A bright future for direct imaging of extrasolar planets

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University of Arizona
Subaru Telescope
• **Science case**
  – Are we alone? Is complex life an unlucky accident?

• **Tools**
  – Coronagraphy
  – Wavefront control
  – PSF / speckles Calibration

• **Projects**
  – PECO
  – Subaru Coronagraphic Extreme–AO (SCExAO)
What does the general public think about imaging exoplanets?

“What an amazing idea - to stay at the fuzzy image of another world with oceans and continents and perhaps even clouds! And what if it did discover O2, methane or another bio marker? How would this world be changed to have proof - visual proof at that (best kind for a visual-oriented primate) - that there is other life in the universe? Well worth $3bill. Maybe Bill Gates or another billionaire could be convinced to pay up some! :-)”
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“Maybe, we could stop wasting money on project like this, and spend it on more important issues?

We have already discovered other life forms, countless of documents explain they came and landed, and were shot at, and downed and retrieved…”
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
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 a 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 volcanic eruption...)

Marine Genus Biodiversity: Extinction Intensity
Extinctions still very poorly understood
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
Imaging

- Orbit
- Atmosphere composition
- Continents vs. Oceans?
- Rotation period
- Weather patterns
- Planetary environment:
  - Planets + dust
Challenges

• Contrast
  – Visible:
    • $10^10$ for Earth/Sun -> space
    • $10^9$ for Jupiter/Sun -> space / ELTs ?
    • ~$10^8$ for close-in planets -> ground ExAO ?
  – Near-IR (~1.6 micron)
    • $10^10$ for Earth/Sun
    • ~$10^{12}$ for Jupiter/Sun
    • ~$10^7$ for young giant planet / Sun -> Ground ExAO
  – Thermal IR (~10 micron)
    • $10^6$ for Earth/Sun
    • $10^7$ for Jupiter/Sun
• Angular separation (HZs at ~0.1")
Coronagraphy

Fig. 4. Plan of the mounting of the coronograph (above) and the spectrograph.
A quick history of coronagraphy ...
Lyot Coronagraph
Lyot Coronagraph

Image is made (top) and occulted (bottom).

Pupil is reimaged (top) and partially blocked (bottom).

Telescope Pupil Evenly Illuminated

The Final image after Coronagraph has only 1.5% of the original Starlight.

Occulting Spot

Lyot Stop

figure from Lyot project website
Lyot Coronagraph

Band limited coronagraph
Lyot Coronagraph

Band limited coronagraph

- 4th order
- 8th order
Band-Limited mask Coronagraph (BL4, BL8)

Focal plane mask optimized to maintain fully dark central zone in pupil (band-limited mask).

4\textsuperscript{th} or 8\textsuperscript{th} order extinction.

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Kuchner & Traub 2002
Kuchner 2005
Apodized Pupil Lyot Coronagraph (APLC) = Prolate Apodized Lyot Coronagraph (PALC)

Lyot Coronagraph with apodized entrance pupil. Prolate apodization is optimal, and can bring contrast to $10^{-10}$. Focal plane mask is smaller than Central diffraction spot: challenging to achromatize.

Output pupil (in Lyot plane) is prolate itself, and can serve as input for another Lyot coronagraph: Multistep APLC.

Adopted for Gemini Planet Imager (GPI).

Aime & Soummer 2004, SPIE, 5490, 456
Abe
Lyot Coronagraph

Phase Mask Coronagraph

Apodized Pupil Lyot Coronagraph

Band limited coronagraph

4th order

8th order
Phase Mask Coronagraph (PM)

Lyot–like design with PI−shiftiting (−1 amplitude) circular focal plane mask:
- smaller mask
- smaller IWA
Requires mild prolate pupil apodization.

Phase shift needs to be achromatic
Mask size should be wavelength dependant
   Dual zone PM coronagraph mitigates chromaticity

2nd order null only.

