# Looking for *New Earth* in the Coming Decade With Direct Imaging

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Co-Authors: Tiffany Glassman, Northrop Grumman Aki Roberge, Goddard Space Flight Center Amy Lo, Northrop Grumman Webster Cash, University of Colorado, Boulder With discoveries like methane on Mars (Mumma et al. 2009) and super-Earth planets orbiting nearby stars (Howard et al. 2009), the fields of exobiology and exoplanetary science are breaking new ground on almost a weekly basis. These two fields will one day merge, with the high goal of discovering Earth-like planets orbiting nearby stars and the subsequent search for signs of life on those planets. The Kepler mission will soon place clear bounds on the frequency of terrestrial-sized planets (Basri et al. 2008). Beyond that, the great challenge is to determine their true natures. Are terrestrial exoplanets anything like Earth, with life forms able to thrive even on the surface? What is the range of conditions under which Earth-like and other habitable worlds can arise? Every stellar system in the solar neighborhood is entirely unique, and it is almost certain that anything that can happen, will.

In this white paper, we show that with current and near-term technology we can make great strides in finding and characterizing planets in the habitable zones of nearby stars. Given reasonable mission specifications, the layout of the stars in the solar neighborhood, and their variable characteristics (especially exozodiacal dust) a direct imaging mission can detect and characterize dozens of Earths. Not only does direct imaging achieve detection of planets in a single visit, but photometry, spectroscopy, polarimetry and time-variability in those signals place strong constraints on how those planets compare to our own, including plausible ranges in planet mass and atmospheric and internal structure (discussed in another white paper, Tinetti et al.).

Such a mission also would precipitate revelations about the entire architectures of nearby star systems and, given the right mission design, could easily accommodate a wide array of revolutionary astrophysical and cosmological programs. A mission dedicated to the direct imaging and characterization of habitable planets is an achievable goal which would not only garner wide approval from the general public but would yield significant advances in astrophysics as a whole. The primary purpose of this paper is to ensure that the discovery and characterization of habitable exoplanets is held as a high priority and feasible goal for NASA in the decade to come.

# Our key findings are as follows:

1. Direct imaging at an inner working angle of 50 milliarcseconds with a limiting planet:star contrast ratio of a few times  $10^{-11}$  allows significant probability (>20%) of single-visit detection and characterization of Earth-like planets in the habitable zones of at least 93 stars, with a net of 35.8 total habitable zones searched, within a mission lifetime of a few years. Those stars are primarily F- (4), G- (59), and K- (28) type dwarfs. This is a conservative estimate, however, and does not account for e.g., the ability to detect fainter planets at angles larger than the IWA.

2. Efficient planet detection/characterization is possible even with high levels of exo-zodiacal light (10 times solar levels or more). A pre-cursor mission (e.g., astrometry) is not required for efficient planet detection and characterization via direct imaging. Unresolved background objects are likely to occur but can be efficiently ruled out by color photometry and spectroscopy.

3. To prepare for any mission to find habitable exoplanets, it is crucial to expand "nearby stars" observing campaigns to identify faint companions (both physical companions and distant background objects), exozodiacal dust levels, and stellar characteristics such as variability (especially useful for transit searches), metallicity, and age estimates. Such observations would

greatly aid in (1) target selection and (2) our interpretation of the data to understand where habitable planets can form and how they evolve over time.

# **The Target Stars**

Because a star's habitable zone is located so near to the star itself, the technology for any mission to image habitable worlds is driven toward extremely high contrast imaging at very small starplanet angular separations. In this paper we are guided by a specific mission concept into which we have invested detailed consideration as part of an Astrophysics Strategic Mission Concept Study, i.e., NASA's New Worlds Observer (NWO). However, NWO is only one example of a direct-detection mission designed for efficient detection and characterization of extrasolar habitable worlds. This 4-m telescope plus starshade concept provides for a planet:star limiting contrast of a few times  $10^{-11}$  or deeper at an inner working angle of ~50 milliarcseconds.

Given those specifications, the most important question in assessing the viability of a direct imaging planet-finding mission is: Given the layout of stars in our neighborhood, which star systems can be searched for Earths? The answer (expressed both in number of stars and types of systems) determines whether any such mission is scientifically viable.

