may be the first to find evidence of extraterrestrial life?
The SCExAO system: a precursor on an 8-m telescope
Complementarity with space projects
Phase-Induced Amplitude Apodization (PIAA) coronagraph

Utilizes lossless beam apodization with aspheric optics (mirrors or lenses) to concentrate starlight in single diffraction peak (no Airy rings).

- high contrast (limited by WF quality)
- Nearly 100% throughput
- IWA $0.64 \frac{\lambda}{D}$ (PIAACMC) to $2 \frac{\lambda}{D}$
- 100% search area
- no loss in angular resol.
- can remove central obsc. and spiders
- achromatic (with mirrors)

Refs: Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present
Lab demos at NASA Ames, NASA JPL for space coronagraphy
Focal plane wavefront sensing
(speckle nulling, EFC, SCC ...)

Use focal plane science image as wavefront sensor:

- No non common path errors → the required 1e9 raw contrast can be obtained with conventional optics
- High sensitivity → nearly optimal use of star photons (as opposed to SHWFS for example)

Current lab raw contrast ~1e-9
PIAA achieved 4e-9 at 2 I/D [JPL/Ames/UofA]
OVC achieved 4e-9 at 2.5 I/D [Serabyn et al., JPL]
Lyot achieved <1e-9 at 4 I/D [Trauger et al., JPL]

Ongoing work to:
- improve contrast to <1e-9
- achieve contrast in polychromatic light (promising results with Lyot)
- pointing control to <mas jitter, <0.1mas calibration
- system level work to simultaneously combine high contrast, low IWA, pointing control and polychromatic WFC
Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM

See also results obtained at NASA JPL HCIT, NASA Ames & Princeton lab

All high contrast coronagraphic images acquired in lab use this technique.
- No conventional AO system has achieved >1e-7 contrast
- Focal plane AO has allowed 1e-9 to 1e-10 contrast in visible light, with ~lambda/10 optics
Fig. 9.— CLOWFS focal plane mask used in the PIAA coronagraph laboratory testbed at Subaru Telescope. The 100 micron radius mask center is opaque (low reflectivity), and is surrounded by a 100 micron wide highly reflective annulus. The science field, transmitting light to the science camera, extends from 200 micron to 550 micron radius.
Pointing control demonstrated to $1\times 10^{-3}$ $\lambda/D$ in visible (3x better in vacuum at JPL)
Mission opportunities

Sub-orbital (balloon, sounding rocket)
low cost, but limited focused science: Exozodi disks (& giant planet(s) ?)
Technology maturation for larger missions
PICTURE MISSION ONGOING

Small mission (Explorer size) – few $100Ms
<1-m telescope, relatively simple instrument
Example: EXCEDE's 0.7-m telescope with PIAA coronagraph in optical
Solid exozodi/disks science case, few giant planets
EXCEDE FUNDED FOR TECHNOLOGY DEV

Probe-class mission – $1B to $2B
~1.5-m telescope, dedicated to direct imaging of exoplanets
Great for Jupiters. Could image few super-Earths ?
Examples: EPIC, ECLIPSE, PECO, some external occulter mission
TOO COSTLY (~$1.6B for 1.5m according to astro2010) FOR THIS DECADE

Flagship - > $2B  - REQUIRED FOR SPECTROSCOPY OF EXOEARTHs
2-m to 4-m general purpose telescope in 2030s ? Larger 4-m to 8-m beyond 2030s ?
Coronagraph would be one instrument in a large flagship mission
Other likely instrument is wide field diffraction limited imaging in optical (nearUV, nearIR ?)
DEDICATED EXOPLANET MISSION (TPF, DARWIN) UNLIKELY DUE TO COST
TOO COSTLY FOR THIS DECADE, COULD GAIN COMMUNITY SUPPORT FOR MISSION IN 2030s
Probe class missions - internal coronagraphs