Roddier & Roddier 1997, PASP, 109, 815 (basic concept)
Guyon & Roddier 2000, SPIE, 4006, 377 (pupil apodization with PM)
Soummer et al. 2003, A&A, 397, 1161 (pupil apodization with PM)
4 Quadrant Phase Mask (4QPM)

Lyot-like design with PI-shifiting (−1 amplitude) of 2 oppose quadrants in focal plane:
- Does not require pupil apodization.
- Less chromatic

Phase shift still needs to be achromatic

2nd order null only.

Used on VLT for science obs.


Fig. 2—Numerical simulation illustrating the principle of the four-quadrant coronagraph. A companion 15 mag fainter (flux ratio of 10%) is located 2.1/D away from the star. The individual images show (a) the shape of the phase mask (white for 0 phase shift, black for π phase shift), (b) the Airy pattern displayed in intensity, (c) the complex amplitude of the star phase shifted by the mask, (d) the exit pupil, (e) the exit pupil through the Lyot stop (0.5% of the pupil diameter) and (f) the coronagraphic image where the companion is clearly visible. Images are displayed with nonlinear scale.
Achromatic Phase Knife Coronagraph (APKC)

Same basic principle as 4QPM. Addresses chromaticity problem with dispersion along one axis.

Lyot Coronagraph

Band limited

coronagraph

4th order

Apodized Pupil

Lyot Coronagraph

Phase Mask

coronagraph

4 quadrant

coronagraph

Phase knife

coronagraph

8 octant
coronagraph

8th order

4th order
Optical Vortex Coronagraph (OVC)

Phase in focal plane mask = Cst x PA

Palacios 2005, SPIE 5905, 196


Fig. 2. (a) Intensity profile, $|U(x',y')|^2$ of a beam containing an optical vortex. (b) Surface profile of a VPM.

Fig. 3. Comparisons for $\alpha_2=\alpha_{\text{diff}}$ and $A_1^2/A_2^2=100$. (a) Lyot coronagraph where $R_{\text{OM}}=r_{\text{diff}}$. (b), (c), (d) Vortex coronagraphs where $m=1$, $m=2$, $m=3$, respectively. In (c) the starlight is essentially eliminated, revealing a high-contrast image of the planet when $m=2$. 
Optical Differentiation Coronagraph

- Phase Mask Coronagraph
  - 4 Quadrant Coronagraph
  - Optical Vortex Coronagraph
    - Angular Groove Phase Mask Coronagraph
      - 4th Order
      - 8th Order
    - 8th Order
  - 8th Order
- Band Limited Coronagraph
  - 4th Order
  - 8th Order

Lyot Coronagraph

- Apodized Pupil Lyot Coronagraph

Phase Knife Coronagraph

- 8 Octant Coronagraph
- 4th Order
- 8th Order
Optical Differentiation Coronagraph (ODC)

Optimized version of a single axis phase knife coronagraph.


Fig. 3.—Simulated images at different planes in the optical differentiation coronagraph illustrating its principle of operation. (a) Image of the star PSF multiplied by the modified differentiation mask. (b) Intensity distribution just before (b) and after (c) the Lyot stop plane. (b) Final image detected at the CCD plane. Images are displayed in different intensity scales.
Pupil Apodization

Since Airy rings originate from sharp edges of the pupil, why not change the pupil?

**Conventional Pupil Apodization/ Shaped pupil**

- **CPA**
  Kasdin et al. 2003
  Make the pupil edges fainter by absorbing light, either with a continuous or "binary" (shaped pupil) mask

**Achromatic Pupil Phase Apodization**

- **PPA**
  Yang & Kostinski, 2004
  Same as CPA, but achieved by a phase apodization rather than amplitude

**Phase Induced Amplitude Apodization Coronagraph**

- **PIAAC**
  Guyon, 2003
  Perform amplitude apodization by remapping of the pupil with aspheric optics

**Phase Induced Zonal Zernike Apodization**

- **PIZZA**
  Martinache, 2003
  Transform a pupil phase offset into an amplitude apodization thanks to a focal plane Zernike mask
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
Pupil Phase Apodization (PPA)

Achromatic solutions exist.


