A bright future for direct imaging of extrasolar planets & disks

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Subaru Telescope
Outline

- Scientific motivation

- Tools for high contrast imaging
  - **Coronagraphy** – optical system to remove starlight
  - **Wavefront control** – keep the image sharp and achieve high contrast
  - **PSF / speckles Calibration**

- Subaru Coronagraphic Extreme-AO (SCExAO)
- Pupil mapping Exoplanet Coronagraphic Observer (PECO)
Exoplanets

How many planets around other stars?
How do they form, evolved?
Mass, size, composition?
Rocky planets with atmospheres?
What is the atmosphere composition?
Weather, rotation period?
Could have life evolved on other planets?
Intelligent life somewhere else?
Current status of exoplanet discoveries

"Planet Semi-Major Axis" vs "Planet Mass" (340)

"Year of discovery" vs "Planet Mass" (347)
Indirect detection techniques

Doppler Shift due to Stellar Wobble

51 Peg ELODIE

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

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

JD - 2 400 000 (d)

TIME AFTER MID-TRANSIT (HR)

P-RADIAL VELOCITY CHANGES (m s\(^{-1}\))
Indirect detection techniques

Doppler Shift due to Stellar Wobble

51 Peg

ELODIE

RV (km s⁻¹)

-33.2

-33.25

-33.3

0 0.5 1

φ

OC (m s⁻¹)

50 0 -50

50000 51000 52000 53000

JD - 2 400 000 (d)

0.016

0.015

0.014

0.013

0.012

0.011

0.010

0.009

0.008

0.007

0.006

0.005

0.004

0.003

0.002

0.001

0.000

-0.001

-0.002

-0.003

-0.004

-0.005

-0.006

-0.007

-0.008

-0.009

-0.010

-0.011

-0.012

-0.013

-0.014

-0.015

0 1

TIME AFTER MID-TRANSIT (HR)

RAMPS DENSITY CHAGE (MMAG/)

0.000

0.005

0.010

0.015

0.020

0.025

0.030

0.035

0.040

0.045

0.050

0.055
Ground-based imaging (Near-IR, with Adaptive Optics)

- Most sensitive to outer young planets: very complementary to Radial Velocity, astrometry, transits -> important for testing planetary formation models (core accretion, gravitational collapse of disk instabilities ?)
- Study planet formation by imaging disks and planets
- Current limitation: mass/age/luminosity relationship (cooling rate) poorly known
- NEED to get closer in to the star / higher contrasts for overlap with radial velocity planets -> constrain mass/age/luminosity models
- NEED to get closer in/higher contrasts to capture REFLECTED light -> “old” planets can then be detected around nearby stars (known targets from radial velocity)
- NEED to increase sample size (currently ~5, possibly most of them are “exceptions” to the rule) with spectral characterization

Space-based imaging (Visible, extremely high high contrast)

- Characterization (spectroscopy) of Earth-mass planets in habitable zone
- Simultaneous imaging of exozodi cloud, massive and rocky planets
- understanding planetary systems formation & evolution
- Planetary atmospheres, physical properties

Kalas et al. 2008

Marois et al. 2008

Lagrange et al. 2009
Why direct imaging of exoplanets?

Measurements

Modeling / Theory

Astrometry

RV

Orbit

Mass

System dynamical stability

Planet dynamical models

Radius

Rotation period

dynamical model

Planet overall structure (Iron, Rock, Water, Atmosphere)

Mass

Habitability

Impact frequency

Asteroid belt

Surface temperature, pressure & composition?

tidal forces

Planet formation models

Direct imaging

Spectra / colors

time photometry & polarization

exozodi map

Atmosphere composition & structure

atmosphere variation?

albedo?

phase function

RV

incl?

dynamical model
- Venus & Mars spectra look very similar, dominated by CO2
- Earth spectra has CO2 + O3 + H2O + O2 + CH4
  - Together, these gases indicate biological activity

Red edge spectral feature

- Red edge in Earth spectra due to plants, and remotely detectable

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 \( \mu m \)) and the data presented in Paper I (0.5–0.8 \( \mu m \)). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and vegetation reflection are most significant.

