Pupil mapping Exoplanet Coronagraph Observer (PECO)

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| M. Marley (ARC) - Co-I | Giant planets: spectral characterization, modeling |
| M. Meyer (UofA) - Co-I | Planetary systems formation, evolution |
| W. Traub (JPL) - Co-I | Science plan and participate in the HCIT test demonstrations. |
| D. Backman (SOFIA) – Collaborator | Exozodiacal dust |
| G. Schneider (UofA) - Collaborator | Exozodiacal dust |
| M. Tamura (NAOJ) – Collaborator | Planetary systems formation |
| N. Woolf (UofA) – Collaborator | Characterization of planetary atmospheres, habitability |

**Architecture Studies** (Lead: Co-I S. Shaklan – NASA Jet Propulsion Laboratory)

| A. Give’on (JPL) - Co-I | WFS&C algorithms for Architecture studies and HCIT test demo |
| R. Vanderbei (Princeton) - Co-I | Coronagraph architecture and analysis |
| R. Belikov (Princeton) – Collaborator | Coronagraph architecture and analysis |
| J. Kasdin (Princeton) - Collaborator | Architecture |
| E. Serabyn (JPL) - Collaborator | Wavefront sensing and speckle nulling |


| R. Angel (UofA) - Co-I | Technology development, Wavefront sensing, primary mirror |
| D. Gavel (UCSC) - Collaborator | Characterization of MEMS type DMs for PECO |
| M. Shao (JPL) - Collaborator | MEMS DMs characterization, wavefront sensing & control |
| J. Trauger (JPL) - Collaborator | Xineks DMs expertise, wavefront sensing & control |

**Mission Implementation** (Lead: Co-I D. Tenerelli – Lockheed Martin)

| R. Woodruff (LM) - Co-I | PECO instrument design, implementation, cost and technology |
| C. Lloyd (ITT) – Co-I | PECO telescope design, implementation, cost and technology |
| J. Wynn (ITT) - Collaborator | PECO telescope design, implementation, cost and technology |
PECO overview

High contrast coronagraphic imaging of the immediate environment of nearby stars

Characterization of planets and dust in habitable zone

1.4m diameter off-axis telescope
0.4 – 1.0 micron spectral coverage / R~20

PECO is one of the “probe-class” (<$1B) NASA-funded Advanced Mission Concept Studies.
Optimal use of photons from 0.4 to 1.0 micron, for WFC and science

- Common detector for WFS and science
- Dichroics
- EMCCDs
- PIAA coronagraph
- CLOWFS

Dichroics for science (R~15) and wavefront control / coronagraphy

Full angular resolution
Exoplanet science with a 1.4 m telescope?
Don’t we need an 8m? (TPF-C)

**Coronagraph technology is making very good progress**

- since “TPF-C”, we know how to reduce telescope diameter by almost 3x with the same science capabilities.

- Lab testbeds are making huge progress

**We can (somewhat) relax number of targets since Eta (Earth+SuperEarth) probably > 0.1 (RV/transits/microlensing)**

- This also means we can also spend more time per target (weeks, months...)

- RV and/or astrometry will help constrain mass of planets and increase efficiency of observations. Will also help tell difference between planets and exozodi clumps

**Biggest risk is Exozodi. How many systems have < 2 to 5 zodi within ~10pc? How clumpy is it?**

**Characterization on very limited # of targets in red. Low resolution spectroscopy (R~15 to 20).**
Coronagraph
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
PIAA coronagraph

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

- high contrast
- Nearly 100% throughput
- IWA ~1.5 l/d
- 100% search area
- no loss in angular resol.
- achromatic (with mirrors)

More info on:
www.naoj.org/PIAA/

Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006
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
x 2.5 to 3 in telescope diameter
PECO Science
<table>
<thead>
<tr>
<th>Telescope size and coronagraph type</th>
<th>Earth @ 1 HZ albedo 0.3</th>
<th>SuperEarth @ 1 HZ albedo 0.3</th>
<th>SuperEarth @ 1.8 HZ albedo 0.3</th>
<th>Jupiter @1AU albedo 0.6</th>
<th>Jupiter @5AU albedo 0.6</th>
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</thead>
<tbody>
<tr>
<td>1.0 m PIAA</td>
<td>5</td>
<td>13</td>
<td>23</td>
<td>21</td>
<td>437</td>
</tr>
<tr>
<td>1.4 m PIAA (PECO)</td>
<td>20</td>
<td>38</td>
<td>56</td>
<td>52</td>
<td>1179</td>
</tr>
<tr>
<td>1.8 m PIAA</td>
<td>41</td>
<td>79</td>
<td>127</td>
<td>103</td>
<td>2545</td>
</tr>
<tr>
<td>1.4 m Shaped Pupil</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>15</td>
<td>131</td>
</tr>
</tbody>
</table>

Table 1.2-1 Number of FGK main sequence stars around which different planet types can be detected (SNR=5 at R=5 at 0.55 micron) with an ideal (perfect wavefront) 1.4m PIAA telescope and other telescope diameter/coronagraph combinations. Details of this simulation can be found in Guyon et al. 2006. This table assumes a 1 zodi cloud around each star and a 50% throughput loss due to coatings and detector. The numbers given are for 20% detection probability for a single 1 day exposure with no prior information on the planet location, corresponding to 90% probability of at least one detection in 10 uncorrelated visits. Super Earths are assumed here to have 2x Earth radius. The HZ unit denotes the distance at which an Earth-like planet would have the same temperature as the Earth.