# Habitable Zone Size

The true location of the habitable zone around a star (where the temperature allows for liquid water on the planet's surface) depends on the atmospheric and geological processes at work in the planet under consideration (e.g., Kasting, Whittet & Sheldon 1996). We can simplify the discussion by noting that for an Earth-like planet, the inner HZ edge does not extend as close to the Sun as 0.7 AU (i.e., Venus). The outer edge is less well-constrained but apparently extends to at least 1.5 AU, because Mars appears to have had copious amounts of surface water in the past, and a more massive planet (with higher surface gravity and carbon cycling) may have remained habitable to this day. The HZ limits for the Sun used here are from 0.7 to 1.5 AU. These limits define the amount of energy a planet can receive to be inside the habitable zone, and to calculate the inner HZ (IHZ) and outer HZ (OHZ) limits for other stars, we scale by the square root of stellar luminosity:

Inner HZ =  $a_{IHZ}$  = 0.7 AU ×  $\sqrt{L_*/L_{sun}}$ Outer HZ =  $a_{OHZ}$  =1.5 AU ×  $\sqrt{L_*/L_{sun}}$ 

In this paper, stellar luminosity is calculated using V-band bolometric corrections from Flower (1996) and Hipparcos corrected Johnson B-V values (Bessel 2000; Turnbull 2004). Translating the linear HZ size in AU into an angular size, we find that the angular HZ size can be expressed in terms of the apparent magnitude alone:

$$\begin{aligned} \vartheta_{HZ}(") &= a_{HZ}(AU)/d(pc) = \sqrt{(L_*/L_{sun})} / d(pc) \\ &= \sqrt{10^{-(M_{BOL} - 4.8)/5}} / d(pc). \end{aligned}$$

Taking  $M_{BOL} \approx M_V$  and  $M_V = V - 5\log d(pc) - 5$ , a convenient rule of thumb is:

 $\theta_{HZ}(") \approx 10^{-V/5}$ .

Thus for a habitable-planet-finding observatory with a ~50 milliarcesecond inner working angle (IWA, the smallest angle where planets can be detected above the stellar signal), no target shall be fainter than V~6.5. This means that from our place within the Solar Neighborhood, the latest spectral type searchable with an inner working angle of 50 mas is ~K5V. Late K and M stars, it would seem, are indeed better suited for transit studies (Gould, Pepper & DePoy 2003). Additionally, sunlike stars beyond a distance of 20 pc are not available to such a design.

Hipparcos' limiting magnitude is V~12, but the catalogue is *complete* only down to V=7.3-9 (depending on star color). As a result, the 30 pc sample of stars is complete for G-, F-, A-, and B-type stars and giants, but not for the fainter K- and M-stars. However, as seen above, these faintest stars are of less interest to us in direct imaging: despite the favorable contrast ratio (discussed below), their habitable zones are too small to resolve and their planets are too faint to characterize. Therefore the sample of 2100 Hipparcos stars within 30 pc includes every viable direct-detection target star, and many more.

### Planet-Star Contrast Ratio

In addition to being very near to the star, a habitable terrestrial planet is very small in size, and thus reflects only a tiny fraction of the star's light. The amount of starlight reflected by a planet in the habitable zone depends on three things: its distance from the star within the HZ, the planet's radius, and the planet's albedo at the wavelength of the detection bandpass. Planet luminosity does *not* depend on the luminosity of the star; by definition, "the habitable zone" is where the planet receives the right amount of energy for an Earthlike planet to have liquid water on its surface (about  $10^{24}$  ergs sec<sup>-1</sup> cm<sup>-2</sup>), regardless of which star it orbits. (That said, the planet's location *within* the habitable zone does affect the planet's brightness; planets at the outer edge of the HZ are fainter than at the inner edge, by a factor of ~4.6.)

A useful note, then, is that for planets of a given size and albedo, the planet-star contrast depends only on the stellar luminosity:  $(F_p/F_*)_{HZ} = 1.155 \times 10^{-10}/L_*$  at the Earth-equivalent insolation distance (which is 1 AU for the Sun). This brings home the challenge for planet-imaging missions: that angular habitable size goes as the stellar luminosity  $L_*$ , while fractional planet brightness goes as  $1/L_*$ , and both are quantities that we wish to maximize.

