PECO Science Requirements Document (SRD)

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Purpose and Scope

This document has been developed to clarify and document the science requirements of the Pupil-mapping Exoplanetary Coronagraphic Observer (PECO) mission. The PECO science team has been involved in its creation, and this document represents their consensus. This document has been written to guide the technical development of the PECO mission study in 2008 and 2009. The secondary purpose of this document is to provide material for a competitive PECO mission proposal, perhaps in response to a NASA Announcement of Opportunity in early 2009. The content and organization of this document have been created with these two purposes in mind.

An observing plan capable of achieving the PECO science goals is detailed in the PECO Design Reference Mission document. The DRM contains lists of specific stars that PECO will observe as well as a strawman observing sequence. This sequence will be devised to allow for PECO to discover and then characterize planets and disks around nearby stars as required by this present document. The details of the PECO observing plan will not be presented in the present Science Requirements Document.
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1 Introduction

Over 300 exoplanets have been discovered to date. Most of these have been observed by the radial velocity technique that is most sensitive to detecting relatively massive planets that are close to their parent stars. Thus most of the known planets have masses half that of Jupiter's or greater, but over a dozen have been reported to have $3 - 15$ Earth masses before correction for orbital inclination. This number is increasing rapidly as radial velocity techniques become more precise, and a significant number of low mass planets ($m \sin i < 10$ MJ) are being announced in 2008. This plethora of planets includes 25 known multiple planet systems, with at least one having Jupiter and Saturn mass planets with scaled locations similar to our own solar system.

Other detection techniques are also discovering and characterizing many exoplanets. Ground- and space-based (CoRoT) transit surveys have discovered approximately 50 transiting planets, many of which have been also had their masses measured via radial velocity observations. Several of these have had their spectra observed with HST (Charbonneau et al. 2002, Barman 2007, Swain et al. 2008b) or Spitzer (Richardson et al. 2007, Swain et al. 2008a), constraining their effective temperatures, atmospheric structures, and compositions (Fortney et al. 2007; Seager et al. 2007). This is truly amazing progress; a mere 15 years ago few astronomers would have believed that so much would be known about exoplanets at this time.

Microlensing surveys are also detecting increasing numbers of planets, some with masses as small as 3 MJ. These surveys and the upcoming Kepler mission will reveal the statistical mass spectrum of exoplanets without the biases of radial velocity or ground-based transit discovery techniques. Kepler data should reveal the frequency and orbital distributions of Earth-sized planets around FGK dwarf stars and whether Super-Earth (1–2 earth radii) planets are common or rare.

This rapid progress is very exciting, and much more should be learned about exoplanets over the next 5 years. More sensitive transit surveys are either underway or being studied, and some may reveal whether there are small-to-large planets in the habitable zones of nearby M stars. The James Webb Space telescope (JWST) should be able to obtain high quality spectra of transiting Jovian planets over near- to mid-infrared (IR) wavelengths and should be able to detect earth-sized planets transiting M dwarf stars.

However, we still do not know what the planetary systems (planets and disks) of nearby stars look like. Direct high contrast images of the nearest stars will be sensitive to discovering systems just like our own solar system! Direct imaging data is also needed to address numerous important questions that require observations that cannot be performed by operating or planned facilities. What are the temperatures and compositions of the nearest Neptune-to-Jovian mass planets discovered by radial velocities that do not orbit their host stars closely? Which stars in our immediate solar neighborhood have Earth-like or Super-Earth planets in habitable zones? Are the low resolution spectra of these
small planets similar to the terrestrial planets in our own solar system, or are they more bizarre water or ice worlds? How much exozodiacal dust is there around nearby stars, and how symmetrically is it distributed? What is the composition of this material, and what can we learn about unseen planets from its distribution?

NASA is aware that both the scientific community and the general public are keenly interested in addressing these outstanding questions. The NASA science mission directorate has announced that it plans to start a series of probe-class exoplanet missions early in the next decade, and the Exoplanet Task Force (ExoPTF) of the Astronomy and Astrophysics Advisory Committee has carefully evaluated what types of techniques and observatories are likely to be successful in this time frame. The ExoPTF has reported (http://www.nsf.gov/mps/ast/exoptf.jsp) that it is important to measure both the mass and spectra (yielding temperatures, temperature profiles, and compositions) of exoplanets to make progress in characterizing them, and this will require different observational techniques.

1.1 PECO Description

NASA has funded a study of the Pupil-mapping Exoplanet Coronagraphic Observer (PECO) mission. PECO is a powerful probe-class mission concept that has significant capabilities for detecting and characterizing exoplanets and exozodiacal dust clouds as well as characterizing exoplanetary systems. PECO will suppress the light of exoplanet host stars and use direct imaging to measure the spectra of planets in habitable zones and beyond for FGK stars as well as make sensitive measurements of their exozodiacal dust. These observations will make significant inroads in addressing the above challenging questions for the next decade, especially when PECO data are combined with exoplanet masses derived from radial velocity or astrometric observations.

PECO is a visible/near-IR probe-class observatory that will search for planets by looking for starlight scattered from the planets’ atmospheres and surfaces. The most difficult technical challenge is observing a planet near its parent star, which is roughly 1010 times brighter at these wavelengths. PECO solves this problem by suppressing the star’s light with an extremely efficient Phase-Induced Amplitude Apodization (PIAA) Coronagraph (Guyon et al. 2003) and an advanced wavefront control system. The PIAA Coronagraph also provides a very small inner working angle (IWA), only 2λ/D in radius or even smaller if small amounts of scattered light can be tolerated. PECO will have 4 optical channels segregated by wavelength, each of which will be divided into a few (~4) filter bands sharing the same focal plane mask. PECO will also provide polarimetric capabilities.

PECO has the ability to detect Jovian type planets around hundreds of stars, it will study the characteristics of exozodiacal disks around these stars, it will detect circumstellar debris disks around nearby stars to levels below that in our own solar system, and it will be capable of detecting Earth to Super-Earth sized planets in the habitable zones of dozens of nearby stars. These are all critical observations that are enabled by PECO’s unique capabilities of small IWA, high contrast, and high optical throughput. A coronagraphic direct imaging spectrophotometric mission like PECO is needed to measure the reflected spectra of planets in habitable zones and beyond; transit spectroscopy of transiting Earths...
around solar type stars by JWST or future larger aperture observatories will not be possible because of the small signal. PECO's coronagraphic technique is also the most sensitive way to measure exozodiacal dust in and near the habitable zones of nearby stars. Besides informing the above related scientific questions, PECO-enabled exozodiacal dust measurements are essential for planning more capable future coronagraphic missions that must distinguish faint exoplanets from clumps of exozodiacal dust.

PECO science data will consist of diffraction-limited images of extrasolar systems obtained simultaneously in intermediate photometric bands (R~15) with extremely high suppression of the central star's diffraction pattern. Even moderate signal-to-noise PECO data will distinguish photometrically between extrasolar giant planets (EGPs), ice giants, and terrestrial planet atmospheres, although PECO may not be able to resolve the smallest separation habitable planets in its longest wavelength bands due to finite inner working angle (IWA). Low resolution spectra assembled from PECO images should contain absorption bands that may provide information concerning the compositions of exoplanet atmospheres, surfaces, and exozodiacal dust. Of particular interest are features that indicate the temperatures and compositions of giant planet atmospheres and whether smaller planets might be habitable, or perhaps even inhabited by life. PECO should be able to look for CH4, alkali gas (for warm Jupiters) and H2O absorption bands, as well as those of O2 and O3. PECO polarimetric data can constrain planetary surfaces or atmospheres and circumstellar debris physical characteristics, systemic geometrical parameters, and will help to distinguish between planets and spatially unresolved “clumps” of co-orbiting dust.

2 Exoplanet characterization with direct imaging observations

2.1 Orbit determination

The first step in the characterization of planets around stars is to determine the mean distance of the planet from the star. This is one of the most difficult challenges for any direct imaging mission, as the planet can be at any phase angle in its orbit, and the orbital plane itself can be inclined at any angle to the line of sight. Hence, a planet that appears to be within the habitable zone of its parent star may actually be considerably more distant. The best way to address this uncertainty is by making multiple observations of the target system separated by intervals of weeks to months and then using this information to determine the planet’s orbital period. The problem is more difficult for planets orbiting larger, more luminous stars because their habitable zones are farther out, and thus the orbital periods are longer. A more thorough treatment of the problem of determining planetary orbits can be found in the TPF-C Science and Technology Definition Team final report.

2.2 Planetary albedo and contrast

Detecting Earth-sized planets close to their parent stars requires that PECO be able to achieve high contrast. As discussed below, the required contrast ratio, C, is $\sim 1.15 \times 10^{-10}$ for an Earth-like planet orbiting a Sun-like star at quadrature (i.e., half-illuminated). For the
inner and outer edge of the habitable zone, C is 1.78 times larger and 3.24 times smaller, respectively.

The ratio of reflected to incident light from a planet, integrated over all wavelengths, is known as the Bond albedo. The Bond albedo governs the planetary effective temperature as the absorbed stellar energy plus any internal heat flow must equal the energy radiated over the entire sphere.

If one assumes that a planet scatters light like a Lambertian sphere, i.e., equally in all directions, then—in integrated reflected light—it should be dimmer than its parent star by a factor (Sobolev, 1975):

$$C'(\alpha) = \frac{2}{3} A(r/a)^{2/\pi} \left[ \sin(\alpha) + (\pi - \alpha) \cos(\alpha) \right]$$

Here, A is the planet’s Bond (bolometric) albedo, r is its radius, a is its orbital distance (assumed constant for simplicity), and α is the phase angle of the planet defined as the star–planet–observer angle. At quadrature (\( \alpha = \pi/2 \)), \( C = (2/3)A(r/a)^{2/\pi} \). For an Earth-like planet orbiting a Sun-like star, \( A = 0.3 \) (Goody and Yung, 1989, p. 1; Goode et al., 2001), \( r = 6371 \) km, and \( a = 1.5 \times 10^8 \) km, so the contrast ratio \( C \) is \( \sim 1.15 \times 10^{-10} \). In reality, Earth is not a Lambertian scatterer, so this value is only approximate.

Since a planet’s brightness is in reality wavelength-dependent, it is common to define a wavelength-dependent albedo, the geometric albedo \( p \), which is the reflectivity of a planet observed at zero phase angle (opposition). For a perfectly reflecting Lambert sphere the geometric albedo is \( 2/3 \); for a semi-infinite purely Rayleigh scattering atmosphere it is \( 3/4 \). Geometric albedo spectra measured for some solar system planets are shown in Figure 2-1.
Figure 2.1: Geometric albedo spectra (Karkoschka 1994) for the solar system giant planets. Note that all four planets are darker at all wavelengths than perfect Rayleigh (3/4) or Lambert (2/3) scattering spheres.

From Sobolev’s equation, one can see that the contrast ratio will be better (worse) for planets that are bigger (smaller) than Earth. If one neglects the variation with mass in a planet’s density, a minimum-mass potentially habitable planet of 1/3 ME would have a contrast ratio that is worse than that of Earth by a factor of (1/3)2/3 ≅ 0.5. A 10-ME planet would have a contrast ratio 102/3 ≅ 4.6 times higher than Earth. Accounting for the compression of typical terrestrial planet constituents, the contrast ratio would only be about 3 times that of Earth. Contrast ratios at the outer edge of the HZ, 1.8 AU, are worse than 1-AU values by a factor of 1/(1.8)2 ≅ 0.3.

2.3 Determination of planetary effective temperature

Given a planet’s orbital distance and the stellar luminosity one can determine the energy flux at the top of the planetary atmosphere. Given a Bond albedo (also defined as the wavelength-dependent geometric albedo integrated over wavelength and weighted by the stellar flux), one can compute the total energy absorbed by a planet. The temperature of a planet in thermal equilibrium with the absorbed incident radiation is known as the equilibrium temperature and gives insight into the characteristics of an atmosphere. Care
must be exercised, however, since if there is a greenhouse effect the surface temperature can be much higher than the equilibrium temperature, as is the case for Earth and Venus.

Whether or not a planet retains an atmosphere depends on the incident flux as well as the escape velocity as shown in Figure 2-2 (and also depends on its formation history). Relatively cool, massive planets are more likely to retain an atmosphere and consequently be considered habitable. PECO will detect and characterize nearby planets in roughly the lower right region of this figure.

**Figure 2-2:** Atmospheres are found where gravitational binding energy is high and solar heating low. This is shown here by plotting escape velocity against insolation for the fully characterized planets. The presence or absence of an atmosphere is indicated by filled or open symbols, respectively. Known transiting extrasolar planets as of April 2008 are also plotted. Figure from Zahnle and Marley (2009).

### 2.4 Rayleigh scattering and clouds

The reflected spectrum of a planet is controlled by a balance between scattering and absorption. An infinitely deep, Rayleigh scattering atmosphere would simply reflect the incident stellar spectrum. In more realistic atmospheres Rayleigh scattering dominates in the blue while absorption by atmospheric gasses (e.g., H2O or CH4) is important in the red.
For terrestrial planets with thin atmospheres the surface becomes important as well, particularly in the red.