Turnbull et al. 2006
Coronagraphy

- R&D in coronagraph has been extremely active in the last 10–15 yrs
- Many good coronagraph designs now exist
- The theoretical limit imposed by fundamental physics is now approached by a few concepts
- Coronagraph performance achieved in labs is already much beyond the requirements of ground-based systems, and at or close to requirements for space mission
Coronagraphy: 1930 to ~15 yrs ago

Lyot Coronagraph
The Lyot Coronagraph

Telescope Pupil
Evenly Illuminated

Image is made (top)
And occulted (bottom)

Pupil is reimaged (top)
And partially blocked (bottom)

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

figure from Lyot project website
What is the theoretical performance limit of coronagraphy?

Coronagraph is a linear filter (in complex amplitude) which removes starlight.

If:

planet = 0.2 x starlight wavefront + 0.8 x something else

then:

coronagraph throughput for planet < 0.8

Theoretical limit would offer high contrast with little loss in throughput and inner working angle close to 1 lambda/D.

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

Fig. 9.—Top: Asymmetric multiopening mask designed to provide high contrast, $10^{-15}$, from $A/D = 4$ to $A/D = 100$ in two angular sectors centered on the $x$-axis. Ten integrations are required to cover all angles. Total throughput and pseudoimage are 24.4%. Airy throughput is 11.8%. Bottom: Associated PSF.
(Note that the mask was originally designed for an elliptical mirror. It has been rescaled to fit a circular aperture.)
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 0.64 I/D to 2 I/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.

Light intensity

PIAA M1

PIAA M2

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 I/D zone:
- $1.5 \times 10^{-7}$ incoherent halo ghost (equivalent to exozodi)
- $7 \times 10^{-9}$ coherent starlight speckles (turbulence, vibrations)

Average contrast in right half of the science field shown above (excludes the ghost on the left) = $7 \times 10^{-9}$
High contrast polychromatic PIAA demonstration in preparation (NASA Ames / NASA JPL)

2nd generation PIAA optics manufacturing completed by Tinsley on Jan 5, 2009 (better surface accuracy, better achromatic design than PIAAgen1)
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.
Wavefront control for coronagraphy
Computer Simulations showing contrast gain with high sensitivity WFS (non-linear curvature)

\[ m \approx 13 \]

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LOWFS efficiently uses starlight to measure tip tilt and a few other low order modes. Subaru Testbed has demonstrated closed loop pointing control to $1 \times 10^{-3} \, \lambda/D \sim 0.1$ 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.
Is is a Speckle, is it a 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)
Focal plane wavefront sensing and calibration

Use Deformable Mirror (DM) to add speckles

**CORRECTION:** Put “anti speckles” on top of “speckles” to have destructive interference between the two

**SENSING:** Put “test speckles” to measure speckles in the image, watch how they interfere

**CALIBRATION:** If there is a real planet (and not a speckle) it will not interfere with the test speckles

Fundamental advantage:
Uses science detector for wavefront sensing: “What you see is EXACTLY what needs to be removed”
Initial problem

- Complex amplitude of speckle

Take a frame -> measured speckle intensity = $I_0$

- $\sqrt{I_0} + \sigma_0$
- $\sqrt{I_0} - \sigma_0$

DM offset chosen to be ~ equal to speckle amplitude
Subaru Lab results with PIAA coronagraph + FPAO with 32x32 MEMs DM
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
Coherent detection works in the lab alongside FPAO

Extremely powerful for ExAO:
- Optically simple
- Non NCPE
- on-the-fly diagnostics
- CDI post-processing
Main source of error in Subaru lab: Moon/Sun tidal forces
The Subaru Coronagraphic Extreme AO Project (SCExAO)

Olivier Guyon, Frantz Martinache, Julien Lozi, Vincent Garrel
System architecture

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
   - Coronagraph
Designed as a highly flexible, evolvable platform
Efficient use of AO188 system & HiCIAO camera
System architecture

Subaru Coronagraphic Extreme–AO (SCExAO) system architecture

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   - Spider Removal Plate (SRP)
   - PIAA optics
   - Inverse PIAA optics

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   - Non Redundant Aperture Mask
   - CORONAGRAPH
   - Spider Removal Plate (SRP)
   - Inverse PIAA optics
   - PIAA optics
   - Focal plane mask

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AO188

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   - 188-actuators curvature Adaptive Optics system (AO188)

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   - 1024 actuators MEMS deformable mirror
   - dichroic

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   - Wavefront Control Algorithm

4. HiCIAO differential imaging camera
   - Non Redundant Aperture Mask

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

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

AO system
Telescope

Laser room

AO system

IR camera & spectrograph
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

15 mm
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

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

(Lab. image)
Expected performance?
H-band ($\lambda = 1.6 \, \mu m$) contrast ratio