Fig. 9.—Broad-bandwidth light reduction effect on one quadrant of focal plane. The simulation is based on a rectangular spectrum distribution with total bandwidth of 0.6λ0. (a) log_10 relative intensity image when phase ϕ(x, y) = a tan[(0.5 – c)2πx/D] + b tan[(0.5 – c)2πy/D], with a = 1 and c = 0.005, is applied to a square pupil. (b) The thicker line represents the log_10 relative intensity along the diagonal line crossing the second and the fourth quadrants in (a). The thinner line represents the one without phase modulation. (c) Same as (a) but with phase ϕ(x, y) from eq. (11), with a = 1 and c = 0.001, applied to a square pupil. (d) Same as (b), but for the quadrants in (c). One can see that the reduction level of 10^{-12}, with an inter-working distance of about 3λ0/D, can still be kept with a broad bandwidth of 0.6λ0 in the second quadrant.
Phase–Induced Zernike Zonal Apodization (PIZZA)

Zernike phase contrast transforms pupil phase aberration into pupil amplitude modulation. This property is used to produce an amplitude apodization.

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.

Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003–2006
Lyot Coronagraph
Band limited coronagraph
4th order
8th order
Apodized pupil
Shaped pupil coronagraph
PIAA coronagraph
PIAA/APLC
Optical vortex coronagraph
Phase apodization
Apodized pupil
Lyot Coronagraph
Phase Mask Coronagraph
Phase–Induced Zonal Zernike Apodization (PIZZA)
Apodized Pupil Lyot Coronagraph
Optical differentiation coronagraph
Phase knife coronagraph
4 quadrant coronagraph
Optical vortex coronagraph
Angular groove phase mask coronagraph
8 octant coronagraph
8 octant coronagraph with Jacquinot mask
4th order
8th order
8th order
Lyot Coronagraph

Band limited coronagraph

4th order
8th order

Apodized pupil

Phase apodization

Shaped pupil coronagraph

Hybrid PIAA coronagraph

PIAA coronagraph

PIAA/APLC

Apodized Pupil Lyot Coronagraph

Optical differentiation coronagraph

Phase Mask Coronagraph

4 quadrant coronagraph

Optical vortex coronagraph

Phase–Induced Zonal Zernike Apodization (PIZZA)

Phase apodization

PIAA/APLC

Band limited coronagraph

4th order
8th order

8 octant coronagraph

Angular groove phase mask coronagraph

4th order

8th order

8 octant coronagraph with Jacquinot mask

8 octant coronagraph
"Interferometric" coronagraphs

= Nulling interferometer on a single pupil telescope
- Creates multiple (at least 2) beams from a single telescope beam
- Combines them to produce a destructive interference on-axis and constructive interference off-axis

Achromatic Interferometric Coronagraph
Common Path AIC
Baudoz et al. 2000, Tavrov et al. 2005
Destructive interference between pupil and flipped copy of the pupil
Achromatic PI phase shift and geometrical flip performed by going through focus

Visible Nulling Coronagraph, X & Y shear, 4th order
VNC
Shao et al., Menesson et al. 2003
Destructive interference between 2 copies of the pupil, sheared by some distance.
4th order null obtained by cascading 2 shear/null

Pupil Swapping Coronagraph
PSC
Guyon & Shao, 2006
Destructive interference between pupil and a copy of the pupil where 4 quadrants have been swapped
Visible Nuller Coron. (VNC)

second order null phase offset prop. to pupil shear x source offset

Small shear : high throughput, low IWA
Large shear : low throughput, small IWA
The 2 shears can also be colinear

Will fly soon on sounding rocket (PICTURE)

Mennesson, Shao ... 2003, SPIE 4860, 32
Pupil Swapping Coronagraph (PSC)

Same basic principle as VNC, higher throughput
Guyon & Shao, 2006, PASP
Achromatic Interferometric Coronagraph (AIC)