Clouds, which form at and above the condensation level in an atmosphere, substantially alter planetary spectra. An optically thick cloud forms a floor to the atmosphere above which Rayleigh scattering and gaseous absorption can be important, although the atmosphere below the cloud is not detectable. The presence of a cloud allows one to infer the temperature and composition of the atmosphere. Photochemical hazes, which preferentially absorb in the blue, are recognizable by depressing the Rayleigh scattering continuum in the blue, as is seen in the spectra of Jupiter and Saturn in Figure 2-1.

Such hazes may be an important constituent of any planet, terrestrial or giant, with a methane rich atmosphere closer to the sun than Jupiter.

**Figure 2-3:** Planetary radii at 4.5 Gyr vs. mass. Models are calculated at 0.02, 0.045, 0.1, 1.0, and 9.5 AU (color-coded, bottom). Black curve: heavy element planet, half ice, half rock. Colored 5 curves over black: planets with 90% heavy elements. Next higher 5 curves are 50% heavy elements. Next higher set, dotted lines, are 10% heavy elements. Highest set: core-free planets of pure H/He. Circles: solar system planets. Diamonds: extrasolar planets. From Fortney et al. (2007).
2.5 Characterizing planets by color

Once the existence of a planet has been established, a zeroth-order estimate of its nature can be obtained from its semi-major axis and its brightness in the detection wavelength band. The planet brightness can be expressed as a planet-star contrast or "delta-magnitude" with respect to its parent star. The absolute planet brightness is derived from the PECO measured planet-star contrast together with a ground-based stellar brightness measurement. Measurements of planet brightness in several broad wavelength bands, at a spectral resolution of roughly 4, might further be useful to estimate a planet’s nature. The ratio of these values to the star’s intrinsic brightness in the same bands provides information about the wavelength dependence of the planet’s albedo. With observations in at least 3 such bands, the planet’s color can be determined and compared with known solar system planets (Figure 2-4).

There are difficulties with this approach, however, since there will certainly be exoplanets with characteristics quite different from solar system objects (warm Neptunes, super-Earths, water worlds, etc.) and their colors may be surprising. In addition photochemical and cloud processes can substantially alter the color of a planet (e.g., Titan). For this reason the ExoPTF felt that low resolution spectra and not colors were the best discriminant of planet composition and size.

![Figure 2-4](image.png)

**Figure 2-4:** Colors of Solar System planets (Traub, 2006). Relative albedos shown.
2.6 Characterizing planets by their polarizations

Just as there is a dependence in a planet’s effective albedo with orbit phase, $A(\alpha)$, there is also a strong dependence in fractional polarization with phase angle (e.g. Seager et al. 2000) that informs orbital inclinations (see Figure 2-5). This effect will further constrain planetary radii (through Bond albedo determined with PECO multi-wavelength imaging; intensity $\sim$ albedo x R2), and thus temperatures (see section 2.4). Wavelength- and phase-dependent polarization fractions constrain the characteristic sizes and compositions of light-scattering grains. For example, strongly peaked backscattering would arise from absorbing particles in planetary atmospheres that are large compared to the observational wavelength. Polarimetric analysis is also diagnostic of planetary surface compositions, and can enable discrimination between “water worlds” from planets with arid surfaces and the presence (or absence) of optically thick clouds (see Fig 2-6). Additionally, multi-wavelength polarimetry can help distinguish between planets and spatially unresolved overdensities in optically-thin co-orbiting circumstellar debris disks (c.f. Figs 5-6 and 5-7).

![Figure 2-5: Model polarization fraction for an Earth/Sun analog of differing global surface compositions. In each panel, the upper curve is cloud-free atmosphere, and the lower panel shows clouds with Earth-like covering fraction. Black circles in upper left panel, for comparison, are earth-orbit phase-mapped measures of Earth-shine off the moon. From Mccullough, 2006.](image)
Figure 2-6: Model star-plus-planet monochromatic light curves and corresponding fractional polarizations diluted by unsuppressed central starlight (from Hough et al. 2003). These are without PECO-like starlight suppression, but illustrate orbit phase dependence of light scattered by submicron particles in a planetary atmosphere of a close-in orbiting EGP (for orbital inclinations $i=90^\circ$ (solid) to $i=21^\circ$ (dash-triple-dot)).

3 Extrasolar Giant Planets

PECO observations will reveal much about extrasolar giant planets (EGPs). Simply imaging the known radial velocity planets will uniquely characterize planet mass and thus provide new constraints on stellar system architectures (orbits and masses). In addition, PECO will constrain:

- The effective temperatures of EGPs by measuring atmospheric composition and condensates.
- The extent of cloud layers from their influence on the reflected spectra.
- Atmospheric composition and determine if EGP atmospheres are enhanced in heavy elements.
- Rotation periods (possibly) and the atmospheric phase function by measuring brightness changes with orbital phase.
- The extent to which these properties vary with planetary mass.

3.1 Giant planet atmospheres

The reflection spectra of mature giant planets are controlled by Rayleigh and Mie scattering from atmospheric gases, aerosols, and cloud particles, and by gaseous absorbers. Scattering of incident light usually dominates in the blue, giving way to absorption by the major molecular components at wavelengths greater than about 0.6 $\mu$m. The major absorbers in
the optical are methane and, for warmer planets, water. Generally speaking, in strong
molecular bands photons are absorbed before they can scatter back to space. In the
continua between bands, photons scatter before they are absorbed. The continuum flux
from a given object is thus controlled by Mie scattering from its clouds and hazes and
Rayleigh scattering from the column of clear gas above the clouds. Figure 3-2 illustrates the
significant impact that clouds can have on exoplanet spectra.

Visible-wavelength spectra of giant planets thus opens a door into their cloud structure
(and, by extension, atmospheric temperature) and composition. Composition is of
particular interest because the atmospheric abundances of all of the solar system giant
planets depart strongly—by at least a factor of three—from that of the sun. Yet this departure
is not uniform: Jupiter shows an enhancement of 2 to 4 times solar for many species while
Saturn is enhanced by a factor of 10 in C and Uranus and Neptune are enhanced in C by a
factor of 30 (see Figure 3-1). A number of mechanisms have been suggested to explain the
diverse atmospheric composition of just Jupiter and Saturn. The data may point to the
enrichment of these atmospheres by late-arriving planetesimals from the outer solar
system, or to erosion of a heavy element core, or perhaps chemical fractionation within the
planet. Measuring the atmospheric composition of a great diversity of extrasolar giant
planets will certainly shed light on their formation and evolution. Wavelength-dependent
grain scattering properties, characterized by polarimetry (as noted in section 2.6) and
polarimetrically-constrained albedos can discriminate between different species posited
for EGP atmospheres (e.g., Sudarsky, Burrows and Pinto, 2000) For example, a survey of
giant planets would reveal how atmospheric composition varies between planets lying
inside and outside of the “ice line,” or with planet mass or stellar properties.

It has also been suggested that the “planetary” and “stellar” formation modes may overlap
at several Jupiter masses. If so, then more massive giant planets might simply reflect the
composition of their primary stars while lower mass planets will exhibit compositional
enrichments from planetesimals in the disk. The orbital dynamics of observed exoplanets
already hint at such a dichotomy, and there may be different eccentricity distributions for
the radial velocity planets above and below 4MJ.

PECO could easily search for strong composition variations among the two classes of
objects, for example by measuring methane or water band depths in objects with similar
equilibria temperatures but differing orbits (e.g., eccentric vs. circular orbits, which may be
a signature of differing formation mechanisms).

For cold giants, like Jupiter and Saturn, the abundance of C will be constrained through the
well-studied methane absorption features that dominate their optical spectra (Figure 3-2).
In somewhat warmer atmospheres (younger or more massive planets, or giants closer to
their primaries, or hotter primaries) ammonia will not condense but instead be present as
a gas in the atmosphere. Such planets will sport water clouds and have a flat, bright
continuum spectra punctuated by methane and ammonia absorption (Figure 3-3). Even
warmer planets, without clouds, will show water vapor bands in the optical and be very
dark in the red. Meanwhile “ice giants” (highly enriched atmospheres like Uranus and
Neptune) will have their own unique spectral sequence characterized by very blue colors
(because of the overwhelming methane absorption in the red) and should be easily
distinguishable from their less enriched, more massive siblings (Figure 2-1 and Figure 2-4). One challenge, however, is that composition information is found in the depth of absorption features, which are of course at less favorable contrast and lower S/N. Thus composition determinations should focus on weak to moderate strength bands (e.g., at 0.62 μm or 0.54 μm) rather than the strongest bands (e.g., the 0.89 μm methane band) which will be quite dark.

![Graph showing composition abundances of C, N, O, and S for planetary atmospheres.]

**Figure 3-1**: Solar System planetary atmosphere abundances. PECO will be able to constrain the C abundances of some giant exoplanets.

Beyond measuring composition, a number of other measurements are possible on extrasolar giant planets. Of foremost importance would be a measurement of a planet’s phase curve as it orbits. This constrains the energy balance and Bond albedo of the planet and is crucial for constraining the atmospheric temperature and cloud properties. For example Voyager 1, which did not visit Uranus but instead imaged it from afar, observed the planet at high phase angles not reachable from Earth to help constrain the scattering phase function of its clouds and Bond albedo (Pollack et al., 1986). It might also be possible to measure rotation rates, although even Jupiter with its Great Dark Spot has a surprisingly subdued light curve (Gelino & Marley 2000). In addition photochemical processes control the albedo in the blue and will likely be of great importance in warmer planets or for those orbiting stars with greater UV flux. Ring systems and large albedo changes with season on highly eccentric planets also would be of interest.
Figure 3-2: Model spectra of a Jupiter-mass planet at different orbital distances from a solar-type star. This figure can also be interpreted as an effective temperature sequence for a planet at 3 AU (younger or more massive giant planets are hotter, all else being equal). Dotted lines: models without clouds, highlighting the role clouds play in reflected spectra. Such models can help assess the clouds present in planets observed by PECO (figure courtesy M. Marley & J. Fortney).

3.2 PECO Observations

PECO low resolution spectra will constrain the temperatures and compositions of EGPs detected in nearby extrasolar systems. A direct imaging observatory such as PECO is needed to measure the intrinsic spectra of EGPs whose atmospheres are not driven by the insolation of a very close parent star. Spitzer, JWST, and other non-coronagraphic observatories may obtain good spectra of transiting “hot Jupiters” but are not capable of observing the intrinsic quiescent spectra of EGPs analogous to those in our own solar system. It may also be possible to learn something about the formation of these planets from their atmospheric temperature profiles and internal energies.

Color will provide the zeroth order characterization of imaged exoplanets. To reliably measure color we set the following mission requirements, defined in terms of a Jupiter twin found in a solar system twin at a distance of 10 pc:

SCIREQ1: PECO shall be able to measure the absolute brightness (flux) of a Jupiter-twin planet at 10 pc in at least one bandpass to within 10% (OK to calibrate with ground-based or other non-PECO data). This is intended to ensure that PECO shall be capable of making high precision measurements of the fluxes of at least several Jovian planets for constraining albedos and sizes. There are at least 20 FGK stars within 10 pc, so PECO could detect 3 Jupiters if the probability of finding a Jupiter around each star is 0.15. There are also 3 stars with known RV planets within 10 AU
that have maximum elongations of 160 mas or greater. Therefore precise flux measurements to 10 pc are required.

**SCIREQ2:** PECO shall be able to measure the relative flux of a Jupiter-twin at 10 pc in at least three broad (R~5) spectral bands spanning at least 450 – 800 nm (goal 400 – 860 nm) wavelength with a precision of 5% or better. This is intended to ensure that PECO shall be able to make high precision measurements of the colors of at least several Jovian planets over the wavelength range of key absorption features (see Fig. 3-3 and SCIREQ1).

A Jupiter-like planet in a 5 AU orbit around a sun-like star at a distance of 10 pc is expected to have a flux level of 4.7E-8 Jy (V=27.2 mag). This is a V-band contrast level of approximately 22.5 mag with the planet having a maximum separation of 500 mas from its star. Detecting such a planet should be relatively insensitive to low levels (~ 1-10 zodi) of exozodiacal dust because of its relatively high brightness and its relatively large distance from its star.

Figure 3-2 (and 2-1, 3-1, and 3-3) shows that relatively weak molecular bands must be detected and measured to constrain the temperatures and abundances of EGPs. In general, we adopt detecting a feature with a depth 10% below the continuum as the baseline requirement and set detecting a 20% deep feature as the minimum science floor.

Figure 3-3 illustrates how a set of moderate and wide band filters could span the PECO wavelength region and be used to measure the strong absorptions of NH3, CH4, and H2O that are present in EGPs.

PECO must observe CH4 and H2O bands in order to constrain EGP temperatures and compositions. Optical NH3 bands are subtle and unlikely to be detected by PECO. A strawman filter set capable of observing CH4, H2O, and continuum bands is presented in Table 3-1. These may be synthesized from 1 or more of PECO's R=20 bands.
Figure 3-3: PECO bands and giant planet geometric albedo spectra. The spectra of Jupiter (red) and Uranus (green) demonstrate the differences between a massive gas giant planet and an 'ice giant' with high metallicity and relatively low cloud opacity. Light and dark blue lines show models (courtesy Sara Seager) of warmer giant planets with atmospheric water vapor and high cloud opacity, respectively.