Projected angular separation (arcsec)

10 M$_J$ models
1 M$_J$ models
Known exoplanets

Extrasolar planets (Baraffe-Marley)

NRMExAO

SCExAO

GPI

Expected performance?
**Pupil mapping Exoplanet Coronagraphic Observer (PECO)**

http://caao.as.arizona.edu/PECO/

<table>
<thead>
<tr>
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<th>Olivier Guyon – University of Arizona</th>
</tr>
</thead>
<tbody>
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<td>Mission Study Manager</td>
<td>Marie Levine – NASA Jet Propulsion Laboratory -California Institute of Technology</td>
</tr>
<tr>
<td>Science Studies (Lead: NASA Ames Research Center)</td>
<td></td>
</tr>
<tr>
<td>K. Cahoy (NASA ARC) – Co-I</td>
<td>Design Reference Mission</td>
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<tr>
<td>J. Kasting (Penn State) Co-I</td>
<td>Terrestrial planets: spectral characterization</td>
</tr>
<tr>
<td>M. Marley (NASA ARC) – Co-I</td>
<td>Giant planets: spectral characterization, modeling</td>
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<td>M. Meyer (U of A) – Co-I</td>
<td>Planetary systems formation, evolution</td>
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<tr>
<td>W. Traub (JPL-Caltech) – Co-I</td>
<td>Science plan</td>
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<td>S. Ridgway (NOAO) – Co-I</td>
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<tr>
<td>D. Backman (SOFIA) – Collaborator</td>
<td>Exozodiacial dust</td>
</tr>
<tr>
<td>G. Schneider (U of A) – Collaborator</td>
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<td>Planetary systems formation</td>
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<td>N. Woof (U of A) - Collaborator</td>
<td>Characterization of planetary atmospheres, habitability</td>
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<tr>
<td>Architecture Studies (Lead: Co-I S. Shaklan – NASA Jet Propulsion Laboratory - Caltech)</td>
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<td>WFS&amp;C algorithms for Architecture studies and HCIT test demo</td>
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<td>E. Jordan (JPL-Caltech) – Co-I</td>
<td>Systems Engineering</td>
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<tr>
<td>R. Vanderbei (Princeton) – Co-I</td>
<td>Coronagraph architecture and analysis</td>
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<tr>
<td>R. Belikov (NASA ARC) – Collaborator</td>
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<td>Architecture</td>
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<tr>
<td>E. Serabyn (JPL-Caltech) – Collaborator</td>
<td>Wavefront sensing and speckle nulling</td>
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<td>R. Angel (U of A) – Co-I</td>
<td>Technology development, wavefront sensing, primary mirror</td>
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<td>D. Gavel (UCSC) – Collaborator</td>
<td>Characterization of MEMS type DMs for PECO</td>
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<td>M. Shao (JPL-Caltech) – Collaborator</td>
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<td>J. Trauger (JPL-Caltech) – Collaborator</td>
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<tr>
<td>R. Egerman (ITT) – Co-I</td>
<td>PECO telescope design, implementation, cost and technology</td>
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PECO overview

High contrast coronagraphic imaging of the immediate environment of nearby stars.

Characterization of planets (including Earths/SuperEarths) and dust in habitable zone

- 1.4m diameter off-axis telescope (sized for medium-class cost cap), 3 yr mission
- Drift-away heliocentric orbit for maximum stability
- Uses high efficiency low IWA PIAA coronagraph
- 0.4 – 0.9 micron spectral coverage / R~20, polarimetric imaging
- Active technology development program includes NASA JPL, NASA Ames, Subaru Telescope, Lockheed Martin
Earth/SuperEarths with a medium-class mission?

