Exoplanet detection & characterization with coronagraphic imaging

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Subaru Extreme-AO Coronagraphic System

Subaru AO188 project:
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Hideki Takami
Outline

Science goals
- ground: Massive exoplanets -> planetary systems architecture, formation
  - young (self-emitting) / old (reflected light)
- Space: Earth-like planets -> habitability, life?

Technology
- coronagraphy
- wavefront control

Projects
- ground & space
Exoplanets

How many planets around other stars?
How do they form, evolved?
Mass, size, composition?
Rocky planets with atmospheres?

Could have life evolved on other planets?
Intelligent life somewhere else?
Earth like planets?

We can’t detect them yet, but there is every indication there are many many Earth-like planets:

1. Formation models show that several rocky planets form in solar systems through collisions. Small rocks collide to form fewer large rocks .... -> planets

2. It’s hard to form large planets and no small one!

3. Our solar system is “dynamically full”, confirming the argument (1)
Radial velocity

Doppler Shift due to Stellar Wobble

RV (km s\(^{-1}\))

\(\phi\)

\(0\) \(0.5\) \(1\)

\(-33.3\) \(-33.25\) \(-33.2\)

0-C (m s\(^{-1}\))

500000 \(510000\) \(520000\) \(530000\)

JD-2400000 (d)
Transits

Planet moves in front of star
-> star gets dimmer

- Planet size
- Planet orbit
- Large atmosphere?
Imaging

- Orbit
- Atmosphere composition
- Continents vs. Oceans?
- Rotation period
- Weather patterns
- Planetary environment:
  Planets + dust
“Red Edge”

Spectral signatures of plants: “Red edge”
Fig. 7.—Earth’s observed reflectance spectrum, at visible and near-infrared wavelengths, created from a composite of the data in this paper (0.8–2.4 μm) and the data presented in Paper I (0.5–0.8 μm). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and vegetation reflection are most significant.

Turnbull et al. 2006
Why haven’t we imaged Earth-like planets yet?

- They are very very faint compared to their star (10 billion times), and also very close (0.1” = hair thickness 150 yards away)
- Star is not a point, it’s a small disk
- There is a lot of Exozodiacal light around, and probably several planets
Exoplanet science with direct imaging

• Ground based telescopes:
  Near-IR with adaptive optics and coronagraphy
  Image disks around stars and young giant planets (Jupiters with age less than 1 Gyr)
  Prepare and test techniques for future space use

• Space:
  work in visible to image and characterize Earths and “Super-Earths”
Technology
Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

+ Simple, robust, achromatic
- low efficiency for high contrast

Jacquinot & Roisin-Dossier 1964

![Image of an apodization mask with graphs showing efficiency and performance.](image)
PIAA coronagraph development at Subaru
co-funded by JPL and Subaru/NAOJ

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

- high contrast
- Nearly 100% throughput
- IWA ~ 1.5 λ/d
- 100% search area
- no loss in angular resol.
- can remove central obsc. and spiders
- achromatic (with mirrors)

For Subaru, Lyot Coronagraph with PIAA– apodized input pupil. IWA ~ 1 λ/d
Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.

Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006
Early demonstration in lab

Lenses made by Masashi Otsubo (ATC, NAOJ)

(Galicher et al. 2005)
PIAA Coronagraph Technology Development

Testbed @ Subaru Telescope
Ground-based coronagraphic ExAO project
2nd generation PIAA design & manufacturing
Space projects studies: TOPS -> PECO, EXCEDE, TPF-C, SPICA

Main funding sources

**Ground-based**
- Subaru Telescope
- MEXT (Japan)

**Space**
- NASA JPL
- Navigator program
- NASA Ames
- TOPS partnership
Lossless apodization by aspheric optics.

Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006
Subaru lab experiment co-funded by Subaru/NAOJ & JPL
Hybrid PIAA/conventional apodization is best

- Optics easier to manufacture
- Good achromaticity

Pointing is critical
- Continuous pointing corrections
MEMS DM control electronics

- 16 bit
- 5 kHz update rate of full DM with high speed serial interface
- 20 Hz update rate with Ethernet
Lab results with PIAA coronagraph + FPAO

Step 1: phase diversity $\rightarrow$ DM correction
Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM

See also results obtained at JPL HCIT & Princeton
So far, these results are obtained at <1 Hz: making FPAO run at ~kHz is challenging (detector, algorithms)
mK Temperature control
-> greatly improved wavefront stability
Wavefront control

- Adaptive Optics (AO) for ground-based telescopes:
  - Measure and correct in REAL TIME (~kHz) wavefront errors induced by atmosphere: goal is ~few x 10nm RMS

- Wavefront correction is space:
  - Accurately measure and correct small wavefront errors due to manufacturing errors and thermal changes: goal is ~0.1 nm RMS
Wavefront sensors "sensitivities" in linear regime with full coherence (Guyon 2005)

Square root of # of photons required to reach fixed sensing accuracy plotted here for phase aberrations only, 8m telescope. Tuned for maximum sensitivity at 0.5” from central star.
Non linear dual stroke WFS, 2000 ph total
8m telescope, 0.65 μm, 373 ill. subapert.

Defocused pupil images

500 ph / frame
Top : +/- 2000km
Bottom: +/- 8000km

Input pupil phase
296nm RMS

Reconstructed phase
Residual: 55nm RMS
SR = 0.763
at 0.65 micron

Magn 16 source -> 2000 ph/ms on 8m 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.

Why is is so good ???> uses HSF to infer LSF
$dl/l = 0.5$

$Nph = 2e8$

After Correction:

$SR = 98.6$

$RMS = 12nm$
SH / nICWFS comparison

<table>
<thead>
<tr>
<th>Performance Comparison Between SH and Non-linear CWFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta(SH) )</td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>8m telescope, tip/tilt sensing</td>
</tr>
<tr>
<td>8m telescope, 2 l/d (41 mas)</td>
</tr>
<tr>
<td>8m telescope, 5 l/d (103 mas)</td>
</tr>
<tr>
<td>30m telescope, tip/tilt sensing</td>
</tr>
<tr>
<td>30m telescope, 2 l/d (11 mas)</td>
</tr>
<tr>
<td>30m telescope, 5 l/d (28 mas)</td>
</tr>
<tr>
<td>30m telescope, 10 l/d (55 mas)</td>
</tr>
</tbody>
</table>

Larger telescope / smaller separation -> bigger gain.

**BUT:** small gain for extended source (LGS) – speckled

LGS from large laser launching telescope would greatly help
(full telescope aperture? Upstream AO?)
Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM

See also results obtained at JPL HCIT & Princeton
So far, these results are obtained at <1 Hz: making FPAO run at ~kHz is challenging (detector, algorithms)
Instruments/Facilities/Projects

Ground:
- AO188 system & HiCIAO
- Subaru Coronagraphic Extreme-AO upgrade to HiCIAO

Space:
- TOPS (1.2 m visible telescope with PIAAC)
- PECO (1.4 m TOPS)
Nasmyth LGS AO

Beam Transfer Optical Fiber

Nasmyth AO
188 element curvature WFS, bimorph DM

Laser Room

Current 36 element AO

Laser Beam

Laser Launching Telescope
AO188 system at the Nasmyth focus (installed in 2006/9)
AO188 Module Layout

- 188 element Curvature sensor for NGS & LGS
- 2 x 2 Shack Hartman Tip/Tilt & Defocus for LGS mode 2.7' FOV
- IR WFS (with MPIA)
- From Telescope
- DM 188 elem.
First Light Images of AO188 (2006/10)

\begin{itemize}
  \item $z(1.03 \mu m)$
    \begin{itemize}
      \item FWHM 0.064"
    \end{itemize}
  \item $J(1.25 \mu m)$
    \begin{itemize}
      \item 0.052"
    \end{itemize}
  \item $H(1.63 \mu m)$
    \begin{itemize}
      \item 0.062"
    \end{itemize}
  \item $K(2.20 \mu m)$
    \begin{itemize}
      \item 0.061"
    \end{itemize}
  \item $L'(3.77 \mu m)$
    \begin{itemize}
      \item 0.10"
    \end{itemize}
  \item AO OFF
    \begin{itemize}
      \item $K$ 0.6"
    \end{itemize}
\end{itemize}
188 element Bimorph Mirror

Number: 188
Effective: 90 mm
Blank Size: 130 mm
Thickness: 2 mm
Manufacture: CILAS

Curvature radius ~10m => sufficient
Resonance is issue
WFS Lenslet Array & Optical

Diamond machined plastic mold lens (Nalux, Co.)