Table 3.1: Strawman PECO filter list for Extrasolar giant planets (also see Figure 3.3)

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<thead>
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<th>Filter</th>
<th>Wavelength (nm)</th>
<th>Width (nm)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
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<td>480.0</td>
<td>60</td>
<td>Blue wide band</td>
</tr>
<tr>
<td>F560W</td>
<td>560.0</td>
<td>84</td>
<td>Survey filter; yellow wide band</td>
</tr>
<tr>
<td>F677W</td>
<td>677.0</td>
<td>85</td>
<td>Red wide band</td>
</tr>
<tr>
<td>F803W</td>
<td>803.0</td>
<td>125</td>
<td>IR wide band</td>
</tr>
<tr>
<td>F460M</td>
<td>460.0</td>
<td>20</td>
<td>Blue-violet continuum</td>
</tr>
<tr>
<td>F575M</td>
<td>575.0</td>
<td>50</td>
<td>Yellow continuum</td>
</tr>
<tr>
<td>F650M</td>
<td>650.0</td>
<td>30</td>
<td>Orange continuum; weak methane</td>
</tr>
<tr>
<td>F728N</td>
<td>727.5</td>
<td>7</td>
<td>Strong methane</td>
</tr>
<tr>
<td>F750N</td>
<td>750.0</td>
<td>6</td>
<td>Continuum</td>
</tr>
<tr>
<td>F793M</td>
<td>792.5</td>
<td>25</td>
<td>Moderate strength methane band</td>
</tr>
<tr>
<td>F830M</td>
<td>830.0</td>
<td>20</td>
<td>Water band, continuum at lower</td>
</tr>
<tr>
<td>F863N</td>
<td>862.5</td>
<td>5</td>
<td>Strong methane</td>
</tr>
</tbody>
</table>
Given the above considerations we can place additional requirements for measuring spectra in narrower bandpasses. Since we recognize that higher spectral resolution requires more photons we define these requirements for a Jupiter twin planet at 7 pc, instead of the 10 pc for the color requirements:

**SCIREQ3:** PECO shall be able to detect CH4 in the atmosphere of a Jupiter twin planet at 10 pc. Detection is defined as the ability to measure the depth of the 650 nm CH4 band absorption (assumed to be 20% deep and R= 20 wide) at SNR = 3 (floor) – 6 (baseline).

**SCIREQ4:** PECO shall be able to measure the continuum flux level between CH4 absorption bands of a Jupiter twin at 10 pc to within 3% (baseline; SNR = 30) - 10% (minimum; SNR = 10) precision at three widely spaced spectral intervals. This is needed to measure scattering and albedo. Systematic noise must not limit signal-to-noise below these levels. The continuum flux level may be computed by assuming a geometric albedo of 0.5.

**SCIREQ5:** PECO shall be able to detect a 20% deep H2O band at 830 nm (R = 20 width) in the atmosphere of a Jupiter twin at 10 pc with SNR = 3 (floor) – 6 (baseline). This requires continuum SNR = 15 (floor) – 30 (baseline). Alternatively, the 725 nm band of H2O may be considered as a minimum requirement if the baseline 830 nm one is unobservable. H2O and methane measurements are needed to derive temperatures and constrain abundances. PECO shall also be able to measure the 450 – 510 nm blue band with identical SNR, with a goal of measuring the 400 nm absorption band in hot EGPs (Fig 3-3).

Low resolution spectra alone are not sufficient to characterize EGPs; we must also know the mass of a planet to determine its temperature and composition with high precision. PECO will be able to observe over a dozen known radial velocity planets with known M sin i masses (Table 3-2). These planets span the 0.5 – 1 Mjup projected mass range at distances 1.7 – 6 AU from their host stars. Most host stars are generally solar type (~1 M☉), but 3 have masses in the 1.3 – 1.9 M☉ and one has mass 0.4 M☉. Two well-separated PECO observations of each will constrain their inclinations and thus their masses. These systems should form a good set of planets that can be used to interpret PECO observations of other EGPs with less well known masses. The number of low mass RV planets observable by PECO is likely to increase significantly before PECO launches as radial velocity precision improves (as HARPS upgrades and laser combs come online).

**Table 3.2:** Known RV exoplanets easily observable by PECO

<table>
<thead>
<tr>
<th>Planet Name</th>
<th>Mass (MJ)</th>
<th>Period (d)</th>
<th>a (AU)</th>
<th>Sep&quot;</th>
<th>550 nm/D</th>
<th>Dist (pc)</th>
<th>Star Spec. Type</th>
<th>M*</th>
<th>Star Mag. V.</th>
<th>Planet mag V</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epsilon Eridani b</td>
<td>1.55</td>
<td>2502</td>
<td>3.39</td>
<td>1.06</td>
<td>13.07</td>
<td>3.20</td>
<td>K2 V</td>
<td>0.83</td>
<td>3.73</td>
<td>25.72</td>
<td>1.60E-09</td>
</tr>
<tr>
<td>55 Cnc d</td>
<td>3.84</td>
<td>5218</td>
<td>5.77</td>
<td>0.43</td>
<td>5.31</td>
<td>13.40</td>
<td>G8 V</td>
<td>1.03</td>
<td>5.95</td>
<td>29.10</td>
<td>5.51E-10</td>
</tr>
<tr>
<td>HD 160961 c</td>
<td>3.10</td>
<td>2986</td>
<td>4.17</td>
<td>0.27</td>
<td>3.36</td>
<td>15.30</td>
<td>G3 IV-V</td>
<td>1.08</td>
<td>5.15</td>
<td>27.59</td>
<td>1.05E-09</td>
</tr>
<tr>
<td>Gj 849 b</td>
<td>0.82</td>
<td>1890</td>
<td>2.35</td>
<td>0.27</td>
<td>3.30</td>
<td>8.80</td>
<td>M3.5</td>
<td>0.36</td>
<td>10.42</td>
<td>31.62</td>
<td>3.32E-09</td>
</tr>
<tr>
<td>HD 190360 b</td>
<td>1.50</td>
<td>2891</td>
<td>3.92</td>
<td>0.25</td>
<td>3.04</td>
<td>15.89</td>
<td>G6 IV</td>
<td>1.04</td>
<td>5.71</td>
<td>28.02</td>
<td>1.19E-09</td>
</tr>
</tbody>
</table>
A census of over a hundred stars will likely produce significant statistics on the spectral properties and constrain the temperatures and compositions of EGPs in the solar neighborhood. Most EGPs will be found near the PECO IWA, but the closest stars (within 5 pc) could have EGPS with maximum elongations > 1 arcsecond. This leads to the following requirements:

**SCIREQ6:** PECO shall be able to detect giant planets 3.3 AU from their stars over a distance range of 3 - 20 pc. This translates to an IWA of 165 mas and an outer working angle (OWA) of 1.1 arc-seconds, corresponding to 2 λ/D and 14 λ/D, respectively, for a D = 1.4-m telescope diameter and λ = 550 nm wavelength. This should be sufficient to observe most or all RV planets in Table 3-2. A larger OWA is desirable for observing the closest stars; 1.9 arcseconds (24 λ/D) would allow imaging a Cen A/B out to 2.5 AU radius.

**SCIREQ7:** PECO must be capable of searching 100 (minimum) – 200 (baseline) stars for EGPs and be capable of detecting Jupiter twin planets around each star outside of the PECO IWA at wavelengths of at least 550 nm. PECO must be capable of characterizing the spectral features (SCIREQ3-5) of at least 5 known RV planets (10 goal).

Simulations predict that PECO will detect Jupiter equivalent planets on circular orbits at 5AU distances in under 2 x 104 seconds integration time for 20% of all possible observations (i.e., including all possible IWA values) of approximately 250 nearby stars. All of these stars are within 31 pc of the Sun.

## 4 Terrestrial Planets

PECO will be capable of detecting even small planets (1 – 2 R⊕) with Earth albedos in the habitable zones of a few dozen of the nearest stars. This is a large enough sample to probe several significant questions:

- Which of the closest stars have Earth-like planets in or near their habitable zones?
- What are the broad-band colors of small planets; are they similar to ones in our own solar system?
- Are any very strong spectral features are seen in the atmospheres of these planets; do any show H2O, O2, or any other molecules needed for life as we know it?
The atmospheres of such warm terrestrial exoplanets may show spectral features produced by water vapor. These can be seen in the albedo spectrum of Earthshine, Figure 4-1. The principal bands in the visible / near-IR spectrum are at 825 +/- 20nm and 720 +/- 20nm. Both of these bands may be detected in low spectral resolution PECO data if sufficient signal-to-noise is obtained (SNR > 25 on continuum). Both would show better if PECO bands and their widths were specially selected to help observe them.

Also visible at PECO resolution in the spectrum of Earth are features produced by oxygen containing molecules. The most prominent at low spectral resolution is the Chappuis band of ozone at 590 +/- 50nm. Next most prominent is the oxygen A band at 760 +/- 10nm. Both of these bands show up in Figure 4-1. The width of the Chappuis band is wider than PECO resolution, and its visibility can be improved by binning. The A band would be hugely improved in visibility by setting a special PECO band at 750-770nm.

![Earthshine spectrum](image)

**Figure 4-1:** The Earth albedo spectrum from Earthshine. From Woolf et al. (2002).

### 4.1 Habitability and the presence of life
Our current understanding of the origin of life and the range of chemical environments in which life could develop leave issues of whether observed planets are potentially habitable or not, without any observational basis for discrimination. One thing we can do is distinguish whether a planet resembles Earth at this present time. The PECO potential indicators for this are:

- The blackbody temperature must be near 255K.
- The planet’s atmosphere should be thick enough, so it should show an appreciable Rayleigh scattering.
- The planet’s atmosphere should show bands of water vapor at 720 and 825 nm.
- The planet should show the presence of oxygen by the 590 nm Chappuis band of ozone and the 760 nm A band of oxygen.

These features would be most detectable by optimizing the PECO band centers and widths. The probability that there is an Earth-like planet sufficiently close as to permit good PECO observations is slight, and equally, the probability that such a planet has life evolved so as to create a substantial oxygen atmosphere is also slight. However, the adjustment of PECO bands so as to permit this distinction is slight and easy, and no other science seems to be harmed by this modification, and so it is recommended. Detection of a planet with an oxygen/water atmosphere would be as interesting as it is improbable.

It is also conceivable that PECO might observe a planet similar to the early Earth. In that case, point 4 from the list above would not be satisfied, as Earth’s atmosphere is thought to have been deficient in both O2 and O3 until ~ 2.4 billion years ago (Holland, 1994; Kasting and Catling, 2005). Earth is thought to have been inhabited, though, since at least 3.5 billion years ago, and possibly earlier (Shopf, 1983). Exactly what the Earth might have looked like at this time is not known, but it has been speculated that its atmosphere may have been rich in CH4 produced by methanogens (Kasting and Catling, 2005). CH4 levels in a post-biotic early Earth atmosphere could conceivably have approached 1000 ppmv, or even greater (ibid.). Spectra of the Earth’s atmosphere at earlier times have been modeled by Kaltenegger, Traub, & Jucks (2007).

This poses the question of whether a CH4-rich atmosphere might potentially be observed by PECO. The answer is ‘yes’, but only if the spectral resolution extends sufficiently far into the near-IR. Figure 4-2 shows that, even though CH4 has numerous absorption bands in the visible/near-IR, all those short-ward of ~0.95 μm are either too weak to be observed or they are strongly overlapped by bands of H2O. The first CH4 band that has a reasonable chance of being observed by PECO (or by TPF-C) is the one centered at 1.00 μm. This is right near the edge of where most existing CCD detectors begin to fall off rapidly in sensitivity. It would be desirable to be able to extend the PECO spectrum to wavelengths well beyond 1.0 μm in order to be able to measure the continuum on each side of this band. However, this is technically difficult or impossible because of the habitable zones of all but the few closest stars are within the PECO IWA at these wavelengths and because of the
detector issues. Therefore PECO is not likely to resolve CH4 from H2O in observations of terrestrial (or other) planets.

**Figure 4-2:** Synthetic R=70 cloud-free spectra of hypothetical Earth atmospheres at various times during the planet’s history from Kaltenegger, Traub, & Jucks 2007. Epoch 0: 3.9 Gyr ago, 10% CO2, current trace CH4. Epoch 1: 3.5 Gyr ago – 1% CO2, 0.2% CH4. Epoch 2: 2.4 Gyr ago – 1% CO2, 0.7% CH4, 0.02% O2. Epoch 3: 2.0 Gyr ago – 1% CO2, 0.4% CH4, 0.2% O2. Epoch 4: 0.8 Gyr ago – 1% CO2, 0.04% CH4, 2% O2. Epoch 5: 0.3 Gyr ago – 0.04% CO2, 21% O2, current trace CH4.