Yes, if:

- **High throughput** instrument & good detector
  - high throughput coronagraph
  - very high efficiency (~45% of photons from the FULL aperture detected), 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 ~20 targets
  - long exposure times & many revisits

- **Risks:** high exozodi & low Earth frequency
  - broader science case:
    - exoplanetary system architecture
    - extrasolar giant planets characterization
    - exozodi disks imaging - **exozodi level measurement**
PECO approaches theoretically optimum coronagraph performance

- High performance PIAA coronagraph
- Simultaneous acquisition of all photons from 0.4 to 0.9 µm in 16 spectral bands x 2 polarization axis, 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
PECO spacecraft & instrument

Univ. of Arizona
Ames Research Center

PECO spacecraft & instrument

PECO
Pupil mapping Exoplanet Coronagraph Observer

OBA
PM
FMS
AMS

OTA supported by 6 struts

OAP1
OAP2
Beam-Splitters
Instrument

Fold
Inv. PIAA L2
Inv. PIAA L1 (pupil)
Apodizer (pupil)
OAP 3
OAP 4
Pupil Relay OAP A
Pupil Relay OAP B
Pupil Relay OA Hyperboloid 1
Pupil Relay OA Hyperboloid 2
DM 2 (pupil)
DM 1
Mask/LOWFS PIAA M2
PIAA M1
PIAA L1
f/60 Bk7/F2 Doublet
• Conduct a “Grand Tour” of ~20 nearby stars searching for small (Earth & Super-Earth) planets in their habitable zones.
  – Multiple (~10 or more) visits for detection
  – Characterization for ~5 days each to get S/N = 20-30 with ability to measure spectral features
  – exozodi distribution measurement
  – compile with other measurements (RV, Astrometry, ground imaging)

• Study known RV planets, observing them at maximum elongation
  – Detect at least 13 RV planets with single visits at maximum elongation
  – Characterize at least 5 RV planets for ~2-5 days each to get S/N > 30 with ability to measure spectral features

• Snapshot survey of ~100 other nearby stars to study diversity of exozodiacal disks and search for / characterize gas giant planets.
PECO can observe an Earth at distance of Tau Ceti

**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 $\lambda=550$ 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.
Table 4-2: Stars with Earth-like planets in habitable zones (1 AU equiv) easily detectable with PECO.

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Table 4-3: Stars with Super-Earth planets in habitable zones (1 AU equiv) easily detectable with PECO.

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<tr>
<th>HIP#</th>
<th>dist (pc)</th>
<th>max el (°/D)</th>
<th>*rad (°/D)</th>
<th>SNR(1s,tp)</th>
<th>t20% (s,tp)</th>
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<td>3114</td>
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<td>Mu Her, G5 IV, V=3.4</td>
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<td>16777</td>
<td>82 Eri, G8 V, V=4.3</td>
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Note: ** indicates the presence of significant dust (~10 zodi or more) and *** indicates a close multiple star system (preventing high contrast observations) in Tables 4-2 and 4-3.
Known EGPs observable with PECO

List of known Radial Velocity EGPs observable with PECO

<table>
<thead>
<tr>
<th>Planet Name</th>
<th>Mp (Mjup)</th>
<th>Period (d)</th>
<th>a (AU)</th>
<th>sep”</th>
<th>550nm/D</th>
<th>Dist (pc)</th>
<th>St. Sp T</th>
<th>M*</th>
<th>St. Mag. V.</th>
<th>Pl mag V</th>
<th>Contrast</th>
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<td>Epsilon Eridani b</td>
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<tr>
<td>55 Cnc d</td>
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</table>
Simulated PECO observation of 47 Uma b (raw image, no zodi or exozodi light subtraction necessary for detection)

Shown is a simulation of 24 hrs of PECO data showing the Jovian planet 47 Uma b with 3 zodis of exozodi dust in a uniform density disk inclined 59 deg.

This is a simulation of 550 nm light in a 100 nm bandpass with predicted PIAA performance in the PECO observatory (1.4-m aperture).

Photon noise and 16 electrons total detector noise (for an electron-multiplying CCD) have been added.

This and other RV planets are very easy detections for PECO even in the presence of significant exozodiacal dust, demonstrating that PECO will likely obtain high S/N data on numerous radial velocity EGPs.
- PECO model shows jitter requirement can be met with no new technology
- Reaction wheels passively isolated
• PECO study shows **direct imaging and characterization of Earths/ Super-Earths possible with medium-scale mission** and:
  - maps exozodi down to <1 zodi sensitivity
  - census of planets and orbits in each exosystem
  - extrasolar giant planets characterization

• “Conventional” telescope with off-axis mirror can be used (stability OK, wavefront quality OK). All the “magic” is in the instrument -> **raising TRL for instrument is key (coronagraph, wavefront control)**
  - technology development at ~$40M, 4yr

• PECO could launch in 2016. Total mission cost ~$810M including technology development

• PECO architecture can be scaled to a flagship 3-4 m telescope without new technologies or new launch vehicles