Fig. 1. Schematic of the Generic Set-up of our coronagraph

Fig. 2. Left: collected wavefronts, one from the central source the other (tilted) from a companion. Center: wavefronts on the recombiner lens. Right: amplitudes and resulting intensity in image plane

Fig. 3. Image of a star off-axis and on-axis. The scale is linear and is the same for the 2 images

Used on sky (CFHT)

Baudoz et al. 2005, PASP, 117, 1004  (Hybrid AIC, no 180 deg ambiguity)
Tavrov et al. 2005, Opt. Letters, 30, 2224  (Common path AIC)
External Occulter

A properly placed and shaped occulter can drop a deep shadow of starlight over a telescope while allowing planet light to pass unimpeded.
Lyot Coronagraph

Band limited coronagraph

4th order

8th order

Apodized Pupil

Lyot Coronagraph

Phase Mask

Coronagraph

4 quadrant coronagraph

Phase knife coronagraph

8 octant coronagraph

8 octant coronagraph with Jacquinot mask

Optical vortex coronagraph

Phase–Induced Zonal Zernike Apodization (PIZZA)

4th order

8th order

Angular groove phase mask coronagraph

4th order

8th order

Band limited coronagraph

4th order

8th order

Optical differentiation coronagraph

Common path AIC

Achromatic Interferometric coronagraph (AIC)

Hyper AIC

PIAA/phase mask

PIAA/APLC

Hybrid PIAA coronagraph

PIAA coronagraph

Hybrid PIAA/EO

Hybrid PIAA coronagraph

Hybrid AIC / EO

External Occulter

Visible nuller

4th order visible nuller

Pupil–swapping coronagraph

Optical differention coronagraph

Phase Mask Coronagraph

Lyot Coronagraph

Phase–Induced Zonal Zernike Apodization (PIZZA)
Coronagraph Performance

Every coronagraph in the previous chart except the classical Lyot can theoretically deliver 1e10 contrast at 4 I/D

Newer coronagraphs tend to be better than older ones, not in contrast, but: smaller inner working angle, higher throughput

New coronagraphs continuously appear

→ Is there a theoretical performance limit? If yes, where is it & what sets it? Have we reached / approached it yet?
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Useful throughput as a metric independent of coronagraph design

Commonly used metrics: IWA, throughput, discovery space

Useful throughput:
fraction of the planet's light that can be isolated from the stellar light
Coronagraph model

Linear system in complex amplitude
Fourier transforms, Fresnel propagation, interferences, every wavefront control schemes: all are linear

Telescope pupil discretized in $N$ elements

$N$ individual "beams" enter the coronagraph optics

Coronagraph output complex amplitudes

Coronagraph outputs not used for planet detection (too much starlight)

Coronagraph "pixels" used for planet detection

Vector $A$ (complex amplitudes)

Unitary matrix $U$

Vector $B = UA$

$U$ is fixed by optical configuration, and is independant of the source position on the sky.
Coronagraph model
What is the theoretical performance limit of coronagraphy?

Coronagraph is a linear filter which removes starlight. If:
planet = 0.2 x starlight wavefront + 0.8 x something else
then:
coronagraph throughput for planet < 0.8

What is the vector C that maximizes C.A(planet) but keeps C.A(star position) < C.A(planet position) * sqrt(1e-10)?
Fundamental physics tells us limits of coronagraphy

Example:
HIP 56997 (G8 star at 9.54pc)
0.55 micron, 0.1 micron band
Planet at maximum elongation (80 mas)
Earth albedo = 0.3 (C=6e9)
4h exposure, 0.25 throughput, perfect detector

Exozodi : 1 zodi
System observed at time when zodi is minimal

Each image is 20x20 lambda/d
Theoretical limit with increasing stellar radius (monochromatic light, $1e10$ contrast)

Fig. 5.— Upper limit on the off-axis throughput of a coronagraph for different stellar radii.