### 4.2 PECO Observations

PECO low spectral resolution images will constrain the colors of small (R = 1-2 R⊕) terrestrial planets detected in or near the habitable zones of nearby stars. PECO imaging data should span the 400 – 800 nm region. Sensitivity below 400 nm is not needed because reflected star light is faint at those wavelengths, and few stars are close enough for PECO to resolve planets in their habitable zones at λ > 800 nm. It is desirable for PECO data to be summed to create broader bandpass observations (R~5) with little signal-to-noise penalty in order to see very small or faint planets in reasonable amounts of time (1 day exposure time or less).
PECO must be able to detect earth-sized planets in the habitable zones (at Earth-equivalent radius) of at least 10 nearby stars and 50 super-earth planets (2.0 $R_\oplus$ with Earth geometric albedo $a=0.2$) when at maximum elongation in at least one $R \sim 5$ PECO channel. Nearly all small planets found with PECO will be near the PECO IWA. These detection considerations, wavelength limits and the spectral identification discussions above result in the following requirements:

**SCIREQ8**: PECO shall be able to measure the absolute brightness (flux) of a super-Earth planet (Earth albedo and 2 $R_\oplus$radius) in the habitable zone of an F V star at a distance of 10 pc in at least one bandpass to within 25% (after calibration). This is intended to ensure that PECO shall be capable of making moderate precision measurements of the fluxes of at least several terrestrial planets and will constrain radii to $\sim12\%$ for given albedos. There are approximately 10 FGK stars within 10 pc that have habitable zones (1 AU equivalent) located at least 165 mas away, outside of the PECO IWA (SCIREQ6). Adopting a probability of terrestrial planets of 0.3 implies that PECO is likely to find 3 Earth or Super-Earth planets around these stars.

**SCIREQ9**: PECO shall be able to measure the relative brightness of a super-Earth planet (Earth albedo and 2 $R_\oplus$radius) in the habitable zone of an F V star at a distance of 10 pc in at least two broad (R~5) bands 450 – 800 nm with a precision of 20% or better to allow characterization by color. PECO must be able to perform these measurements for at least 10 nearby FGK stars.

**SCIREQ10**: PECO must provide filters capable of detecting ozone (590 nm), water vapor (725 and 820 nm) and oxygen (760 nm) in the atmospheres of terrestrial planets as listed in Table 4-1. The water vapor filter at 940 nm is desired but not required.

<table>
<thead>
<tr>
<th>Species</th>
<th>nm</th>
<th>R (%)</th>
<th>Comment (depth/utility)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O3</td>
<td>590</td>
<td>15</td>
<td>oxygen surrogate, weak and broad</td>
</tr>
<tr>
<td>H2O</td>
<td>725</td>
<td>25</td>
<td>~0.12 depth for 1000ppm T=300K</td>
</tr>
<tr>
<td>O2</td>
<td>760</td>
<td>80</td>
<td>A band, narrow and deep</td>
</tr>
<tr>
<td>H2O</td>
<td>820</td>
<td>20</td>
<td>~0.12 depth for 1000ppm T=300K</td>
</tr>
<tr>
<td>H2O</td>
<td>940</td>
<td>20</td>
<td>~0.40 depth for 1000ppm T=300K, IWA for terrestrial planets may be challenging at this $\lambda$</td>
</tr>
<tr>
<td>Continuum</td>
<td>TBD</td>
<td>10—20</td>
<td>Needed to measure broadband colors and absorption depths</td>
</tr>
</tbody>
</table>

An Earth-like planet in a 1 AU orbit around a sun-like star at a distance of 5 pc is expected to have a flux level of $2.2E-8$ Jy (V=28.0 mag). This is a V-band contrast level of approximately 24.9 mag with the planet having a maximum separation of 200 mas from its star. The effects of our own zodiacal dust and a modest amount of exozodiacal dust ($\sim1$ zodi) are significant and must be included when modeling PECO performance on small (Earth-like and super-Earth) planets in or near habitable zones.
We expect that PECO shall be able to detect Earth-like (Earth albedo and 1 R⊕radius) and Super-Earth planets in the habitable zones (1 AU equivalent flux) of the stars listed in Table 4-2 and 4-3 within 2.2 x 104 seconds (6 hours of integration time for 20% of all possible observations (i.e., including all possible IWA values). This integration time (t_20% in tables) is calculated for SNR=5 for an effective filter centered at 550 nm with a 100 nm (R=5.5) bandpass and includes the effects of zodiacal light and exozodiacal light equal to that of our own solar system’s zodiacal light using the simulation code of Guyon et al. (2006). The optical throughput (not including the PIAA) times the quantum efficiency is assumed to be 0.45. SNR values in the tables are for 1 s integration times at planetary quadrature. The 7 Earth-like planets and 20 Super-Earths in Tables 4-2 and 4-3 change to 4 and 21 respectively if the planets’ orbital radii are allowed to increase to 1.8 AU equivalents. The drop off in sensitivity to small planets at larger distances from their host stars demonstrates the importance of PECO having a small IWA and an efficient optical train. The similar numbers of super-Earths is caused by some at greater distances from their stars having greater angular separations, IWA > ~2λ/D.

### Table 4-2: Stars with Earth-like planets in habitable zones (1 AU equiv) easily detectable with PECO

<table>
<thead>
<tr>
<th>HIP#</th>
<th>dist (pc)</th>
<th>max el (λ/D)</th>
<th>*rad (λ/D)</th>
<th>SNR (1s, tp)</th>
<th>t20% (s, tp)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>71683</td>
<td>1.3</td>
<td>11.5</td>
<td>0.06</td>
<td>0.49</td>
<td>35</td>
<td>Alf Cen A G2 V, V=0</td>
</tr>
<tr>
<td>71681</td>
<td>1.3</td>
<td>6.6</td>
<td>0.04</td>
<td>0.45</td>
<td>44</td>
<td>Alf Cen B K2 IV, V=1.3</td>
</tr>
<tr>
<td>8102</td>
<td>3.6</td>
<td>2.3</td>
<td>0.01</td>
<td>0.08</td>
<td>2750</td>
<td>Tau Cet G8.5 V, V=3.5 **</td>
</tr>
<tr>
<td>16537</td>
<td>3.2</td>
<td>2.2</td>
<td>0.01</td>
<td>0.09</td>
<td>2968</td>
<td>Eps Eri K2 V, V=3.7 **</td>
</tr>
<tr>
<td>3821</td>
<td>6.0</td>
<td>2.3</td>
<td>0.01</td>
<td>0.04</td>
<td>14329</td>
<td>Eta Cas G0 V, V=3.5 ***</td>
</tr>
<tr>
<td>2021</td>
<td>7.5</td>
<td>3.1</td>
<td>0.01</td>
<td>0.03</td>
<td>14878</td>
<td>Bet Hyi G0 V, V=2.8</td>
</tr>
<tr>
<td>99240</td>
<td>6.1</td>
<td>2.2</td>
<td>0.01</td>
<td>0.03</td>
<td>19636</td>
<td>Del Pav G8 IV, V=3.6</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>HIP#</th>
<th>dist (pc)</th>
<th>max el (λ/D)</th>
<th>*rad (λ/D)</th>
<th>SNR (1s, tp)</th>
<th>t20% (s, tp)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>71683</td>
<td>1.35</td>
<td>11.48</td>
<td>0.06</td>
<td>1.16</td>
<td>7</td>
<td>Alf Cen A G2 V, V=0</td>
</tr>
<tr>
<td>71681</td>
<td>1.35</td>
<td>6.57</td>
<td>0.04</td>
<td>1.08</td>
<td>9</td>
<td>Alf Cen B K2 IV, V=1.3</td>
</tr>
<tr>
<td>8102</td>
<td>3.65</td>
<td>2.30</td>
<td>0.01</td>
<td>0.25</td>
<td>328</td>
<td>Tau Cet G8.5 V, V=3.5 **</td>
</tr>
<tr>
<td>16537</td>
<td>3.22</td>
<td>2.19</td>
<td>0.01</td>
<td>0.26</td>
<td>338</td>
<td>Eps Eri K2 V, V=3.7 **</td>
</tr>
<tr>
<td>2021</td>
<td>7.47</td>
<td>3.08</td>
<td>0.01</td>
<td>0.10</td>
<td>1248</td>
<td>Bet Hyi G0 V, V=2.8</td>
</tr>
<tr>
<td>3821</td>
<td>5.95</td>
<td>2.29</td>
<td>0.01</td>
<td>0.12</td>
<td>1286</td>
<td>Eta Cas G0 V, V=3.5 ***</td>
</tr>
<tr>
<td>99240</td>
<td>6.11</td>
<td>2.25</td>
<td>0.01</td>
<td>0.11</td>
<td>1743</td>
<td>Del Pav G8 IV, V=3.6</td>
</tr>
<tr>
<td>22449</td>
<td>8.03</td>
<td>2.57</td>
<td>0.01</td>
<td>0.09</td>
<td>2310</td>
<td>Pi3 Ori, F6 V, V=3.2</td>
</tr>
<tr>
<td>88601</td>
<td>5.09</td>
<td>1.88</td>
<td>0.01</td>
<td>0.09</td>
<td>3114</td>
<td>V* 70 Oph, K0 V, V=4.0 ***</td>
</tr>
<tr>
<td>86974</td>
<td>8.40</td>
<td>2.39</td>
<td>0.01</td>
<td>0.07</td>
<td>3820</td>
<td>Mu Her, G5 IV, V=3.4</td>
</tr>
<tr>
<td>81693</td>
<td>10.80</td>
<td>3.11</td>
<td>0.01</td>
<td>0.05</td>
<td>4240</td>
<td>Zet Her, G0 IV, V=2.9 ***</td>
</tr>
<tr>
<td>61941</td>
<td>11.83</td>
<td>3.15</td>
<td>0.01</td>
<td>0.04</td>
<td>5545</td>
<td>Gam Vir, F0 V, V=3.6 ***</td>
</tr>
<tr>
<td>77952</td>
<td>12.31</td>
<td>3.03</td>
<td>0.01</td>
<td>0.04</td>
<td>6880</td>
<td>Bet TrA, F1 V, V=2.9</td>
</tr>
<tr>
<td>108870</td>
<td>3.63</td>
<td>1.50</td>
<td>0.01</td>
<td>0.06</td>
<td>7719</td>
<td>Eps Ind, K4 V, V=4.7 ***</td>
</tr>
<tr>
<td>27072</td>
<td>8.97</td>
<td>2.14</td>
<td>0.01</td>
<td>0.05</td>
<td>7786</td>
<td>Gam Lep, F6.5 V, V=3.6</td>
</tr>
<tr>
<td>19849</td>
<td>5.04</td>
<td>1.54</td>
<td>0.01</td>
<td>0.04</td>
<td>13513</td>
<td>V* DY Eri , K0.5 V, V=4.4</td>
</tr>
</tbody>
</table>
Detecting O₃, H₂O, and O₂ in the atmospheres of terrestrial planets will be possible for those orbiting the nearest stars. The H₂O and O₃ features are broad and shallow (~10% deep; Fig. 4-1 and Table 4-1), requiring SNR ~ 30 on the continuum for detection. This would require 100 times the integration times in Tables 4-2 and 4-3, still reasonable (~1 day or less) for characterizing Earths or Super-Earths found around the nearest 4 – 12 stars. It is important that PECO systematic noise be low over this duration of integration time. The following requirements are distilled from this discussion:

**SCIREQ11:** PECO shall be able to detect earth-like or super-Earth planets 1-1.8 AU from their stars over a distance range of 1.35 - 6 pc. This translates to an IWA of 167 mas and an outer working angle (OWA) of 1.33 arc-seconds, corresponding to 2 λ/D and 16.5 λ/D, respectively, for a D = 1.4-m telescope diameter and λ = 550 nm wavelength. This should be sufficient to observe planets 1 – 1.8 AU from most or all stars in Tables 4-2 and 4-3.

**SCIREQ12:** PECO shall be able to detect H₂O, O₂, or O₃ in the atmosphere of a Super-Earth planet 1 AU from a sun-like star at 5 pc distance. Detection is defined as the ability to measure the a 10% deep, R~10-20 H₂O or O₂ feature with SNR=3 (SNR = 30 on continuum). A similar continuum SNR is required for the much deeper but much more narrow O₂ feature at 760 nm wavelength. PECO must have a sufficiently small IWA to make these measurements out to 760 nm (and it barely does). PECO must be able to perform these measurements for super-Earth planets in the habitable zones of at least 6 nearby stars.

**SCIREQ13:** PECO shall be able to measure the continuum flux level between H₂O, O₂, and O₃ absorption bands of a Super-Earth planet 1 AU from a sun-like star at 5 pc distance to within 3% precision (1 sigma) at three widely spaced spectral intervals. This is important for measuring absorptions and constraining planet colors. The continuum flux level may be computed by assuming a geometric albedo of 0.2.

**SCIREQ14:** PECO shall constrain the positions and orbits of planets in or near the habitable zones of nearby stars. It would be useful to constrain the projected position of a detected (SNR > 5) planet to approximately 0.3 AU at a distance of 10 pc and 0.1 AU at a distance of 3 pc, corresponding to an astrometric precision of 30 mas.

Small planets found in or near habitable zones will be studied repeatedly with PECO. These observations will likely include short term monitoring for variation with rotation and longer term monitoring for seasonal effects (perhaps snow) and phase effects in
atmospheric scattering. Such monitoring will be included in the PECO Design Reference Mission document.