DAViNCI
EPIC
ACCESS
PECO
Assumptions:
- Stars within 25 pc (2110 stars – no selection of particular spectral type)
- Detection contrast limit = 1e-10
- Planet Flux limit: $m_V = 28.5$ (SNR=5 detection in 30hr with 3x zodi background, 50% throughput and 40% wide band)

Performance Requirements (D=1.5m)

Inner Working Angle, Contrast and Sensitivity

- $D = 1.5m, \lambda = 500nm$

Earth-sized planets (Earth radius, albedo = 0.3, at 1-AU equivalent HZ)
- SuperEarths (2x Earth radius, albedo = 0.3, at 1-AU equivalent HZ)
- Giant planet (jupiter radius, albedo = 0.3, at 5x 1-AU equivalent HZ)

Earth-like planet
- Albedo = 0.3
- 1 Earth radius
- At 1AU-scaled HZ

SuperEarth
- Same as above
- 2 Earth radius

Giant planet
- Jupiter size
- Albedo = 0.3
- At 5x HZ
Technology Status

Contrast & IWA

Earth-sized planets (Earth radius, albedo = 0.3, at 1-AU equivalent HZ)
SuperEarths (2x Earth radius, albedo = 0.3, at 1-AU equivalent HZ)
Giant planet (jupiter radius, albedo = 0.3, at 5x 1-AU equivalent HZ)

D = 1.5m, λ = 500nm

PIAA (Ames)
PIAACMC (theory, point source, no WF error)
VVC (JPL)

Zodi + EZ level (assuming 1 zodi face-on, m_v=4)

BLLC: Band limited Lyot coronagraph
PIAA: Phase induced amplitude apodization
PIAACMC: PIAA- complex mask coronagraph
VNC: Visible nullig coronagraph
VVC: Vortex vector coronagraph
Exoplanet direct imaging mission: what should we aim for?

Spectra of Jupiters in 2030s will not be attractive at the >$1B level
JWST transit spectroscopy in IR
Competition from smaller missions and ground-based transit spectroscopy
Direct imaging with ELTs will do spectroscopy (in near-IR) of giant planets 2030s

exoEarth spectra will require flagship (2-m or larger)
mission performance is a very steep function of aperture: sample size grows as 3\textsuperscript{rd} power of telescope diameter. Spectroscopy requires collecting area

Flagship would eat up large part of astrophysics budget for > decade
→ will require broad community support, multiple science goals/instruments

Science return per $ is much higher by building instrument for flagship (>2-m) than paying for full mission
Coronagraph instrument may cost $100Ms, as part of a multi-$B mission

→ we need to think very hard about building a coronagraph instrument that is not driving the telescope cost (central obstruction, wavefront quality)
→ we need to look very hard into combining several measurements into a single mission (detection, spectroscopy, astrometry ?) instead of queuing missions over several decades
High performance coronagraphy on complex apertures is possible

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

IWA < 1 I/D
100% throughput
No stellar residual light
Polychromatic light focal plane mask under fabrication
Astrometry with a general purpose wide field telescope?

Single telescope with coronagraph instrument and wide field camera working simultaneously

Diffractive pupil (dots on primary mirror)
Astrometry with a general purpose wide field telescope?

Dots on primary mirror create a series of diffraction spikes used to calibrate astrometric distortions.

Primary mirror is covered with small dots.

The center of the field is missing from the astrometric camera (central light is sent to coronagraph).

Dots create spikes in the wide field astrometric camera.
Astrometry with a general purpose wide field telescope?

Epoch #1

Ideal system (no distortions)

Epoch #2

Real system (with distortions)
Lab data (E. Bendek et al.)
Lab data (E. Bendek et al.)
Direct imaging with ELTs: Science goals

ExAO instrument on ELT timescale for science return
~ 2020s

Detection of Jupiter-like giants
Good science (statistics), but not Earth-shattering
Competition from indirect techniques and space (JWST?)