$0 \ l/d \rightarrow IWA \sim 0.5 \ l/d$

$0.1 \ l/d \rightarrow IWA \sim 2 \ l/d$
LOWFS efficiently uses starlight to measure tip tilt and a few other low order modes. Subaru Testbed has demonstrated closed loop pointing control to 1e-3 I/D ~ 0.1 mas on 1.4m PECO. ref: Guyon, Matsuo, Angel 2009

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.

Fig. 10.— Laboratory performance for the CLOWFS. Upper left: Measured CLOWFS reference frame and influence functions for the 5 axis controlled in the experiment. Pre-PIAA and post-PIAA modes look extremely similar, as expected. Top right: Open loop simultaneous measurement of pre and post-PIAA modes. The measured amplitudes match very well the sine-wave signals sent to the actuators, and the CLOWFS is able to accurately measure all 4 modes shown here with little cross-talk. Since this measurement was performed in open loop, the measurement also include unknown drifts due to the limited stability of the testbed. Bottom left: Closed loop measurement of the residual error for the 5 modes controlled. The achieved pointing stability is about 10^{-3} \lambda/D for both the pre-PIAA and post-PIAA tip/tilt. Bottom right: Position of the actuators during the same closed loop test.
PIAA coronagraph development at Subaru
co-funded by Subaru/NAOJ, NASA JPL & NASA Ames

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

- high contrast
- Nearly 100% throughput
- IWA ~1 l/D to 2 l/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 lambda/d
Phase–Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.

Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003–2006
PIAA optics – Diamond turning
Recent lab results demonstrate PIAA coronagraph + Focal plane AO + coherent differential imaging

Contrast achieved in 1.6 to 4.5 l/D zone:
1.5e-7 incoherent halo ghost (equivalent to exozodi)
7e-9 coherent starlight speckles (turbulence, vibrations)

Average contrast in right half of the science field shown above (excludes the ghost on the left) = 7e-9
2nd generation PIAA optics manufacturing completed by Tinsley on Jan 5, 2009 (better surface accuracy, better achromatic design than PIAAgen1)
PIAA-dedicated testbed at NASA Ames testing WFC architectures & MEMs DMs.

Coronagraph labs in:
NASA JPL (vacuum)
NASA Ames
Princeton Univ.
Subaru Telescope
Japan/ISAS (vacuum)
Vacuum tests at NASA JPL have reached close to $1 \times 10^{-10}$ contrast at 4 l/D with band-limited masks.

"Classical" speckle nulling with the HCIT

Contrast obtained in a sequence of images over a representative one-hour period. At left is the high contrast field: the inner and outer target areas are highlighted in blue and red respectively; an asterisk marks the location of the occulted "star". Plotted at right are contrast values averaged over the inner and outer areas (again in blue and red respectively) for each image in the sequence. 1-$\sigma$ error bars indicate the measurement noise estimated from pairwise data.
Pupil mapping Exoplanet Coronagraph Observer (PECO) (caao.as.arizona.edu/PECO)

- 1.4m diameter off-axis telescope
- Uses high efficiency low IWA PIAA coronagraph
- 0.4 – 0.9 micron spectral coverage / R~20

- Conduct a “Grand Tour” of 10 nearby stars searching for small (Earth & Super-Earth) planets in their habitable zones.
- Study known RV planets, observing them at maximum elongation
- Snapshot survey of ~100 other nearby stars to study diversity of exozodiacal disks and search for / characterize gas giant planets.
Earth/SuperEarths with a medium-class mission?