5 Debris disks and exozodiacal dust

Disks of circumstellar material are both the progenitors, and outcomes, of the processes of planet formation and planetary system evolution. While there has been enormous progress in developing testable theories of these processes over the past quarter century, the specific interplay between planets and circumstellar disks is still very uncertain. This is primarily because there has been a paucity of exoplanetary/debris systems identified with both components detectable with currently implemented imaging technologies. Hundreds of sun-like stars have been found to exhibit excess IR emission attributable to dusty circumstellar debris, but in the vast majority of these systems, the dust remains spatially unresolved (Meyer et al. 2008) and undetected in scattered-light. In all but a very few of these IR bright disk-bearing systems, embedded planets have eluded direct detection with the very recent and notable exceptions of EGPs orbiting Fomalhaut (Kalas et al 2007), perhaps Beta Pictoris (Lagrange et al 2008; second epoch confirmation pending, and HR 8799 (Marios et al 2008; but its disk remains unimaged) far beyond their ice-lines. For the remainder, dust temperatures and covering fractions are estimated from long wavelength spectral energy distributions (SEDs), but the inferred locations of the thermally emissive star-orbiting dust depends upon the properties assumed for the particles (Backman & Paresce 1993). Reasonable ranges of particle sizes and compositions result in models for the dust-producing planetesimals that vary by an order of magnitude (or more) in orbital radius and total dust mass (e.g., Fig. 5 in Hines et al. 2006). High-resolution scattered-light images of debris disks with dust density distributions comparable to our own solar system and in their habitable zones will reveal the morphology of solar system analog disks and trace the location of the dust-producing planetesimals.

Terrestrial temperature circumstellar debris, while likely relatively common (est. > 20%) around young stars (e.g., Siegler et al. 2007), appears to be rare overall (Beichman et al. 2006). This may be a consequence of dust depletion during terrestrial planet formation, but is predicated largely on interpretation of thermal SEDs unconstrained by images otherwise informing on the spatial distribution of light-scattering dust. A simplistic assumption of large (blackbody) grains in radiative equilibrium with the stellar radiation field leads to dust temperatures derived from thermal SEDs indicating that 10–20% of main sequence stars have planetesimal belts with large inner holes (20–80 AU), i.e., massive analogues of our Kuiper belt; but this conclusion is largely untested observationally. The need for spatially resolved imaging of disks is clear. Combined with IR SEDs (e.g., from IRAS, Spitzer, and JWST), such images place very tight constraints on the composition, mass, and physical properties of the dust particles (e.g., Schneider et al. 2006).

Dynamical interactions of planets with residual planetesimal belts likely play a vital role in the architectures of planetary systems. Kenyon & Bromley (2004b) have shown that recently formed terrestrial planets can generate copious quantities of dust in the early phases of planetary system formation. In our own solar system, Jupiter is thought to have
wrought considerable destruction in the early evolution of the asteroid belt (Bottke et al. 2005). Concomitantly, volatile-rich planetesimals scattered towards our inner solar system may have contributed significantly to terrestrial water abundance, possibly affecting (contributing to) the habitability of the early Earth (Raymond et al. 2004). The Nice Model (Tsiganis et al. 2005; Morbidelli et al. 2005) for the dynamical re-arrangement of the solar system self-consistently explains: a) the migration of the outer planets; b) an order of magnitude increase in the depletion of dust-producing planetesimals in both the asteroid and Kuiper Belts; and c) evidence for a period of Late-Heavy Bombardment in the lunar cratering record (Strom et al. 2005). High-resolution spatial mapping of the dusty circumstellar debris in exoplanetary systems, enabled by PECO, is needed to test the generic applicability of such models in planetary systems other than our own.

Currently deployed "high contrast" imaging technologies can detect only the largest, most massive (and brightest) circumstellar disks, and cannot effectively probe their innermost regions. The (few) images obtained to date have provided crucial insights into the formation, evolution, and architectures of exoplanetary systems; but they are just the tip of the iceberg waiting to be fully revealed. The existing sparse sample of debris disks imaged with scattered starlight represents only the youngest (10–100 Myr), or extremely anomalous, disk systems around older stars. A new observational facility - PECO - is required to advance the field. Several fundamental issues associated with dusty disks will be addressed with PECO observations:

- What is the amount and distribution of circumstellar dust around the stars in the solar neighborhood? How is dust distributed in their habitable zones and how does this impact direct planet detection?
- Are there dynamical structures visible in the circumstellar disks of nearby stars, and what can we learn about unseen planets from zones of different material or disk gaps?
- What are the physical properties of the exozodiacal debris material; what are the grain properties and distributions?

We now explore these issues and how PECO observations will address them.

5.1 Planetary debris systems comparable to our own Solar System

Results from Spitzer suggest the possibility that most stars could have debris disks similar to our own solar system’s (Bryden et al. 2006). Debris disks are the analogs of our solar system’s zodiacal dust cloud, asteroid and Kuiper belts and provide great insight into planetary formation, composition, and architectures. A circumstellar debris system with a surface density of light-scattering particles similar to that our own solar system’s around a solar analog star at 10 pc would have a 0.6 micron brightness of ~ 2x10^-6 Jy compared to ~ 47 Jy for the central star; well within the reach of PECO’s ~ 1010 starlight suppression. Direct images in scattered light of debris disks around a sample of 100 or more nearby FGK dwarfs will reveal the frequency, amount, properties, and distribution of solar-like debris disks and their constituent materials. PECO will provide the capability of ascertaining the Spitzer-suggested prevalence of debris disks with multi-wavelength (0.4 - 0.8 micron)
direct images enabling the correlation of their properties with stellar type and environment inclusive of co-orbiting planets. Importantly, the bulk scattering properties of the disk grains, as a function of wavelength and polarization, provides robust constraints on particle size and composition. Such spatially resolved images enable self-consistent modeling of disk geometry and total mass when combined with thermal SEDs (e.g., Schneider et al. 2006). This synergistic capability, extensible by PECO to the full range of debris disk systems catalogued by Spitzer, will enable us to break degeneracies between disk geometries/morphologies and SEDs (see Fig 5-1) and to determine, for the first time, accurate disk properties as functions stellar mass and age (on the ensemble), as well as a dependencies of disk properties on stellar metallicity, stellar rotation, and other stellar parameters.

**Figure 5-1:** Disk geometries and morphologies cannot be determined from thermal IR excesses alone. Small grains radiate less efficiently than large grains. Therefore, at a given equilibrium temperature, small grains reside farther from their central stars. E.g., IR excesses measured by IRAS (squares) and Spitzer (dots) for the dominant grain populations around HD 181327 and HD 61005 with very similar SEDS indicate similar temperatures, but drastically different disk morphologies are revealed with scattered light imaging (HST/NICMOS; Schneider et al 2006, Hines 2007).

A sensitive scattered light disk census will also enable us to address why some disks are bright in optical scattered light, while others appear faint (Wyatt 2007). In the prototypical example of Vega, the relatively large mass-loss rate, estimated at two Earth masses per Myr for its small grain population (Su et al. 2005), should produce a bright visible scattered light signature; but none has so far been found with currently available technology. The
short timescale for the retention of such small grains within the Vega system implies that the population must be stochastic and suggests transient dust originating in recent collisions. Such events are thought to have occurred within our own solar system; e.g., the creation of the Earth-Moon system, the retrograde rotation of Venus, and the obliquity of Uranus (e.g., Canup & Asphaug 2001). The fact that the small grains in the Vega system are not (yet) seen in scattered light is informing us about the optical properties of the small grains. This in turn provides clues to their origin. There are many systems with IR-identified circumstellar debris, but which are beyond the imaging capabilities of current instrumentation. A large increase in sensitivity to light-scattering circumstellar debris provided is needed to place strong constraints on systemic dust mass-loss rates, and observationally test models of dust production throughout the epochs of planet formation, and their subsequent dynamical evolution.

5.1.1 Mapping circumstellar dust distributions into Habitable Zones

Until recently, the inner 20 AU of many IR-identified debris systems was thought to be relatively devoid of dust. However, it is now known from near-IR interferometric (di Folco et al. 2007) and mid-IR photometric (e.g., Stapelfeldt et al. 2004; Wyatt et al. 2005) detections that at least some such systems must possess dust in close proximity to their central stars (e.g., Beichman et al. 2005; Song et al. 2005; Hines et al. 2006). The origin of this hot dust remains uncertain and its detection is beyond the imaging capabilities of existing coronagraphs, but the rapid dust depletion timescales at these orbital distances imply that the grains must be transient in nature (Wyatt et al. 2007). It is also not yet known whether this dust originates in planetesimals that have been scattered through some kind of systemic (possibly extrinsic) instability, or from recent collisions between massive protoplanets. Spatially resolved imaging with small PECO-like IWAs with sensitivity to ~ 1 zodi of circumstellar dust can arbitrate these possibilities.

5.2 Dynamical structures in circumstellar disks

It has now been demonstrated that spatially resolved images of debris disks can be used to infer the presence, and constrain the locations, of unseen planets as dynamical theories have predicted. The presence of an EGP orbiting interior to inner edge of the Fomalhaut dust ring (Kalas et al. 2005) was suggested from the ring’s stellocentric offset and very steeply rising radial surface brightness profile at the inner edge of the ring – and later a ~ 3 Mjup planet was later found (Kalas et al. 2007) orbiting where theory had suggested. High resolution high contrast images of low surface-brightness sub-structures within other planetary debris disks circumscribing nearby stars will likely reveal the radial locations of the planetesimal belts in these systems—a powerful indicator of the outcome of planet formation processes. In our own solar system, the planetesimal asteroid and Kuiper belts respectively reside within, and exterior to, the planetary orbital zones (0.3 – 40 AU) in the only regions that are dynamically stable on the timescale of the age of the Solar System (4.5 Gy). Sensitive imagery of extrasolar planetary debris systems, as solar system analogs, will not only elucidate where planetesimals have grown and populate their circumstellar environments, but also locate “gaps” (regions devoid of light-scattering dust) that may reveal the locations of unseen planets (see Fig. 5-2).
The majority of the 17 debris disks that have been imaged to date with existing coronagraphic technologies\(^1\) exhibit non-axisymmetric features including: photocentric offsets (Kalas et al. 2005), warps (Heap et al. 2000), clumps (Holland et al. 1998; Greaves et al. 1998), spirality (Clampin et al. 2003), brightness asymmetries (Telesco et al. 2000; Kalas et al. 2007), and non-coplanar features (Golimowski et al. 2006). These are exactly the morphological features that are predicted to arise in debris disks perturbed by currently undetectable co-orbiting planets (Wyatt et al. 1999; Augereau et al. 2001; Kuchner & Holman 2003; Wyatt 2003; Wyatt 2005b; Wolf, Moro-Martin & D'Angelo 2007). Several of these disks are shown in Figure 5-3. Dynamical modeling of disk sub-structures, observable uniquely with PECO, will be used to set constraints on planetary masses, orbital eccentricities and evolutionary history; and deduce the existence of planets not directly detected. Even in the absence of non-axisymmetric structure, as in the case of Fomalhaut, the shape and location of an inner edge of a debris belt constrains the mass of a perturbing planet (Kalas et al. 2005; Quillen 2006).

High sensitivity, high resolution scattered light disk images are needed to test specific dynamical models of systems that are a priori known to have both giant planets (found by

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\(^1\) The objects so far observed are the “low hanging fruit” with L\(_d\)/L\(\ast\) ≥ 10\(^{-4}\) that have been accessible with HST’s limited coronagraphic image contrasts and IWAs for disk grains optically scattering and thermally radiating with near-equal efficiency.
radial velocity studies) and substantial dusty debris (found by their thermal infrared emission). Spatially resolved visible light images will also trace small dust grains that are indicative of transient phenomenon such as recent collisions between massive protoplanets. For example, the exceptionally bright Beta Pic (see Figure 5-4) and AU Mic debris disks both extend to several hundred AU at visible wavelengths (Kalas & Jewitt 1995; Kalas et al. 2004) while their thermal IR emission is dominated by dust much closer to the stars at 30–70 AU.

**Figure 5-3:** Four of the 17 brightest debris disks imaged with HST from 104 targets attempted. These NICMOS (1.1μm) PSF-subtracted coronagraphic images represent HST's smallest coronagraphic inner working angle of 3.2 λ/D (0.3″). PECO will image disks ~1E5 times fainter in contrast, and 2.3x closer in distance to their central stars, at spatial resolutions 3x better then the best that JWST will deliver. Debris Disks (from left): Vega analogs HR 4796A (A0V, 8 My) and HD 33297 (A0; 10 Myr), older and lower stellar mass HD 181327 (F5.5V; 30 My) and HD 107146 (G2V; 100 Myr).

Conversely, the thermal IR emission and light scattered by dust orbiting HR 4796A (a very close analog to Beta Pic), is spatially coincident in a narrow debris ring circumscribing the star at 70 AU (Jayawardhana et al. 1998, Koerner et al 1998; Schneider et al. 1999). These seemingly contradictory observations are explained for Beta Pic and Au Mic by models in which dust is created in collisions within planetesimal belts at 30-70AU (Augereau et al. 2001; Strubbe & Chiang 2005). Larger grains are near the star and warm (thus IR detected), while micron size dust grains acted upon by radiation pressure are pushed into highly elliptical orbits (thus colder, but detectable as they scatter shorter wavelength starlight) and sub-micron grains are expelled from the systems. Dynamical mechanisms such as dust confinement by (yet unseen) shepherding planetesimals have been suggested for HR 4796A (Schneider et al. 1999); but in all cases, the models remain quite uncertain.