Spectroscopy of Jupiter-like giants

Planet formation
ELT well suited for this science goal

Imaging and low resolution spectroscopy of rocky planets
In habitable zones
Unique to ELTs for low-mass stars
May also be first opportunity to image
Habitable planets (timing of space mission ?)
Challenges and strategy

Earth twin at 10pc (nominal system for space-based mission studies)
**NOT DETECTABLE WITH ELTs**
Too faint, contrast too extreme (~1e10)

*Thermal emission from young planets*

Young = not habitable ...
**NOT DETECTABLE WITH ELTs**
Strategy works well for massive young planets, but:
(1) luminosity drops rapidly with lower mass
(2) young systems are not very close to us (~50 - 100 pc ?)
   → Rocky planets too faint

**OPTIMAL STRATEGY:**

*Reflected light imaging around nearby low mass stars*
Key advantage of ELTs is IWA
   Reduced contrast challenge
   Nearby stars → apparent luminosity is more favorable
Reflected light imaging
Science vs instrument performance

**Thermal emission:**
Flux is steep function of planet mass
0.5 MJ is much harder than 1 MJ
Increased science return (lower mass) requires significant instrument performance improvement

**Reflected light:**
Flux is shallow function of planet mass
0.5 MJ is about as hard as 1 MJ
Large increase in science return (lower mass) obtained by moderate instrument performance improvement

**Prediction:**
Once the first planets are imaged in reflected light, steady and fast progress expected
Fundamental limits of ExAO system:

(1) **Raw contrast**
- Expected to be 14x better than on 8-m telescope
- 1e-5 on 8-m telescope → 7e-7 on 30-m telescope

(2) **Detection contrast**
- Expected to be 14x better than on 8-m telescope
- 1e-7 on 8-m telescope → 7e-9 on 30-m telescope

(3) **IWA ~ 1 lambda/D**
- Scales as 1/D: 40mas on 8-m, 10mas on 30-m

(4) **Background-limited sensitivity (1hr, SNR=5)**
- mH: 23.5 on 8-m telescope → mH = 26.5 on 30-m

Assuming Super-Earths (~2x Earth diameter)
- Still potentially habitable
- Easier than Earths: 1e9 contrast at 1 AU separation (Earth ~ 2e10)
- Abundant (HARPS results: ~30% occurrence)

Detection, colors: mH = 26.5 limit on planet
Spectroscopy (R=200, SNR = 5): mH = 21.5 limit on planet
→ ability to analyze atmosphere composition, biological activity
Reflected light imaging: Contrast vs separation

Known stars within 25pc
→ computed bolometric luminosity
→ computed location of habitable zone (1 AU equivalent)
→ placed a 2x Earth size planet, Earth albedo, at max elongation

2MASS for near-IR colors
Reflected light imaging:
Contrast vs separation (H band)

8-m telescope, 1 lambda/D
30-m telescope, 1 lambda/D
Is coronagraphy at $< 1$ lambda/D possible on ELTs?

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)
PIAACMC performance on various pupils
Reflected light imaging: ELT targets first cut

<table>
<thead>
<tr>
<th>Limit/constraints</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Angular Separation</td>
<td>Limit imposed by coronagraph (see section 4). Corresponds to 11 mas on a 30-m telescope in H band.</td>
</tr>
<tr>
<td>Contrast</td>
<td>High contrast imaging limit (see section 5)</td>
</tr>
<tr>
<td>Star brightness</td>
<td>Required for high efficiency wavefront correction (see section 5)</td>
</tr>
<tr>
<td>Planet Brightness</td>
<td>Faint detection limit</td>
</tr>
</tbody>
</table>

The first cut limits are shown in the table above. The number of targets kept is mostly driven by the contrast and separation limits, and to a lesser extent by the planet brightness limit. The planet brightness limit is derived from a required SNR=10 detection in 10 mn exposure in a 0.05 μm wide effective bandwidth (equivalent to a 15% efficiency for the whole H-band) on a 30-m diffraction limited telescope, taking into account only sky background and assuming all flux in a 20 mas wide box is summed. The assumed sky background (continuum + emission) is $m_H = 14.4$ mag/arcsec$^2$ [E-ELT sky background model, ESO] and [Cuby et al. 2000].