Science is steep function of telescope diameter
PECO design could be applied to larger telescope size
A “difficult” PECO target

PECO one day image in 0.4-0.5 micron band of an Earth/Sun system analog at 4.5 pc

Illustrates:
- very high SNR detection of exozodi
- risk of confusion with exozodi
- risk of confusion with other planets
“Earths” are at limit of PECO
super-Earths are significantly easier
- High contrast needs to be maintained at 1e-10
PECO’s goal is to image and characterize nearby exoplanetary systems (Planets + dust) down to Earth/”SuperEarth” mass

- deep survey:
  50 targets (~2/3 of observing time)
- large survey:
  +150 targets (~1/3 of observing time)

Spectral characterization at R~20

-> Planets orbits, colors and map of exozodi cloud
-> understand planetary systems architecture & habitability
Technical challenges

**Coronagraph** - can you build it? does it really work?

Wavefront control with coronagraph

**Pointing stability/calibration**

**Telescope wavefront stability**

vibration isolation & good thermal design

drift-away orbit

**Detectors**

~zero readout noise visible CCD are now available
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
9.5 PIAA optics sets made so far:
1 refractive PIAA system, diamond turned plastic [NAOJ]
2 reflective PIAA systems, Nickel-plated diamond turned Al (1 design x2) [Axsys]
6 refractive PIAA systems, diamond turned CaF2 (3 designs x2) [Axsys]
+ 1 reflective PIAA system, Zerodur, currently in manufacturing [Tinsley]
Subaru lab experiment
co-funded by Subaru/NAOJ & JPL
4 mm pupil size
4 mm pupil size

2006/12/13  Lens: X 50
4 mm pupil size
4 mm pupil size
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)
Next important step is to test PIAA coronagraph in High Contrast Imaging Testbed @ NASA JPL

New refractive PIAA optics which are being polished for this 1e-10 polychromatic contrast test (Funding: NASA Ames)

Figure 1.3-2 Comparison between the IWA of a PIAA coronagraph and a Lyot-type band limited coronagraph. Actual laboratory PSFs are shown at the same scale. The high sensitivity regions are in blue (PIAA) and black (band limited).
0.4 mas pointing accuracy

0.13 mas pointing knowledge
Fig. 1.— Optical layout of a coronagraphic low order wavefront sensor system, shown here with a PIAA coronagraph. See text for details.

Guyon, Matsuo, Angel, 2008 - to be submitted
Can also be applied to phase mask type coronagraphs (Matsuo & Guyon, in preparation)
Why a central dark spot?

(1) Signal amplification
(2) Accurate reference

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.
RMS values:

- Source x: 0.00079 l/D
- Source y: 0.0015 l/D
- Source focus: 0.0018 waves
- DM tip: 0.00053 l/D
- DM tilt: 0.0011 l/D
**Table 1**

**Pointing stability requirements for a PIAA coronagraph with and without CLOWFS**

<table>
<thead>
<tr>
<th></th>
<th>Without CLOWFS</th>
<th>With CLOWFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required pointing calibration accuracy</td>
<td>0.0016 λ/D (0.13 mas)</td>
<td></td>
</tr>
<tr>
<td>Maximum RMS pointing excursion</td>
<td>0.005 λ/D (0.4 mas)</td>
<td></td>
</tr>
<tr>
<td>Required sampling time(^{b})</td>
<td>5 s(^{c})</td>
<td>38 μs</td>
</tr>
<tr>
<td>Maximum allowed uncalibrated pointing drift rate</td>
<td>0.026 mas/s</td>
<td>3.4 arcsec/s</td>
</tr>
</tbody>
</table>

\(^{a}\) For a \(m_V = 6\) star observed with a 1.4-m telescope in a 0.2\(\mu\)m wide band centered at 0.55 \(\mu\)m with a 50% system throughput.

\(^{b}\) Sampling time required to measure the pointing error with a 1-\(\sigma\) error equal to the "Required pointing calibration accuracy".

\(^{c}\) Assumes that 50% of the observing time is dedicated to measurement of low order aberrations. Also assumes that the signal is well above readout noise and zodi/exozodi background.
PIAA refractive optics (CaF2)

6 CaF2 refractive PIAA systems have been made so far (3 different designs)
One design also removes central obstruction for Subaru
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
- Wavefront control computer
- Fine wavefront correction
  Removes starlight
- DM commands
- HiCIAO images
- HiCIAO commands to HiCIAO

HiCIAO
- HiCIAO camera
- Differential imaging for efficient planet detection
- (1) measures wavefront
- (2) acquires final images
We are hiring a postdoc for Subaru Coronagraphic ExtremeAO system and PIAA technology development:
www.naoj.org

More info on coronagraph on:
www.naoj.org/PIAA

guyon@naoj.org
Coronagraph model

Linear system in complex amplitude
Fourier transforms, Fresnel propagation, interferences, every wavefront control schemes: all are linear
Graphical representation of the coronagraph throughput

Planet position

On-axis point source

A(0)

A₀(α₀)

A₁(α₀)

A(α₀). C

square root of coronagraph throughput at position α₀

A(0). C

square root of on-axis coronagraph throughput

Unity sphere in N dimension space
Graphical representation of the coronagraph throughput

Central star is made of a group of vectors, ALL of which need to be cancelled to some degree.
Problem: stars are not points!
Sun diameter \(\sim 1\%\) of 1 AU
If 1AU = 2 l/d, Stellar radius \(\sim 0.01\) l/d
Wavefront control cannot solve it
Useful throughput – average, 0.1 l/d
AO188 system at the Nasmyth focus (installed in 2006/9)
HiCIAO first light (2007)
Spider Removal Plate

Section (1)

Section (2)

Section (3)

Section (4)

(dx) 4.45 mm diameter

(dy) 17.96 mm diameter

β
Spider Removal Plate (SRP)