Starlight-scattered debris disk imaging also enables probing into a unique region of planet-populating msin(i)-vs.-orbit radius parameter space not covered by radial velocity surveys. Debris disks are the extrasolar counterparts of our solar system's asteroid and Kuiper belts, and the planets that have thus-far been inferred from the few currently observable disks are analogs to Neptune (see Figure 5-5).
Figure 5-4: Left: Four basic resonant structures induced by a planet within a circumstellar disk (I: low mass, low eccentricity, II: high mass, low eccentricity, III: low mass, moderate eccentricity, IV: high mass, moderate eccentricity). Right: HST/ACS observations (Golimowski et al., 2006) of the Beta Pic disk showing a second, inclined, disk posited to be sustained by a co-orbital planet prior to the recent putitive imaging detection of a close-in planet by Lagrange et al. 2008. These images accentuate the sharply-peaked midplane of the disk and support the notion that the inner warp is a secondary disk, distinct from the main outer disk and inclined from it by ~5°. A circular mask of radius ~30 AU has been imposed on the innermost region of the disk to reduce confusion from PSF-subtraction residuals.
**Figure 5-5:** Planet detections by radial velocity surveys (+) are observationally constrained to the mass/distance domain in the grey region. Massive planets inferred from dynamical modeling of currently observable disk sub-structures with spatially resolved imaging (•), compared to the planets in our own solar system, are the tip of the sub-Neptune mass exoplanetary menagerie awaiting PECO scattered-light imagery.

### 5.3 Characterizing debris in exoplanetary systems with multi-color imaging and spatially-resolved polarimetry

Though spatial information is a key to achieving many disk science goals, multi-color imaging and polarimetry provides a wealth of additional information regarding the composition and size of starlight scattering dust grains. For an optically thin medium (e.g., the dust in a debris disk) and given scattering phase angle, the efficiency (brightness) of the starlight scattered along the line-of-sight is color (wavelength) dependent and, within parametric constraints, correlated with grain size. So multi-wavelength images place strong constraints on particle sizes as a function of position in the disk (see Figure 5-6).

**Figure 5-6:** Light-scattering models predict significant differentiation in observationally derivable parameters; e.g., opacity (κ), albedo (ω), scattering phase efficiency (g=<cos>; g=0 for isotropic scattering, g=1 for completely forward scattering), and polarization fraction (P) with dependence on grain properties and distributions: ISM [solid], Cotera et al. 2001 [dotted], Wood et al. 2002 [dashed]). Blue and red lines indicate the PECO 0.4 and 0.8 micron bands.
Additionally, the polarization as a function of azimuth angle is also a strong function of the particle size (Fig. 5-7), so images of the polarized light will place strong constraints on particle size as a function of position in the disk. (PECO’s polarimetry mode is unique given that polarimetry is not planned for any future NASA missions, such as JWST, with comparable target lists).

**Figure 5-7:** Polarization as a function of azimuth (scattering phase) angle and particle sizes \((x = 2pa/l, a \text{ is the grain radius})\) for Mie scattering in a centrally illuminated optically thin disk. Fractional polarization is a strong function of azimuth, which places strong constraints on particle sized, easily distinguishes large grains \((x=5)\) from small grains \((x=1)\). Deviations from simple spherical grains can be diagnosed when grain size can be independently estimated.

With spatially resolved multi-color imaging and spatially resolved polarimetry, we will determine and/or constrain the intrinsic properties of the disk systems (e.g., vertical height distributions, inclinations) through modeling, which in turn informs (or constrains) dynamical interactions with planets. This information, combined with existing longer wavelength SEDs, further enables us to assess dust grain albedos, density distributions and total dust masses. Without the imaging information, these geometrical and physical properties that are the keys to understanding disk evolution leading to planetary system formation, cannot be determined uniquely using SEDs alone due to degeneracies between disk geometries and grain properties (e.g., see Fig 5 in Hines et al. 2006). We have demonstrated this method of approach in modeling HST observations of the classical T Tauri star GM Aurigae (Schneider et al. 2003), and more recently as applied to the discovery imaging of the HD 181327 circumstellar debris ring (Schneider et al. 2006), but using only two, and three, spectral bands, respectively. By extension thanks to its scattered-
light detection sensitivity, PECO imaging will allow the physical characterization of extrasolar circumstellar planetary debris systems directly analogous to our own solar system (optical depth $\tau_{\text{dust}} \sim 10^{-7}$).

5.4 PECO Observations

PECO starlight-suppression will achieve disk-imaging contrasts of 10-9 to 10-10 beyond a 130 mas IWA (at 0.4 microns), an increase of $\sim$ 5 to 6 orders of magnitude in contrast beyond what HST and ground-based 6–10 m telescopes with adaptive optics can provide. JWST will have contrast-limited performance no better than HST. The PECO IWA and spatial resolution is similar to what the Large Binocular Telescope Interferometer (LBT-I) will provide at 11 microns, enabling a comparison of circumstellar dust in scattered light and thermal IR emission at unprecedented spatial resolution. PECO will also be at least 10 times as sensitive to interstellar dust in habitable zones as LBT-I. This high sensitivity to light-scattering circumstellar debris at the PECO IWA will provide strong constraints on systemic dust mass-loss rates, and observationally test models of dust production throughout the epochs of planet formation, and their subsequent dynamical evolution.

PECO will be capable of providing the first direct images in scattered light of debris disks (the analogs of our solar system’s zodiacal dust cloud, asteroid and Kuiper belts) around a large sample of nearby FGK stars. The disk sizes will likely vary from unresolved (interior to the PECO IWA) to much more than 10 arc-seconds from some stars (e.g., the very large disk circumscribing Fomalhaut).

PECO imagery will probe far interior to the Kuiper belt regions circumscribing nearby stars, into the now-elusive terrestrial planet and habitable zones in dusty planetary systems, providing evidence for asteroid belts, comets and unseen planets. PECO’s 130 mas (0.4 micron) IWA will probe inside 4 AU for stars within 31 pc, including all 200 of the baseline giant planet sample (SCIREQ7), and within 1 AU for stars closer than 8 pc, providing the capability of imaging regions comparable to the locations of the terrestrial planets in our solar system. We will probe for dust in the Habitable Zones (e.g., Kasting et al. 1993) of 50 nearby stars, where the temperature allows the presence of liquid water, which is considered a vital ingredient for life.

PECO's short-wavelength 72 mas spatial resolution (e.g., 0.36 AU at 5 pc) will enable detailed spatial mapping of high contrast (low surface brightness) dust distributions to test and constrain predictive models of disk structures. PECO will provide the first imaging data sets to test specific dynamical models of systems that are apriori known to have both giant planets (found by radial velocity studies) and substantial dusty debris (found by their thermal infrared emission). PECO’s spatially resolved visible light images will also trace small dust grains that are indicative of transient phenomenon such as recent collisions between massive protoplanets.

Starlight-scattered debris disk imaging with PECO enables probing into a unique region of planet-populating $\text{msin}(i)$-vs.-orbit radius parameter space not covered by radial velocity surveys. Debris disks are the extrasolar counterparts of our solar system’s asteroid and Kuiper belts, and the planets that have thus-far been inferred from the few currently observable disks are analogs to Neptune. PECO’s extraordinary image contrast...
improvement over other space stellar coronagraphs will not only vastly increase the complement of Neptune-analogues discovered via direct imaging, but will enable studying their dynamical influences on co-orbital debris disks.

Multi-wavelength PECO imaging and polarimetry will allow the physical characterization of extrasolar circumstellar planetary debris systems directly analogous to our own solar system. In addition to determining grain size and opacity information from continuum colors, PECO observations of circumstellar disks in molecular band filters may show evidence of H2O or CH4 ices.

We adopt the following debris disk science requirements for PECO after considering the above discussion:

**SCIREQ15:** Prevalence of low density debris disks. PECO shall be capable of detecting the integrated surface flux of 10 zodi circumstellar disks inclined 59 degrees around 50 (minimum) to 100 (baseline) stars within 31 pc observed in the giant planet survey (SCIREQ 7). Detection is defined as 5 times the noise spatially integrated over the PECO field in a single R ~ 5 PECO channel with a center at 550 nm.

**SCIREQ16:** Resolving disks of the nearest stars. PECO shall be capable of detecting spatially resolved 1 zodi disks around 5 nearby stars and 5 zodi disks (all 59 deg inclinations) around 20 nearby stars down to their habitable zones. Here detection is defined as a flux measurement at least 10 times the noise level per resolution element in a R~5 PECO channel centered at 550 nm. Structures (rings, gaps, clumps, voids) 0.5 AU in size must be resolved at a distance of 5 pc (equivalent to 1 AU at 10pc, requiring 100 mas resolution). The 1 zodi star sample can be identical to that searched for Earth-like planets (Table 4-2) and the 5 zodi sample can be identical to that searched for Super_Earths (Table 4-3).

**SCIREQ17:** Extent of disks and planet-disk interactions. PECO shall be able to image disks out to a radius of at least 2.5 AU at a distance of 1.3 pc (10 AU at 5 pc) in order to study the outer regions of disks and observe the impact that seen or unseen planets have on disk structures. This corresponds to an outer working angle (OWA) of 1.9 arcseconds, equivalent to 24 l/D for a D = 1.4-m telescope and \( \lambda = 550 \) nm.

**SCIREQ18:** Dust in habitable zones. PECO shall be able to image disks to within 1 AU of stars out to a distance of 6 pc at 550 nm wavelength. This will include the closest 6 stars to search for Earth-like planets and super-Earths (see Tables 4-2 and 4-3). This requires an IWA < 167 mas and an aperture D > 1.36-m if IWA = 2 \( \lambda / D \).

**SCIREQ19:** Dust grain properties. PECO shall characterize and constrain the optical, physical, and compositional properties of circumstellar dust. R ~ 5 imaging data over the 400 – 800 nm range and polarimetric precision s s-P = 0.5% and s-q = 5 degrees per resolution element for sources with intrinsic polarization fractions of 0.01 or greater shall be sufficient for this task.
SCIREQ20: Discrimination of dust from planets. PECO shall be capable of distinguishing unresolved dust clumps from planets with multi-epoch (multi-phase) polarimetric data. The polarimetric precision requirements given in SCIREQ19 shall be sufficient for this task.

6 A “Grand Tour” of the planetary systems of nearby stars

PECO's unique combination of high contrast, high sensitivity, and small IWA will result in absolutely fantastic new observations of the planetary systems of nearby stars as detailed in the previous sections of this document. Here we illustrate what can be learned and discovered about these systems by showing simulations of PECO observations.

6.1 Simulations of PECO observations

We have used a high fidelity simulation code based on Guyon et al. (2006) to determine what PECO images of the planetary systems of nearby stars will look like. This code simulates the image of a chosen type of planet around nearby stars, and K. Cahoy has modified it to also simulate the images of model circumstellar disks (provided by G. Schneider) as observed by PECO. The code accounts for the effective temperatures and angular sizes of each star, residual scattered star light, and the local zodiacal light along the line of sight to each system. Model Stellar distances were determined from HIPPARCOS data. These simulations were done for an architecture that also includes an inverse PIAA with reimaging optics to produce Nyquist sampling (~38 mas per pixel at 550 nm wavelength), like the current PECO architecture. The model assumes a typical PECO throughput value of 0.45, consistent with the estimated product of surface transmission / reflectivity (0.98 on each of ~20 surfaces per band) and CCD QE (conventional devices, not deep depletion). Photon noise was added to the images, but the dark currents and other detector noise of the EM CCDs was not added; we estimate these noise terms to be insignificant for the relatively bright results shown here. Models of residual star light were subtracted from the images. Earth-like and Super-Earth (2 R⊕) planets were assigned effective albedos of 0.2, and Jupiter analog planets were assigned effective albedos of 0.5 and orbital distances of 5 AU. Habitable zones were scaled from 1 AU based on the luminosity of each host star, and all planets were assumed to be on circular orbits.

This code also estimated the integration times required to image planets and disks around the stars in this document (i.e., Tables 4-2, 4-3, and all objects and integration times noted in the text). The integration times produced by this code and in this document were computed for a random single detection probability of 20% in a λ = 550 nm filter that is 100 nm wide. Each planet would have a 90% detection probability if observed for its 20% probability integration time in 10 uncorrelated visits spanning its orbital period (p = 1 – (1-0.2)^N where N = 10 in this case). Tables 4-2 and 4-3 list the planets with Earth and super-Earth planets at 1 AU equivalent habitable zone distances (see previous paragraph) that have a 20% single observation integration time of 2E4 seconds or less.
6.2 Simulations of nearby planetary systems

The PECO simulation code described in section 6.1 was used to simulate images of the following hypothetical planetary systems to illustrate the scientific and discovery potentials of PECO:

- Sun at 3.3 pc with unseen embedded Earth at 3.3 AU producing resonant disk perturbations
- Inner ring structure of the disk around Eps Eri
- Alp Cen A with a 10 zodi disk and planets (Earth and Super-Earth)
- Sun at 10 pc with 1 zodi disk along with Earth and Jupiter planets

Figure 6-1 shows a simulation of 10,000 s (2.8 hrs) of PECO data showing the impact of an unseen Earth-like planet that is 3 AU from a Sun-like star in a 1 zodi face-on disk at a distance of 3.3 pc. A model provided by C. Stark is on the left and the simulated PECO observation is on the right. The disk dust grains have $b = 0.023$ (product of grain density in cgs and particle size in microns) and the images are at a central wavelength of $l = 550$ nm with a bandwidth $dl = 110$ nm. A field of 85 x 85 PECO pixels (about 3.2 x 3.2 arcseconds, 10.6 x 10.6 AU, or 40 x 40 l/D) is shown, slightly smaller than the expected corrected PECO field of 48 x 48 l/D (about 3.9 x 3.9 arcseconds or 13 x 13 AU). The model and PECO simulation both have approximately the same spatial scaling. The resonant perturbations induced in the disk by the Earth-mass planet can be seen clearly in this relatively short 1E4 second exposure.