The Earth is near the inner edge of its habitable zone and is thus brighter than the average habitable planet might be. For a limiting contrast ratio of  $10^{-10}$  (a number often used as the baseline requirement for direct imaging), a sun-like star is too luminous for detection of an Earth at the outer HZ. Indeed, a  $10^{-10}$  contrast requirement would mean that the maximum luminosity for stars whose planets are detectable at the outer HZ is only ~0.5 L<sub>sun</sub>. Requiring that the entire HZ be searchable would thus rule out stars brighter than spectral type ~G8V from the target list. At the inner HZ, this maximum luminosity is 2.4 L<sub>sun</sub>, or ~F5V. It is for this same reason (i.e. contrast) that A- and early F-type stars and giants could be difficult targets in the visible band.

However, there need not be a sharp cutoff in planet detectability when the planet-star separation is equal to the IWA or when the planet-star contrast is equal to starlight suppression level. For a starshade design like NWO, planets should be detectable at several times below the starlight suppression level, given sufficient integration time. A limiting contrast "floor" (below which,

due to systematic effects, no amount of integration time results in a detection) of a few times 10<sup>-11</sup> is feasible for such a system. Suppression of starlight also improves at larger working angles, meaning that fainter planets at wider angular separations (i.e., for nearby systems) can still be detected. A starshade mission also does not have an outer working angle (Cash 2006) and this means that the nearest star system, alpha Centauri, would be a viable target in the search for Earths.

## **Completeness**

To assess the number of target stars available for a given mission and to provide a means of judging the relative science return from each star, we calculate the *completeness* for each star on the 30 parsec Hipparcos list. For each star, we create a set of orbits within the HZ and populate them with planets. We then make cuts at the IWA and contrast limit and determine what fraction of the planets would have been detected. This fraction is the completeness for that star, which can also be thought of as the probability of finding a HZ resident at that star, if every star has 1 such planet (i.e.  $\eta_{Earth}=1$ ). For simplicity at this time, we assume that planets are visible if they are farther from their parent star than the IWA and have a fractional brightness greater than the contrast floor. We also assumed Earth-twin planets with a constant size and albedo. In the future, we can take into account the variation of planet detectability with offset and contrast as well as a range of planet characteristics.



Figure 1 shows completeness for the stars within 30 pc, as a function of distance and apparent magnitude. Completeness quickly falls to near zero for stars fainter than V~6.5. The nearest K stars top the list in terms of likelihood of detecting an Earth in the habitable zone, followed by G dwarfs (which have smaller planet:star contrast but larger angular HZs) out to ~20 pc. For IWA of 50 mas and contrast floor of  $4x10^{-11}$ , there are 93 stars with a completeness of greater than 20%, for a total of 35.8 habitable zones searched.

This represents a conservative estimate, as we have not taken into account effects such as the ability to detect planets fainter than this at larger working angles (note that there is no outer working angle for a starshade). For example, alpha Centauri A, a sun at 1pc, has an angular habitable zone that is entirely visible outside the IWA, extending from ~70 mas to 1500 mas.

Our calculations put the system at only  $\sim$ 75% completeness, however, due to the higher contrast ratio required to see Earths orbiting early G-type stars. In reality, this star likely has nearly 100% completeness because a deeper contrast ratio can be achieved at these larger working angles. Meanwhile, the innermost habitable zone of alpha Cen B is just inside the 50 mas IWA, giving ~87% completeness, but planets in that system would be fractionally brighter and may still be detectable.

## **Distinguishing Planets and Their Orbits**

In order to find and characterize exoplanets using direct detection, we not only need to see the planet's light, we also need to distinguish between planets and background sources, differentiate between multiple planets in a extra-solar system, and measure the orbits of planets we find.

#### Exo-zodiacal Light and Mission Lifetime

An important question in direct imaging of habitable planets is whether dust in the system will overwhelm the planet signal. Figure 2 shows, for Hipparcos stars within 30 parsecs, the integration times required to detect Earth-like planets at quadrature ( $M_V = 30$ ) at S/N=10, assuming every star has an exozodiacal light level of 10 times the solar value. Choosing targets to maximize completeness and limit total integration time to 1 year (for both detection and spectroscopy) results in a favored sample of primarily G- and K-type stars (shown in color). For a starshade mission, the total mission lifetime would also include transit of the starshade between targets. Our mission planning simulations show that 30-50% of the total observing time would be spent on these exoplanet science targets, with the remaining 50-70% available to general astrophysics while the starshade is in transit to the next exoplanet target.