$D = 30 \rightarrow 700 \text{ m}^2$
background = 16412 ph / sec / um / m$^2$ / arcsec$^2$ -> 230 ph/sec on the 20 mas box

With N photon/sec from source: $\text{SNR}(t) = \frac{N \sqrt{t}}{\sqrt{N + 230}}$

With $t = 600$ sec -> $\text{SNR} = 24.5 \frac{N}{\sqrt{N + 230}}$  

$\text{SNR} = 10 \rightarrow N = 6.3 \text{ ph/sec}$  

$\text{flux} = 6.3 \text{ ph/sec} = 0.18 \text{ ph/sec/um/m}^2 \rightarrow m_H = 26.8$
Reflected light imaging: ELT targets first cut
Reflected light imaging: ELT targets first cut $\rightarrow$ 274 targets
Top targets for ELTs

The most favorable target, listed in the table below, were selected with the following criteria:

- Angular separation at maximum elongation > 15 mas
- Contrast > 1e-7
- Planet brightness $m_H < 24$, allowing spectroscopy

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Distance</th>
<th>$L_{bol}$</th>
<th>$m_V$</th>
<th>$m_R$</th>
<th>$m_H$</th>
<th>Separation</th>
<th>Contrast</th>
<th>$m_H$</th>
<th>Notes, Multiplicity</th>
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<tbody>
<tr>
<td>Proxima Centauri (Gl551)</td>
<td>M5.5</td>
<td>1.30 pc</td>
<td>8.64e-04</td>
<td>11.00</td>
<td>9.56</td>
<td>4.83</td>
<td>22.69 mas</td>
<td>8.05e-07</td>
<td>20.07</td>
<td>-</td>
</tr>
<tr>
<td>Barnard's Star (Gl699)</td>
<td>M5</td>
<td>1.83 pc</td>
<td>4.96e-03</td>
<td>9.50</td>
<td>8.18</td>
<td>4.83</td>
<td>38.41 mas</td>
<td>1.40e-07</td>
<td>21.97</td>
<td>-</td>
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<tr>
<td>Kruger 60 B (Gl860B)</td>
<td>M6</td>
<td>3.97 pc</td>
<td>5.81e-03</td>
<td>11.30</td>
<td>9.90</td>
<td>5.04</td>
<td>19.20 mas</td>
<td>1.20e-07</td>
<td>22.35</td>
<td>-</td>
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<tr>
<td>Ross 154 (Gl729)</td>
<td>M4.5</td>
<td>2.93 pc</td>
<td>5.09e-03</td>
<td>10.40</td>
<td>9.11</td>
<td>5.66</td>
<td>24.34 mas</td>
<td>1.37e-07</td>
<td>22.82</td>
<td>-</td>
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<tr>
<td>Ross 128 (Gl447)</td>
<td>M4.5</td>
<td>3.32 pc</td>
<td>3.98e-03</td>
<td>11.10</td>
<td>9.77</td>
<td>5.95</td>
<td>18.99 mas</td>
<td>1.75e-07</td>
<td>22.84</td>
<td>-</td>
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<tr>
<td>Ross 614 A (Gl234A)</td>
<td>M4.5</td>
<td>4.13 pc</td>
<td>5.23e-03</td>
<td>11.10</td>
<td>9.82</td>
<td>5.75</td>
<td>17.51 mas</td>
<td>1.33e-07</td>
<td>22.95</td>
<td>Double star (sep=3.8 AU)</td>
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<tr>
<td>Gl682</td>
<td>M3.5</td>
<td>4.73 pc</td>
<td>6.41e-03</td>
<td>10.90</td>
<td>9.70</td>
<td>5.92</td>
<td>16.93 mas</td>
<td>1.09e-07</td>
<td>23.33</td>
<td>-</td>
</tr>
<tr>
<td>Groombridge 34 B (Gl15B)</td>
<td>M6</td>
<td>3.45 pc</td>
<td>5.25e-03</td>
<td>11.00</td>
<td>9.61</td>
<td>6.19</td>
<td>20.98 mas</td>
<td>1.33e-07</td>
<td>23.39</td>
<td>150 AU from M2 primary</td>
</tr>
<tr>
<td>40 Eri C (Gl166C)</td>
<td>M4.5</td>
<td>4.83 pc</td>
<td>5.92e-03</td>
<td>11.10</td>
<td>9.88</td>
<td>6.28</td>
<td>15.93 mas</td>
<td>1.18e-07</td>
<td>23.61</td>
<td>35AU from 40 Eri B (white dwarf), 420 AU from 40 Eri A (K1)</td>
</tr>
<tr>
<td>Gl 3379</td>
<td>M4</td>
<td>5.37 pc</td>
<td>6.56e-03</td>
<td>11.30</td>
<td>10.06</td>
<td>6.31</td>
<td>15.09 mas</td>
<td>1.06e-07</td>
<td>23.75</td>
<td>-</td>
</tr>
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</table>
What kind of ExAO system is required?