12 June 2008
Laser projection to the sky
2006/10/12
Laser Launching Telescope (50cm)
LGSAO+HiCIAO (2008~)
Exoplanet search

LGSAO188 (2006 FL)
Differential polarization/spectral imaging modes

HiCIAO (2007 FL)
2048x2048 Hawaii array
Warm optics, SDI mode, Coronagraph, Easy upgrade

12 June 2008
LGSAO+HiCIAO (2008~)
Exoplanet search

PIAA
Coronagraph +
MEMS $32^2$
focal plane
WFS
2009

HiCIAO (2007 FL)
2048×2048 Hawaii array
Warm optics, SDI mode,
Coronagraph, Easy upgrade

LGSAO188 (2006 FL)
Differential polarization/spectral imaging modes

12 June 2008
HiCIAO first light (2007)
Subaru Telescope
Coronagraphic ExAO system architecture

LGSAO188 system
- Light from Subaru Telescope
- 188 act. DM
- Curvature Wavefront Sensor
- Flattens the wavefront to about 50% Strehl in H band

CEAO upgrade
- 1024 actuators Deformable Mirror
- PIAA Coronagraph
- DM drive electronics
- Fine wavefront correction Removes starlight
- DM commands
- Wavefront control computer
- HiCIAO images
- Commands to HiCIAO

HiCIAO
- HiCIAO camera
- Differential imaging for efficient planet detection
- (1) measures wavefront
- (2) acquires final images
Subaru PIAA optics
Spider Removal Plate (SRP)
Subaru Coronagraphic Extreme-AO system

2008 (NOW):
- Curvature system, 188 actuators, 2kHz, ~50% SR in H on bright stars
- Lyot type coronagraph, ~2.5 l/D IWA
- Differential imaging camera, 4 channels, Hawaii 2RG, ASIC, spectral/polarimetric differential imaging

2009 – HiCIAO upgrade / step 1 (Funded, under construction)
Move HiCIAO back, insert optical table with upgrade components, high flexibility
  + PIAA coronagraph (1 l/D IWA)
  + Spider Removal Plate
  + 1024 actuators MEMs DM for slow focal plane AO
  (+ Low order WFS)

Future upgrades (not funded yet)
  + faster focal plane WFS
  + visible (~0.8 micron) high performance non-linear WFS
  + upgrade to 64x64 DM
  + IFU (Princeton University)
  + visible (Ex)AO system
Imaging exoplanets from space
TOPS overview

High contrast coronagraphic imaging of the immediate environment of nearby stars

Originally proposed as a DISCOVERY-class mission:
1.2m diameter off-axis telescope -> If sized at ~2m, can detect & characterize Exo-Earths
0.4 – 0.9 micron spectral coverage / R~20
High contrast coronagraphic imaging of a narrow field of view with efficient PIAA coronagraph
Active primary mirror -> thermal actuation
Efficient wavefront control scheme
Extremely stable Optical Telescope Assembly (OTA)

Ongoing technology development
TOPS Optical Telescope Assembly
Providing a stable environment for high contrast imaging

**Earth-trailing orbit** (Spitzer-like) receding at ~0.11 AU per year
3-year mission baseline (5-year would be possible)

**Disturbance-free payload**
OTA “floats” within the spacecraft with no mechanical contact. Electromagnets control OTA position & pointing within spacecraft
Effective exposure times in 0.5–0.6 micron band

<table>
<thead>
<tr>
<th></th>
<th>TOPS (1.2-m)</th>
<th>PIAA (1.5-m)</th>
<th>TOPS2 (2-m)</th>
<th>PIAA (3-m)</th>
<th>PIAA (4-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#Exo-Earths within 2 l/D</td>
<td>10</td>
<td>23</td>
<td>67</td>
<td>212</td>
<td>476</td>
</tr>
<tr>
<td>... within 4 l/D</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>23</td>
<td>67</td>
</tr>
<tr>
<td>#Exo-Earths, t=1hr</td>
<td>2 / 3</td>
<td>3 / 5</td>
<td>7 / 16</td>
<td>24 / 49</td>
<td>51 / 118</td>
</tr>
<tr>
<td>#Exo-Earths, t=10hr</td>
<td>3 / 7</td>
<td>7 / 17</td>
<td>22 / 40</td>
<td>65 / 147</td>
<td>172 / 299</td>
</tr>
</tbody>
</table>