Yes, if:

- **High throughput** instrument & good detector
  - high throughput coronagraph
  - no photon lost, use dichroics instead of filters
  - combined imaging & spectroscopy
  - photon counting (no readout noise allowed)
- Small **Inner Working Angle** AND full telescope **angular resolution**
  - good coronagraph
  - use blue light for discovery & orbit determination
- Large amount of **observation time** on few targets
  - small sample of the easiest 10 to 20 targets
  - long exposure times & many revisits
- Accept risk of high exozodi & low Earth frequency
  - broader science case:
    - exoplanetary systems architecture
    - extrasolar giant planets characterization
    - exozodi disks imaging
PECO approaches theoretically optimum coronagraph performance

**High performance PIAA coronagraph**
- IWA = 2 \(\lambda/D\)
- 90% coronagraph throughput
- No loss in telescope angular resolution: max sensitivity in background-limited case
- Full 360 deg field probed

**Simultaneous acquisition of all photons from 0.4 to 0.9 µm in 16 spectral bands, combining detection & characterization**
- High sensitivity for science and wavefront sensing
- Polarization splitting just before detector (helps with exozodi & characterization)

**Wavefront control and coronagraph perform in 4 parallel channels**
- Allows scaling of IWA with lambda
- Allows high contrast to be maintained across full wavelength coverage
Number of Earths & Super Earths detected with PECO scales gracefully with aperture

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Earths still detectable at shorter wavelengths and smaller D

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<tr>
<td>1.6</td>
<td>70</td>
<td>33</td>
</tr>
<tr>
<td>1.8</td>
<td>87</td>
<td>44</td>
</tr>
<tr>
<td>2.0</td>
<td>131</td>
<td>61</td>
</tr>
</tbody>
</table>

Left: a simulation of 24 hr of PECO data showing an Earth-like planet (a=0.2) around Tau Ceti with 1 zodi of exododi dust in a uniform density disk inclined 59 degrees. This is a simulation of λ= 550 nm light in a 100 nm bandpass PECO (1.4-m aperture). Photon noise and 16 electrons total detector noise for an electron multiplying CCD have been added.

Right: the PECO image after subtracting the right half from the left half, effectively removing the exozodiacal dust and other circularly symmetric extended emission or scattered light. The Earth-like planet is obvious as the white region on the left, and the dark region on the right is its mirror image artifact.

- Trade study shows number of Earths detected for different telescope diameters
- PECO simulation of Earth-radius planet with Earth albedo in habitable zone of candidate star
- Assumes detection in < 5 attempts of < 12 hr integration
- IWA of 2 lambda/D
PECO top 5 key technologies are identified and under study

- **PIAA Coronagraph System Path to TRL6**
  - PIAA mirror fabrication
  - Performance demonstrations in JPL HCIT
  - Brassboard component qualification
    - Note that existing PIAA coronagraph bench is the same scale as flight components

- **Broadband Wavefront Control**
  - Baseline Xinetics DM near TRL 6
  - MEMs DM technology in progress as potential cheaper alternative (NASA Ames Funding)
  - Algorithms tested in HCIT

- **Pointing Control Demonstration**
  - LOWFS provides fine guidance, to be tested in HCIT
  - Models predict 0.5 mas possible with existing technology (1 mas demonstrated with PIAA in the lab in air)

- **Thermal-Structural-Optical modeling**
  - Needed for final system verification
  - HCIT will validate optical models
  - SIM TOM testbed demonstrated thermo-structural

- **Photon-counting EMCCD Detectors**
Simulated PECO imaging of Alpha Cent exozodi

Model
1 zodi enhancement at 1AU

PECO image
3 hr exposure
400 nm, 20% band
Wavefront control (& coronagraphy)
Why do we need coronagraphs?

Coronagraph can only remove known & static diffraction pattern

**BUT:**
- static & known diffraction can be removed in the computer
- coronagraphs don’t remove speckles due to WF errors

**Fundamental reasons:**
(1) Photon Noise
(2) Coherent amplification between speckles and diffraction pattern

**Practical reasons:**
(3) Avoid detector saturation / bleeding
(4) Limit scattering in optics → “stop light as soon as you can”
Coherent amplification between speckles and diffraction pattern

Final image = PSF diffraction (Airy) + speckle halo

This equation is true in complex amplitude, not in intensity. Intensity image will have product term → speckles are amplified by the PSF diffraction.