Small IWA coronagraph

Good WFS sensitivity, working in I (or R) band → need diffraction-limited WFS (pyramid, nlCWFS)

~50 mas OWA → 12x12 actuators required

Fast AO control (>kHz)
Possible system architecture

Planet imaging experiment

Coronagraph + WFC
- Small IWA, efficient coronagraph (example: PIAA, PIAACMC, APCMLC)
- Fast, High sensitivity WFS (examples: pyramid, nICWFS, Zernike), working in red visible light
- Few actuators (~12x12)
- Fast control (~ 5 kHz)
- LOWFS for pointing calibration

IFS
- 50 mas radius FOV (20x20 elements)
- R ~ 10 to 50
- Fast readout (~sec)

Facility AO system
- Provides > 50% SR
- Several 1000s actuators system, running at ~1kHz

No feedback to facility AO system

Light from Telescope
Wavefront sensing at the sensitivity limit imposed by the telescope diffraction limit

Seeing limited wavefront sensing (what we do now)
   \textit{Example: SH WFS}

Diffraction limited wavefront sensing (what needs to be done for ExAO)
   \textit{Examples: Pyramid (non-modulated), non-linear curvature}

Tip-tilt example (same argument applicable to other modes):
With low coherence seeing-limited WFS, $\sigma^2 \sim 1/D^2$ (more photons)
Ideally, one should be able to achieve: $\sigma^2 \sim 1/D^4$ (more photons + smaller \(\lambda/D\))

This makes a big difference for Extreme-AO on large telescopes

For Tip-Tilt, SHWFS on ELT is 40000x less sensitive than
diffraction-limited WFS (11.5 mag)
Similar gain on other low order modes
Wavefront sensing at the diffraction limit of the telescope

Fig. 9.— Wavefront reconstruction using the algorithm shown in fig. 8. Four noisy defocused pupil images (images (a), (b), (c) and (d)) are acquired to transform the pupil phase aberrations (e) into intensity signals. The input pupil phase is 609 nm RMS, yielding the PSF (f) before correction. After correction, the residual pupil phase aberration (g) is 34.4 nm RMS, allowing high Strehl ratio imaging (h). All images in this figure were obtained at 0.65 μm. The total number of photons available for wavefront sensing in 2e4.
Computer Simulations showing contrast gain with high sensitivity WFS (non-linear curvature)

\[ m \approx 13 \]