Figure 6-2 shows the inner 3 AU radius dust ring the Eps Eri disk believed to be produced by collisions in its asteroid belt (Stapelfeldt private communication; Backman et al. 2009), analogous to the main asteroid belt in our own solar system. The ring is inclined 22 degrees, approximately co-planar with the larger Eps Eri debris disk (Kuiper belt analog). The ring was modeled by G. Schneider with a composition of rocky silicates, a width of 1 AU, and a total flux density of 1 zodi. The simulated PECO image is shown for a central wavelength of $l = 550$ nm with a bandwidth $dl = 110$ nm and an exposure time of 1E4 seconds. The field size is 85 x 85 PECO pixels (about 3.2 x 3.2 arcseconds, 10.2 x 10.2 AU, or 40 x 40 l/D) is shown, slightly smaller than the expected corrected PECO field of 48 x 48 l/D (about 3.9 x 3.9 arcseconds or 12.5 x 12.5 AU).

Alp Cen A is shown in Figure 6-3 with a 10 zodi circumstellar disk inclined 59 degrees and an Earth-like planet at 1 AU (~ 1HZ radius). This simulated PECO observation was generated for a central wavelength of $l = 600$ nm with a bandwidth $dl = 120$ nm ($R = 5$) and an exposure time of 1E4 seconds. Earth is easily detectable at good signal-to-noise even in the presence of a large amount of exozodiacal light in this image of SIZE 85 x 85 pixels or 4.3 x 4.3 AU (3.2 x 3.2 arcseconds or 40 x 40 l/D).

The left panel of Figure 6-4 is a simulated PECO image of the Sun at 10 pc with a 10 zodi disk and Jupiter at 5AU distance (left). The right panel is a simulated image of the Sun at 10 pc and with a 10 zodi disk with Earth at 1 AU distance. Each simulation was computed for
86,400 sec (10 days) integration time and disk inclinations of 59 degrees. Jupiter is easily seen at high signal-to-noise even in the presence of this very large amount of exozodiacal light. Earth is not detected because it is within the nominal PECO IWA and is dwarfed by the extreme disk flux at 1 AU from the star. A super-Earth could barely be detected at the same location and integration time with a 1 zodi disk. The field size is 85 x 85 pixels (about 3.2 x 3.2 arcseconds, 32 x 32 AU, or 40 x 40 l/D) is shown, slightly smaller than the corrected PECO field of 48 x 48 l/D (about 3.9 x 3.9 arcseconds or 39 x 39 AU).

We note that observed disk brightnesses are much lower for more distant stars because their surface brightness falls off steeply with radius (greater than r-2) and their innermost radii move within the PECO IWA as stellar distance increases.

Figure 6-1: Face-on disk model provided by C. Stark (left) and simulated 1E4 s PECO 550nm image (right) of the Sun at 3.3 pc with a 1 zodi disk with the Earth (unseen) embedded at a distance of 3 AU, with β=0.023.
Figure 6-2: Eps Eri ring simulation. The 3 AU radius ring was modeled by G. Schneider with a composition of rocky silicates, a width of 1 AU, inclined 22 degrees (same as its debris disk), and a total flux density of 1 zodi. Simulated for a central wavelength $\lambda = 550$ nm with a bandwidth $d\lambda = 110$ nm and an exposure time of $1E4$ seconds.

Figure 6-3: Alp Cen A with 10 zodi disk $i = 59$ deg with Earth (L) and Super-Earth (right), both 1 AU from the G2 V star and easily detectable in these $1E4$ second exposures.
**Figure 6-4**: Sun at 10 pc with a 10-zodi circumstellar disk and Jupiter (left) and with Earth (right), each 86,400 sec (10 days) integration time. The 10 zodi disk has inclination $i = 59$ degrees in each image. Jupiter is clearly visible at high signal-to-noise because it is far outside the IWA where the disk surface brightness is low. The Earth has disappeared within the IWA and is drowned by the disk flux.

### 7 Requirements Summary
We now collect and summarize the performance requirements needed to enable the above PECO observations and science goals as detailed in sections 2 – 5 of this document. We also comment on some implications of these requirements and then present a requirements summary table.

#### 7.1 Extrasolar Giant Planets

**SCIREQ1**: PECO shall be able to measure the absolute brightness (flux) of a Jupiter-twin planet at 10 pc in at least one bandpass to within 10% (OK to calibrate with ground-based or other non-PECO data). This is intended to ensure that PECO shall be capable of making high precision measurements of the fluxes of at least several Jovian planets for constraining albedos and sizes. There are at least 20 FGK stars within 10 pc, so PECO could detect 3 Jupiters if the probability of finding a Jupiter around each star is 0.15. There are also 3 stars with known RV planets within 10 AU that have maximum elongations of 160 mas or greater. Therefore precise flux measurements to 10 pc are required.

**SCIREQ2**: PECO shall be able to measure the relative flux of a Jupiter-twin at 10 pc in at least three broad (R~5) spectral bands spanning at least 450 – 800 nm (goal 400 – 860 nm) wavelength with a precision of 5% or better. This is intended to ensure that PECO shall be able to make high precision measurements of the colors of at least
several Jovian planets over the wavelength range of key absorption features (see Fig. 3-3 and SCIREQ1).

**SCIREQ3:** PECO shall be able to detect CH4 in the atmosphere of a Jupiter twin planet at 10 pc. Detection is defined as the ability to measure the depth of the 650 nm CH4 band absorption (assumed to be 20% deep and R= 20 wide) at SNR = 3 (floor) – 6 (baseline).

**SCIREQ4:** PECO shall be able to measure the continuum flux level between CH4 absorption bands of a Jupiter twin at 10 pc to within 3% (baseline; SNR = 30) - 10% (minimum; SNR = 10) precision at three widely spaced spectral intervals. This is needed to measure scattering and albedo. Systematic noise must not limit signal-to-noise below these levels. The continuum flux level may be computed by assuming a geometric albedo of 0.5.

**SCIREQ5:** PECO shall be able to detect a 20% deep H2O band at 830 nm (R = 20 width) in the atmosphere of a Jupiter twin at 10 pc with SNR = 3 (floor) – 6 (baseline). This requires continuum SNR = 15 (floor) – 30 (baseline). Alternatively, the 725 nm band of H2O may be considered as a minimum requirement if the baseline 830 nm one is unobservable. H2O and methane measurements are needed to derive temperatures and constrain abundances. PECO shall also be able to measure the 450 – 510 nm blue band with identical SNR, with a goal of measuring the 400 nm absorption band in hot EGPs (Fig 3-3).

**SCIREQ6:** PECO shall be able to detect giant planets 3.3 AU from their stars over a distance range of 3 - 20 pc. This translates to an IWA of 165 mas and an outer working angle (OWA) of 1.1 arc-seconds, corresponding to 2 λ/D and 14 λ/D, respectively, for a D = 1.4-m telescope diameter and λ = 550 nm wavelength. This should be sufficient to observe most or all RV planets in Table 3-2. A larger OWA is desirable for observing the closest stars; 1.9 arcseconds (24 λ/D) would allow imaging a Cen A/B out to 2.5 AU radius.

**SCIREQ7:** PECO must be capable of searching 100 (minimum) – 200 (baseline) stars for EGPs and be capable of detecting Jupiter twin planets around each star outside of the PECO IWA at wavelengths of at least 550 nm. PECO must be capable of characterizing the spectral features (SCIREQ3-5) of at least 5 known RV planets (10 goal).

Note: A Jupiter-like planet in a 5 AU orbit around a sun-like star at a distance of 10 pc is expected to have a flux level of 4.7E-8 Jy (V=27.2 mag). This is a V-band contrast level of approximately 22.5 mag with the planet having a maximum separation of 500 mas from its star. Detecting such a planet should be relatively insensitive to low levels (~ 1-10 zodi) of exozodiacal dust because of its relatively high brightness and its relatively large distance from its star.
7.2 Terrestrial planets near habitable zones

**SCIREQ8**: PECO shall be able to measure the absolute brightness (flux) of a super-Earth planet (Earth albedo and 2 R⊕ radius) in the habitable zone of an F V star at a distance of 10 pc in at least one bandpass to within 25% (after calibration). This is intended to ensure that PECO shall be capable of making moderate precision measurements of the fluxes of at least several terrestrial planets and will constrain radii to ~12% for given albedos. There are approximately 10 FGK stars within 10 pc that have habitable zones (1 AU equivalent) located at least 165 mas away, outside of the PECO IWA (SCIREQ6). Adopting a probability of terrestrial planets of 0.3 implies that PECO is likely to find 3 Earth or Super-Earth planets around these stars.

**SCIREQ9**: PECO shall be able to measure the relative brightness of a super-Earth planet (Earth albedo and 2 R⊕ radius) in the habitable zone of an F V star at a distance of 10 pc in at least two broad (R~5) bands 450 – 800 nm with a precision of 20% or better to allow characterization by color. PECO must be able to perform these measurements for at least 10 nearby FGK stars.

**SCIREQ10**: PECO must provide filters capable of detecting ozone (590 nm), water vapor (725 and 820 nm) and oxygen (760 nm) in the atmospheres of terrestrial planets as listed in Table 4-1. The water vapor filter at 940 nm is desired but not required.

**SCIREQ11**: PECO shall be able to detect earth-like or super-Earth planets 1-1.8 AU from their stars over a distance range of 1.35 - 6 pc. This translates to an IWA of 167 mas and an outer working angle (OWA) of 1.33 arc-seconds, corresponding to 2 λ/D and 16.5 λ/D, respectively, for a D = 1.4-m telescope diameter and λ = 550 nm wavelength. This should be sufficient to observe planets 1 – 1.8 AU from most or all stars in Tables 4-2 and 4-3.

**SCIREQ12**: PECO shall be able to detect H2O , O2 , or O3 in the atmosphere of a Super-Earth planet 1 AU from a sun-like star at 5 pc distance. Detection is defined as the ability to measure the a 10% deep, R~10-20 H2O or O2 feature with SNR=3 (SNR = 30 on continuum). A similar continuum SNR is required for the much deeper but much more narrow O2 feature at 760 nm wavelength. PECO must have a sufficiently small IWA to make these measurements out to 760 nm (and it barely does). PECO must be able to perform these measurements for super-Earth planets in the habitable zones of at least 6 nearby stars.

**SCIREQ13**: PECO shall be able to measure the continuum flux level between H2O , O2 , and O3 absorption bands of a Super-Earth planet 1 AU from a sun-like star at 5 pc distance to within 3% precision ( 1 sigma) at three widely spaced spectral intervals. This is important for measuring absorptions and constraining planet colors. The continuum flux level may be computed by assuming a geometric albedo of 0.2.

**SCIREQ14**: PECO shall constrain the positions and orbits of planets in or near the habitable zones of nearby stars. It would be useful to constrain the projected position
of a detected (SNR > 5) planet to approximately 0.3 AU at a distance of 10 pc and 0.1 AU at a distance of 3 pc, corresponding to an astrometric precision of 30 mas.

Note: An Earth-like planet in a 1 AU orbit around a sun-like star at a distance of 5 pc is expected to have a flux level of 2.2E-8 Jy (V=28.0 mag). This is a V-band contrast level of approximately 24.9 mag with the planet having a maximum separation of 200 mas from its star. The effects of our own zodiacal dust and a modest amount of exozodiacal dust (∼1 zodi) are significant and must be included when modeling PECO performance on small (Earth-like and super-Earth) planets in or near habitable zones.

7.3 Circumstellar debris disks

SCIREQ15: Prevalence of low density debris disks. PECO shall be capable of detecting the integrated surface flux of 10 zodi circumstellar disks inclined 59 degrees around 50 (minimum) to 100 (baseline) stars within 31 pc observed in the giant planet survey (SCIREQ 7). Detection is defined as 5 times the noise spatially integrated over the PECO field in a single R ~ 5 PECO channel with a center at 550 nm.

SCIREQ16: Resolving disks of the nearest stars. PECO shall be capable of detecting spatially resolved 1 zodi disks around 5 nearby stars and 5 zodi disks (all 59 deg inclinations) around 20 dearby stars down to their habitable zones. Here detection is defined as a flux measurement at least 10 times the noise level per resolution element in a R~5 PECO channel centered at 550 nm. Structures (rings, gaps, clumps, voids) 0.5 AU in size must be resolved at a distance of 5 pc (equivalent to 1 AU at 10pc, requiring 100 mas resolution). The 1 zodi star sample can be identical to that searched for Earth-like planets (Table 4-2) and the 5 zodi sample can be identical to that searched for Super_Earths (Table 4-3).