Fig. 3.—PDF of the light intensity at four different constant background intensity levels $I_c$ and a single value of $I_s = 0.1$. High values of $I_c$ correspond to locations near the perfect PSF maxima (rings), and low values of $I_c$ correspond to locations near the zeros of the perfect PSF or far from the core. For $I_c = 0$ we have the pure speckle exponential statistics. The width of the distribution increases with an increase in the level of $I_c$. This explains speckle pinning; speckle fluctuations are amplified by the coherent addition of the perfect part of the wave.
When do we need coronagraphs?

Coronagraphs serve no purpose if dynamic speckle halo is > diffraction
- > Very important to keep in mind to avoid over-designing the coronagraph, as this usually would mean giving up something (usually throughput)

“Side effects” of coronagraphs:

- (Usually) requires very good pointing. Risk of low order aberrations (for example pointing) creating additional scattered light in the region of interest

- data interpretation & analysis can be challenging (especially at inner working angle)

- Astrometry more difficult (solutions exist)
None of the recent ground-based planet discoveries has been done with coronagraph.

With current Telescopes+AO systems, coronagraphs offer almost no help beyond ~0.3" in H band.

PSF calibration with coronagraphs is more complicated.
Speckles vs. planet

**Spectra differential imaging (SDI)**
Optimized for methane-bearing giant planets
Will only detect planets with a given spectral feature

**Polarization differential imaging (PDI)**
Degree of polarization may be low (few %)
Only works on reflected light

**Angular differential imaging (ADI)**
Performs well if static speckles are strong
Does not work well at small angular separations

**Coherent differential imaging (CDI)**
Use DM to introduce a known variation in the WF to modulate speckle intensity
Can reach photon noise limit if system is very well calibrated and CDI is performed quickly (or simultaneously)
Initial problem

Take a frame $\rightarrow$ measured speckle intensity $= I_0$

DM offset chosen to be $\sim$ equal to speckle amplitude
Speckle calibration with active coherent modulation
Focal plane wavefront sensing and CDI use the same modulation: if something is a speckle, we can kill it with the DM!

With FPAO, separation between coronagraph and wavefront control becomes blurry.
Coherent detection works in the lab alongside FPAO.

Extremely powerful for ExAO:
- Optically simple
- Non NCPE
- on-the-fly diagnostics
- CDI post-processing
The Subaru Coronagraphic Extreme AO Project (SCExAO)

Olivier Guyon, Frantz Martinache, Julien Lozi, Vincent Garrel
Subaru Coronagraphic Extreme–AO (SCExAO) system architecture

1. High sensitivity visible wavefront sensor for ExAO (VWFS)
   - 188 actuators curvature Adaptive Optics system (AO188)
   - 1024 actuators MEMS deformable mirror

2. Low Order Wavefront Sensor (LOWFS)
   - Spider Removal Plate (SRP)
   - PIAA optics
   - Inverse PIAA optics

3. Coherent Detection Processing
   - Wavefront Control Algorithm

4. Non Redundant Aperture Mask
   - HiCIAO differential imaging camera

5. Visible science camera
   - CORONAGRAPH

System architecture
System architecture

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Extreme–AO (SCExAO)
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Designed as a highly flexible, evolvable platform
Efficient use of AO188 system & HiCIAO camera
System architecture

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1. High sensitivity visible wavefront sensor for ExAO (VWFS)
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188-actuators curvature Adaptive Optics system (AO188)

1024 actuators MEMS deformable mirror

SPIDER REMOVAL PLATE (SRP)

PIA optics

Inverse PIA optics

Non Redundant Aperture Mask

HiCIAO differential imaging camera

CORONAGRAPH

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   - Coherent Detection Processing

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5. Visible science camera

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System architecture

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   - 188-actuators curvature Adaptive Optics system (AO188)

2. Low Order Wavefront Sensor (LOWFS)
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3. Coherent Detection Processing
   - Wavefront Control Algorithm