<table>
<thead>
<tr>
<th>WFS</th>
<th>Loop freq</th>
<th>RMS</th>
<th>SR @ 0.85 um</th>
<th>SR @ 1.6 um</th>
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<tbody>
<tr>
<td>nlCurv</td>
<td>260 Hz</td>
<td>101 nm</td>
<td>57%</td>
<td>85%</td>
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<tr>
<td>SH - D/9</td>
<td>180 Hz</td>
<td>315 nm</td>
<td>(~4%)</td>
<td>22%</td>
</tr>
<tr>
<td>SH - D/18</td>
<td>180 Hz</td>
<td>195 nm</td>
<td>(~13%)</td>
<td>56%</td>
</tr>
<tr>
<td>SH - D/36</td>
<td>160 Hz</td>
<td>183 nm</td>
<td>(~16%)</td>
<td>60%</td>
</tr>
</tbody>
</table>
Performance gain for ExAO on 8-m telescopes


Large gain at small angular separation: ideal for ExAO
Expected AO contrast

$\sim 1e^{-5}$ raw contrast, diffraction-limited WFS

$\rightarrow \sim 1e^{-8}$ detection contrast in 1hr (limited by speckle noise)
The Subaru Coronagraphic Extreme-AO (SCExAO) system

High contrast imaging at small angular separation is scientifically extremely valuable:

- allows system to probe inner parts of young planetary systems (<10 AU)
- constrain planet formation in the habitable zone of stars
- direct imaging of reflected light planets may be possible (reflected flux goes as a^{-2})

Coronagraphy:
High efficiency 1 λ/D PIAA coronagraph

Wavefront control:
- NIR focal plane WF control/calibration
- ExAO-optimized visible WFS visible channel
- Exquisite pointing control

Aux. Science modes:
- Non-redundant masking
- Visible light imaging

Designed as a highly flexible, evolvable platform
(reduce time from lab demo to science)
Efficient use of AO188 system & HiCIAO camera
Technology development overlap with space coronagraphy
SCExAO at Subaru Telescope (Aug 2010)
[note: HiCIAO camera not in this image]
[note: IFS under design, built by Princeton]
The Subaru Coronagraphic Extreme-AO (SCExAO) system
The Subaru Coronagraphic Extreme-AO (SCExAO) system
The Subaru Coronagraphic Extreme-AO (SCExAO) system
Experimental pupil  Simulated image  Experimental image

Without SRP  With SRP

+ PIAA lenses

+ SRP

45
SCExAO Wavefront Control architecture and speckle calibration

Under development at Subaru, UofA, HIA (currently Pyramid)

AO188

Facility AO system AO188 (bimorph curvature DM, 188 elements, 1 kHz update)

AO188 curvature WFS
Uses photon-counting APDs

Coherent light component

Tip-tilt, focus

High order aberrations, high speed

High speed high sensitivity ExAO visible WFS (non-linear curvature)

32x32 actuators MEMS
Deformable mirror
(600 actuators illuminated, low stroke, fast)

Near-IR fast frame imaging camera

600nm ≤ λ < 900nm

H-band filter

Science image

Estimate of light due to coronagraph leaks and fast speckles

Science focal plane Camera / WFS

Calibrated Science image

Focal plane AO loop (measures focal plane coherent and incoherent components)

Coronagraph

Dichroic

λ < 600nm

λ > 900nm

Science focal plane mask

Coronagraph

Focal plane AO loop

Current development at Subaru, UofA, HIA (currently Pyramid)
SCExAO Results

LOWFS validated on sky
- robust performance at low gain (≈0.1) in difficult conditions
- on-sky calibration can be time consuming

PIAA coronagraphy at 1.2 lambda/D validated
- Inverse PIAA image sharpening validated
SCExAO first visible images (V. Garrel PhD)

SCExAO acquired first visible light diffraction limited on Subaru in Feb and Sept 2011

Despite moderate AO performance (seeing 1” to 2” + clouds in Feb, poor AO perf in Sept) selection + new Fourier-based reconstruction allowed diffraction-limited imaging.
Habitable planets spectroscopy

Space (~4m telescope): F-G-K type stars, visible light

Ground (ELT): M type stars, nearIR