**Figure 2:** Colored asterisks corresponding to different types of stars show the targets in a possible observing program lasting 1 year (including imaging and spectroscopy), assuming  $\eta_{Hab. Earth} = 0.25$ . For each type of star, the number chosen for observation appears in parentheses to the right of the type label. Most selected stars are G and K type; no M stars were chosen. In this scenario, 61 stars are observed, giving 34.4 total HZs searched and 8.6 Earths characterized. Instrumental assumptions used here are consistent with a starshade mission: observatory throughput = 50%, telescope diameter = 4-m.

# **Background** Objects

Depending on galactic latitude and longitude, background sources will unavoidably appear in many of our target fields. In order to identify a point source in the field as a planet, we need to be able to differentiate between planets and background stars or distant galaxies. The stellar background at magnitudes below V~28 is not well characterized but can vary wildy depending on galactic latitude and longitude. Near the galactic poles, the odds for a background galaxy contamination can be as high as several hundred sources per square arcminute (Beckwith et al. 2006), or several tens of sources in the field of interest around a target star. Most bright galaxies will be resolved, but faint unresolved galaxies (near V~30) are potential sources for confusion that can be ruled out (or determined to be unlikely planet candidates) through a combination of color photometry and proper motion.

Because planets are seen in reflected starlight, even low resolution spectra (and in many cases broadband photometry) can immediately distinguish whether these objects are indeed associated with the star in question. Furthermore, given that the viable target stars are all within ~20 pc of the Sun, they have relatively high proper motions. Therefore it will not take much time at all for a potential planet to be confirmed as co-moving with the target star. In fact, common proper motion objects can usually be confirmed within a single observing session of a few weeks. Bright exo-zodiacal clumps, interesting in their own right (discussed in another white paper, Roberge et al.), may require spectra to distinguish them as non-planets.

### **Multiple Planets**

If multiple planets are seen in an initial observation of a stellar system, there is a worry that it might be unclear which planets are which when we return to the system for a second observation. In fact, it is relatively easy to determine the identity of each planet just based on its position in the field at the two times. In addition, if colors and even spectra are taken of each planet immediately after it is discovered, a unique identity can be established.

# **Orbit Determination**

Another perceived difficultly of using direct-detection to search for exoplanets is that it would be difficult to determine the orbit of any planets that are found. In fact, direct images of a stellar system have several advantages. The two-dimensional position of each planet is determined in each observation, which gives more information per observation than e.g. radial velocity or astrometry measurements. Any dust that is present in the system (proto-planetary, debris, or exo-zodi) will most likely be arranged in a disk with a discernable inclination. We expect planets in the system to have orbits with a similar inclination to this disk, which eliminates a source of degeneracy.



Figure 4: If exozodiacal light can determine inclination and orientation of ecliptic plane, then, under assumption of circularity, orbits of planets may be immediately determined.

# **Requirements (and Non-requirements) for Direct-Detection Missions**

To summarize, the basic requirements for a successful search for terrestrial exoplanets with a direct-detection mission are limiting planet:star contrast ratio of a few times  $10^{-11}$  and an IWA < ~50 mas. The success of the mission will be improved by the ability to immediately get several colors of the planets (to distinguish planets from background sources). Good photometric accuracy is also important in order to detect longer term variability in planet signals due to phases, rotation, and seasons. The ability to take a spectrum of each planet shortly after its discovery will allow an assessment of atmospheric composition, surface signatures, habitability and possibly biosignatures. Imaging the entire solar system at once is critical in order to study outer planets, debris disks, and exozodiacal structure. In order to determine the orbit of the detected planets, the mission must be able to revisit the system 2-3 times.

It is useful to note here that a pre-determined list of exo-planet targets is NOT a requirement for a successful direct-detection mission. Since planet detection and characterization takes less than several days (for starshade missions), all of the viable targets can be studied within a mission lifetime of ~5 years. Indirect-detection precursor missions (e.g., astrometry missions) add little to the efficiency of a direct imaging program and are perhaps most useful as follow-up programs for precise mass and orbit determinations.

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