4. HiCIAO differential imaging camera
   - Non Redundant Aperture Mask
   - Spider Removal Plate (SRP)
   - PIAA optics
   - Focal plane mask

5. Visible science camera

Designed as a highly flexible, evolvable platform
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Subaru Coronagraphic Extreme–AO (SCExAO) system architecture

1. High sensitivity visible wavefront sensor for ExAO (VWFS)
   - 188-actuators curvature Adaptive Optics system (AO188)

2. Low Order Wavefront Sensor (LOWFS)
   - 1024 actuators MEMS deformable mirror
   - Dichroic

3. Coherent Detection Processing
   - Wavefront Control Algorithm

4. HiCIAO differential imaging camera
   - Non Redundant Aperture Mask

5. Visible science camera
   - Spider Removal Plate (SRP)
   - PIAA optics
   - Inverse PIAA optics
   - Focal plane mask

Designed as a highly flexible, evolvable platform
Efficient use of AO188 system & HiCIAO camera
AOI88 system at the Nasmyth focus (installed in 2006/9)

Telescope

AO system

Laser room

IR camera & spectrograph
Integration

pupil wheel
f.p. mask
bin. mask
PIAA
SRP

Light from AO-188
3rd generation PIAA optics
3rd generation PIAA optics

- On-axis lenses
- Lenses are 96 mm apart
- Apodize the beam
- Remove the central obscuration

Optics tested, and good to go!
Apodized beam
Apodized beam

The PIAA does its job but spider vanes remain...
Spider Removal Plate
Spider Removal Plate

- 15 mm thick precision window
- Fused Silica
- Tilt angle: 5 ± 0.02°
Fig. 8.— Effect of the SRP on the pupil. The three top panels show (from left to right): an image taken with the camera in a location conjugated with the pupil plane, showing the mask simulating the Subaru telescope pupil, as well as the corresponding simulated and experimental images. The three bottom panels show the same images when the SRP is inserted into the beam (cf. Sec. 3.3 for details).
Putting things together: SRP+PIAA
Putting things together: SRP+PIAA

(Lab. image)
Putting things together: SRP+PIAA

✓ Spider vanes gone
✓ Cent. obscur. gone
✓ Pupil apodized

-> coronagrapy with no losses with with inner working angle = 1 lambda/D

(Lab. image)
Recover the Field of view with “inverse PIAA” optics
Fig. 12.— Comparison between simulated and experimental images of an off-axis source, from 0 to 20 $\lambda/D$ with a 5 $\lambda/D$ step. The field of view of each image is $\pm 12\lambda/D$. 
Expected performance?
Expected performance?

Extrasolar planets (Baraffe-Marley)

H-band ($\lambda = 1.6 \mu m$) contrast ratio

Projected angular separation (arcsec)

10 M\(_J\) models
1 M\(_J\) models
Known exoplanets

NRMExAO
Taurus

SCExAO
GPI
Summary

- **Coronagraphy**: Many high performance coronagraph concepts. Recent advances are Improved IWA, throughput, PSF calibration. Some coronagraph concepts now approach theoretical limit imposed by fundamental physics.

- **Ground-based coronagraphy**
  - Lab results now exceed requirements even with the highest performance coronagraphs (see for example lab PIAA results)
  - Performance will be driven by wavefront control & PSF calibration
    - Coherence-based PSF calibration & focal plane AO attractive
    - Conventional wavefront sensors are terribly inefficient. Higher performance WFS exist and should be used (Pyramid, FPWFS...)
  - Very efficient, fast AO (~10 kHz) system with few x100 actuators
  - Tip-tilt control is very important to get close to the optical axis
  - Subaru Coronagraphic ExAO system plans to take advantage of these recent advances with flexible architecture
  - Potential to detect reflected light -> older planets closer to us

- **Space-based coronagraphy**
  - Direct imaging of Earths possible around the ~ 10 most favorable stars with a 1.4-m telescope and advanced coronagraph
  - A 4-m would allow atmosphere characterization for habitable planets