Approximate cost

- ~$1B
- ~$2B
- ~$??B

Notes: Rows 3 and 4 list the number of Exo-Earths which would be detected at SNR=7 with respectively 1hr and 10 hr effective exposure times. Two numbers are given: the small number requires a 50% detection probability for a single observation; for the larger number, a 20% detection probability per observation is required. Alpha Cent A and B are included in this table, but may not be suitable targets due to their duplicity and the fact that Exo-Earths might lie beyond the Outer Working Angle of the instrument. If they are to be excluded, each number in this table should be reduced by two.

Costs estimates given in the table do not include the completion and operation of our 1-m PIAA telescope test-bed, required to bring up the TRL of key technologies.

50 % WFC overhead
50 % mission overhead
20 % Quantum Efficiency
x 6 observations

2 yr mission time

→ 260 hr effective time available

40 targets @ > 74% detection
or 22 targets @ > 98.5% detection
Planet characterization with TOPS 16 spectral channels
Backup slides
Life on other planets?
Warped Disk · Beta Pictoris

PRC96-02 · ST ScI OPO · January 17, 1995 · C. Burrows and J. Krist (ST ScI)
Star/planet interactions
Active stars are a challenge for life
Active stars are a challenge for life
Planetary atmospheres blown away

HD209458b -->

Planet magnetic field offers protection
When is a planet habitable?

- Too many collisions in the first few 100 Myr
- Stellar activity decreases with time -> challenge for life around young stars
- Stars get brighter with time -> HZ moves out!
  We have ~400 Myr left before CO2 cycle fails to regulate Earth’s temperature
- Magnetic field is a good thing, but WILL “freeze away” with time
Water...

Mars & Venus lost their oceans

H₂O → Hydrogen + Oxygen

Oxygen oxydizes rocks (Mars is red), Hydrogen escapes in space

Why not Earth ??? Right size, right spot.

~2 billion years ago Oxygen concentration went up (bacteria) → recaptures Hydrogen, stops H₂O loss.
Carbon cycle regulates temperature on Earth

- **Production:**
  - Volcanos & direct emission from Earth’s crust (~0.5 Gt/yr)
  - Humans burning fossil fuels (~6 Gt/yr)

- **Removal (depletion in 10 000 yrs for atmosphere, 500 000 yrs for atm+oceans):**
  - Silicate weathering
  - Carbonate deposition
  - Burial of organic matter
Are planets geared towards life?

- Lab experiments have produced, “from scratch”:
  - All 20 amino acids found in living organisms
  - Complex sugars
  - Lipids
  - All five bases of DNA and RNA (A,T,G,C,U)
- Comets and meteorites also contain amino acids.
- So the basic ingredients were rapidly available in Earth’s early soil and oceans and are probably present wherever water, soil and energy are present.
What kind of life?

- On Earth, bacteria got an early start and ruled Earth for the first 2 billion yrs
- Bacteria live in many environments (extremophiles)
- Complex life started with unlikely merging of Bacteria + Archaea -> Eukaryote
- Complex life may be rare event...
How much time needed to have complex life?

Life on Earth does not evolve at a constant pace
BIG jumps forward:
~2 Gy ago: Eukaryotes appear
560 Myr ago: Cambrian explosion
But also...

“Snowball Earth” episodes 2.3 Myr and 790 to 630 Myr ago

Several mass extinctions since Cambrian explosion (large impact, massive...
Conclusions

COMPLEX life, AS WE KNOW IT requires special conditions on planet

simple life forms (bacteria / Archaea) might be much more common

BUT many many “suitable” planets in our galaxy, and many many galaxies... (Drake equation)

Within next decades, we will finally be able to probe for life on exoplanets not too different from Earth