SCIREQ17: Extent of disks and planet-disk interactions. PECO shall be able to image disks out to a radius of at least 2.5 AU at a distance of 1.3 pc (10 AU at 5 pc) in order to study the outer regions of disks and observe the impact that seen or unseen planets have on disk structures. This corresponds to an outer working angle (OWA) of 1.9 arcseconds, equivalent to 24 l/D for a D = 1.4-m telescope and λ = 550 nm.

SCIREQ18: Dust in habitable zones. PECO shall be able to image disks to within 1 AU of stars out to a distance of 6 pc at 550 nm wavelength. This will include the closest 6 stars to search for Earth-like planets and super-Earths (see Tables 4-2 and 4-3). This requires an IWA < 167 mas and an aperture D > 1.36-m if IWA = 2 λ/D.

SCIREQ19: Dust grain properties. PECO shall characterize and constrain the optical, physical, and compositional properties of circumstellar dust. R ~ 5 imaging data over the 400 – 800 nm range and polarimetric precision s-P = 0.5% and s-q = 5 degrees per resolution element for sources with intrinsic polarization fractions of 0.01 or greater shall be sufficient for this task.
SCIREQ20: Discrimination of dust from planets. PECO shall be capable of distinguishing unresolved dust clumps from planets with multi-epoch (multi-phase) polarimetric data. The polarimetric precision requirements given in SCIREQ19 shall be sufficient for this task.

### 7.4 Implied requirements

The science requirements SCIREQ1 – 20 above contain some information on derived functional and / or performance requirements in addition to pure scientific needs. In addition to the noted items, PECO will also require superb starlight suppression (~1010) to meet nearly all of these science requirements. There is no formal requirement for PECO to detect or characterize Earth analogs, but it is expected to be able to do so for the ~5 stars in Table 4-2.

### 7.5 Requirements Summary Table

We have consolidated the above requirements into a single summary table. This includes the required parameter, the baseline and floor values, comments, and the specific requirement number.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Baseline</th>
<th>Floor</th>
<th>Comment</th>
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<td>10% abs, 5% rel</td>
<td>10 pc distant</td>
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<td>1, 2</td>
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<td>15</td>
<td>10 pc, R=20, continuum</td>
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<td>Range-EGPs</td>
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<td>450-850 nm</td>
<td>see Fig. 3-4, Table 3-1</td>
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<td>IWA-EGPs</td>
<td>165 mas</td>
<td>2λ/D, D=1.4 m, 550 nm</td>
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<td>6</td>
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<tr>
<td>OWA-EGPs</td>
<td>1900 mas</td>
<td>1100 mas</td>
<td>14-24λ/D, D=1.4 m</td>
<td>6</td>
</tr>
<tr>
<td># Stars w/EGPs</td>
<td>200</td>
<td>100</td>
<td>t(20%) &lt; 2E4 seconds</td>
<td>7</td>
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<tr>
<td># RV planets</td>
<td>10 (goal)</td>
<td>5</td>
<td>characterization required</td>
<td>7 (3, 4, 5)</td>
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<tr>
<td>Super-Earth flux</td>
<td>25% abs, 20% rel</td>
<td>1 AU from G2V * at 5 pc</td>
<td></td>
<td>8, 9</td>
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<tr>
<td>Range-Super-Earth</td>
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<td>5 pc distant, continuum</td>
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<td></td>
<td>Resolved SNR=5, ea res el R=5</td>
<td>16</td>
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8 References


Holland, 1994


Kasting and Catling, 2005


Marois, C., et. al., 2008, “Direct Imaging of Multiple Planets Orbiting the Star HR 8799”, Science, 322, 10.1126/science.1166585


9 Appendix A: Notes on Grand Tour candidate list

<table>
<thead>
<tr>
<th>Name</th>
<th>HIP</th>
<th>Spectral Type</th>
<th>App. Mag. V</th>
<th>Dist. (pc)</th>
<th>1 HZ Max Elongation (λ/D)</th>
<th>Star Radius (λ/D)</th>
<th>Comments</th>
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<tr>
<td>Alp Cen A</td>
<td>71683</td>
<td>G2V</td>
<td>0</td>
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<td>11.5</td>
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<td>Alp Cen B</td>
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<td>K2IV</td>
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<td>1.3</td>
<td>6.6</td>
<td>0.04</td>
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</tr>
<tr>
<td>Tau Ceti</td>
<td>8102</td>
<td>G8.5V</td>
<td>3.5</td>
<td>3.6</td>
<td>2.3</td>
<td>0.01</td>
<td>Dust disk radius 18” at 850μ and 60 deg incl, dust mass est 10x solar system</td>
</tr>
<tr>
<td>Eps Eri</td>
<td>16537</td>
<td>K2V</td>
<td>3.7</td>
<td>3.2</td>
<td>2.2</td>
<td>0.01</td>
<td>Debris disk tens of “, sub-mm bright, dust mass est 1000x solar system, 2 suspected planets</td>
</tr>
<tr>
<td>Eta Cas</td>
<td>3821</td>
<td>G0V</td>
<td>3.5</td>
<td>6.0</td>
<td>2.3</td>
<td>0.01</td>
<td>RS CVN binary with 480 yr period, secondary K7V, V=7.51, 12” semimajor axis, e=0.49, 6” periastron separation in 1890, 25” in 2015, mean separation 68 AU, in galactic plane background</td>
</tr>
<tr>
<td>Bet Hydri</td>
<td>2021</td>
<td>G0V</td>
<td>2.8</td>
<td>7.5</td>
<td>3.1</td>
<td>0.01</td>
<td>Single (SIM list)</td>
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<td>Delta Pav</td>
<td>99240</td>
<td>G8IV</td>
<td>3.6</td>
<td>6.1</td>
<td>2.2</td>
<td>0.01</td>
<td>High metallicity, Fe/H = +0.38, near galactic plane</td>
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<td>Pi3 Ori</td>
<td>22449</td>
<td>F6V</td>
<td>3.2</td>
<td>8.03</td>
<td>2.57</td>
<td>0.01</td>
<td>Near galactic plane, in front of Orion molecular cloud</td>
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<tr>
<td>70 Oph</td>
<td>88601</td>
<td>K0V</td>
<td>4.0</td>
<td>5.09</td>
<td>1.88</td>
<td>0.01</td>
<td>Delta mag 1.8 binary, secondary K4V, V=6.0, 90-yr period, e=0.49, 2015 apastron 6” sep, in brightest part of galactic plane</td>
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<td>Star</td>
<td>Code</td>
<td>Type</td>
<td>V</td>
<td>B-V</td>
<td>V-R</td>
<td>RV</td>
<td>Notes</td>
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<tr>
<td>Mu Her</td>
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<td>G5IV</td>
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<td>0.01</td>
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<td>81693</td>
<td>G0IV</td>
<td>2.9</td>
<td>10.8</td>
<td>3.11</td>
<td>0.01</td>
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<td>61941</td>
<td>F0V</td>
<td>3.6</td>
<td>11.83</td>
<td>3.15</td>
<td>0.01</td>
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<tr>
<td>Bet Tri Aus</td>
<td>77952</td>
<td>F1V</td>
<td>2.9</td>
<td>12.31</td>
<td>3.03</td>
<td>0.01</td>
<td>Single</td>
</tr>
<tr>
<td>Eps Ind</td>
<td>108870</td>
<td>K4V</td>
<td>4.7</td>
<td>3.63</td>
<td>1.5</td>
<td>0.01</td>
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<td>F6.5 V</td>
<td>3.6</td>
<td>8.97</td>
<td>2.14</td>
<td>0.01</td>
<td>Close visual binary, max separation &lt; 1”, near galactic plane</td>
</tr>
<tr>
<td>V* DY Eri</td>
<td>19849</td>
<td>K0.5 V</td>
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<td>F9V</td>
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<td>36 Oph</td>
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<td>4.3</td>
<td>6.06</td>
<td>1.61</td>
<td>0.01</td>
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</table>

### 10 Appendix B: Scientific definitions

#### 10.1 Terrestrial planet

A terrestrial planet is a planet which is primarily supported from gravitational collapse through Coulomb pressure, and which has a surface defined by the radial extent of the liquid or solid interior. Terrestrial planets are often referred to as “rocky planets.” A gaseous atmosphere may exist above the surface, but this is not a defining feature of a terrestrial planet. Theory suggests that most terrestrial planets will have masses less than about 10 times Earth’s mass (ME), as planets larger than this are likely to capture gas during accretion and develop into giant planets. Terrestrial planets that undergo final accretion after their protostellar nebula has dissipated may, however, achieve larger masses while still remaining “rocky.”

Earth-like planet is defined as a planet with Earth’s radius and albedo (geometric albedo =0.2), and a super Earth is defined as a planet with twice Earth’s radius and Earth’s albedo.

Habitable planet
A habitable planet is a terrestrial planet on whose surface liquid water can exist in steady state. This definition presumes that extraterrestrial life, like Earth life, requires liquid water for its existence. Both the liquid water, and any life that depends on it, must be at the planet’s surface in order to be detected remotely. This, in turn, requires the existence of an atmosphere with a surface pressure substantially above the triple point pressure of water, 6.1 mbar, and a mean surface temperature somewhere between 0oC and 374oC (the critical point for water). Planets habitable by Earth-like life must have surface temperatures below ~120oC. For the purposes of the mission, the lower-mass limit for a habitable planet is set at 1/3 ME. Objects smaller than this are unlikely to hold onto their atmospheres effectively and are therefore lower priority targets for PECO.

10.2 Habitable zone and continuously habitable zone
The habitable zone, or HZ, is the region around a star in which a planet may maintain liquid water on its surface. Its boundaries are defined empirically in Section 1.1.3, based on the observation that Venus appears to have lost its water some time ago and that Mars appears to have had surface water early in its history.

The continuously habitable zone, or CHZ, is the region that remains habitable over some finite period of time as a star ages. All main sequence stars brighten with time, and so the HZ moves outward with time. For our own Solar System, the CHZ is usually defined over the entire solar lifetime, ~4.6 billion years (Hart, 1978).

10.3 Habitable zone location and width
In order to search for planets within the habitable zone (HZ), one needs to define the HZ around different star types. The HZ limits used here are 0.75 AU for the inner edge and 1.8 AU for the outer edge, scaled by the square root of stellar luminosity. These HZ boundaries are empirical limits based on observations of Venus and Mars. Venus’ semi-major axis is 0.72 AU. Radar maps of Venus’ surface suggest that liquid water has not been present there for at least the last 1 billion years (Solomon and Head, 1991). The Sun was ~8% dimmer back at that time, according to standard solar evolution models (e.g., Gough, 1981). Thus, the solar flux at Venus’ orbit then was equal to that at a distance of 0.72 AU (1/0.92)1/2 ≅ 0.75 AU today. The outer edge of the HZ is based on the observation that Mars, which orbits at 1.52 AU, looks as if it may well have been habitable at or before 3.8 billion years ago (Pollack, 1979; Pollack et al., 1987). The Sun is thought to have been ~75% as bright at that time. Hence, the solar flux hitting Mars back then was equivalent to that at a distance of 1.52 AU (1/0.75)1/2 = 1.8 AU.

The empirical HZ values adopted for this SRD can also be justified theoretically. The inner edge of the HZ is thought to be set by loss of surface water (Rasool and DeBergh, 1969; Ingersoll, 1969; Kasting, 1988). Photodissociation of stratospheric H2O by stellar UV radiation, followed by escape of hydrogen to space, causes an ocean to be lost with a geologically short period of time—tens to hundreds of millions of years. The outer edge of the HZ is determined by condensation of CO2. CO2 is a greenhouse gas that keeps the planet warm enough for liquid water. If a planet is too far from its parent star, CO2 begins to condense out of the gas phase into CO2 ice and the temperature-stabilizing CO2 feedback cycle (Walker et al., 1981) disappears.
The 0.75 AU and 1.8 AU HZ boundaries apply to planets orbiting a Sun-like star. The Sun is a 4.5 billion-year-old G2V star with an effective temperature of ~5700 K. The HZ around more or less massive (i.e., more or less luminous) stars are shifted by a factor of \((L/L_\odot)^{0.5}\). The approximate location of the HZ around different main sequence stars is illustrated in Figure A-1. For illustration, the boundaries shown in the diagram are the zero-age-main-sequence (ZAMS) values, based on theoretical “runaway” and “maximum” greenhouse limits from Kasting et al. (1993). An additional complication is that the HZ moves outwards, at different rates for different types of stars, as the stars age. Also, see Kasting et al. (1993) for additional correction factors to this \((L/L_\odot)^{0.5}\) scaling for different star types, based on their effective temperatures. These correction factors can shift the HZ boundaries inward (outward) by up to 10 percent for stars that are hotter (cooler) than the Sun.

Figure 10-1: The instantaneous habitable zone around different stars at the time when they first entered the main sequence. The dotted curve shows the distance at which a planet's rotation would become locked within 4.5 Gyr. The nine planets in our own Solar System are shown as well. (Modified from Kasting et al., 1993).
10.4 1-zodi exozodiacal dust disk
We define an exozodiacal disk with the same dust properties (composition, distribution, mass) as our solar system’s zodiacal disk as a 1 zodi disk. A 1 zodi disk is defined to have optical depth $\tau_{\text{dust}} \sim 10^{-7}$ and $\text{LIR}/L^* = 10^{-7}$. 