Comparative Planetology and the Search for Life Beyond the Solar System

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The study of planets beyond the solar system and the search for other habitable planets and life is just beginning. Ground-based (radial velocity and transits) and space-based surveys (transits and astrometry) will identify planets spanning a wide range of size and orbital location, from Earth-sized objects within 1 AU to giant planets beyond 5 AU, orbiting stars as near as a few parsec and as far as a kiloparsec. After this initial reconnaissance, the next generation of space observatories will directly detect photons from planets in the habitable zones of nearby stars. The synergistic combination of measurements of mass from astrometry and radial velocity, of radius and composition from transits, and the wealth of information from the direct detection of visible and mid-IR photons will create a rich field of comparative planetology. Information on proto-planetary and debris disks will complete our understanding of the evolution of habitable environments from the earliest stages of planet-formation through to the transport into the inner solar system of the volatiles necessary for life.

The suite of missions necessary to carry out the search for nearby, habitable planets and life requires a “Great Observatories” program for planet finding (SIM PlanetQuest, Terrestrial Planet Finder-Coronagraph, and Terrestrial Planet Finder-Interferometer/Darwin), analogous to the highly successful “Great Observatories Program” for astrophysics. With these new Great Observatories, plus the James Webb Space Telescope, we will extend planetology far beyond the solar system, and possibly even begin the new field of comparative evolutionary biology with the discovery of life itself in different astronomical settings.

1. STUDIES OF PLANETARY SYSTEMS AND THE SEARCH FOR LIFE

The search for habitable planets and life beyond Earth represents one of the oldest questions in natural philosophy, but one the youngest fields in astronomy. This new area of research derives its support among the scientific community and the general public from the fact that we are using 21^{st} Century technology to address questions that were first raised by inquiring minds almost 2,500 years ago. Starting in 1995, radial velocity and, most recently, transit and microlensing studies have added more than 168 planets to the nine previously known in our own solar system. With steadily improving instrumentation, the mass limit continues to drop while the semi-major axis limit continues to grow: a 7.5 $M_\oplus$ planet orbiting the M star GL 876 at 0.02 AU (*Rivera et al.*, 2005) and a 4 M_{Jup} planet orbiting 55 Cnc at 5.2 AU (*Marcy et al.*, 2002) define boundaries which are sure to be eclipsed by newer discoveries. While we do not yet have the tools to find true solar system analogues or an Earth in the habitable zone of its parent star, evidence continues to accumulate (*Marcy et al.*, 2005) that the number of potential Earths is large and that some could be detected nearby, if only we had the tools. In this article on space missions, we assess the prospects for the discovery and eventual characterization of planets of all sizes — from gas-giants to habitable terrestrial analogues. Considerations of length necessarily make this discussion incomplete and we have omitted discussion of valuable techniques which do not by their nature, e.g. microlensing, lend themselves to follow-up observations relevant to physical characterization of planets and the search for life.

Papers in these proceedings describe many results from

Table 1: Space Projects Presently Under Consideration

	Approx. Sensitivity Planet Size, Orbit, Dist.	Planet Yield[1]	Approximate Launch Date
Survey for Distant Planets (Transits)			
COROT	$2R_\oplus$ at 0.05 AU (500 pc)	10s-100	2006
Kepler	$1R_\oplus$ at 1 AU (500 pc)	100s	2008
GAIA	$10R_\oplus$ at $<$0.1 AU	4,000	2012
JWST	$2R_\oplus$ (100-500 pc)	250[2]	2013
Determine Masses/Orbits (Astrometry)			
SIM	$3M_\oplus$ at 1 AU (10 pc)	250	2012[4]
GAIA	$30M_\oplus$ at 1 AU ($<$200 pc)	10,000	2012
Characterize Planets and Search for Life (Direct Detection)			
JWST	$1R_{Jup}$ at $>$ 30 AU (50-150 pc)	250 young stars	2013
TPF-Coronagraph[3]	$1R_\oplus$ at 1 AU (15 pc)	250	2018[4]
TPF-Interferometer/Darwin[3]	$1R_\oplus$ at 1 AU (15 pc)	250	2018[4]

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[1] Yield is highly approximate and assumes roughly 1 planet orbiting each star surveyed.

[2] Approximate number of follow-up of ground-based, COROT and Kepler transit targets.

[3] Parameters for TPF-C and TPF-I/Darwin are still being developed.

[4] Launch dates are uncertain in light of recent NASA budget submissions for 2007 and beyond.

planet-finding experiments. With the exception of a few (very exciting) HST and Spitzer observations, these are drawn primarily from ground-based observations. This chapter on space activities necessarily focuses on future activities. While the space environment is highly stable and offers low backgrounds and an unobscured spectral range, the technology needed to take full advantage of the environment will take many years to develop and the missions to exploit the technology and the environment will be expensive to construct, launch and operate. But when the missions described here are completed, they will revolutionize our conception of our place in the Universe.

Table 1 identifies the major space-based projects presently under consideration grouped by observing technique: transit photometry, astrometry, and direct detection. Plate 1 summarizes the discovery space of these projects as well as some ground-based activities in the Mass–Semi-Major Axis plane. COROT, Kepler and SIM will provide the many order-of-magnitude improvements in sensitivity and resolution relative to ground-based efforts needed to detect other Earths in the habitable zones of their parent stars using indirect techniques of transits, radial velocity and astrometry.

Once we have detected these planets via indirect means (Section 2 and Section 3), we argue below that we will need a number of missions to characterize these planets physically and to search for evidence of life in any atmospheres these planets may possess. Analogously to the improved knowledge gained about astrophysical phenomena from using all of NASA's four Great Observatories (the Hubble Space Telescope, the Compton Gamma Ray Observer, the Chandra X-ray Observatory, and the Spitzer infrared telescope) and ESA's Cornerstone missions (ISO and XMM), a comparable "Great Observatories" program for planet finding will yield an understanding of planets and the search for life that will greatly exceed the contributions of the individual missions.

As discussed in Section 2, the combination of transit photometry with COROT and Kepler, follow-up spectrophotometry from the James Webb Space Telescope (JWST) and follow-up radial velocity data gives unique information on planetary mass, radius, density, orbital location, and, in favorable cases, composition of the upper atmosphere. These data, available for large numbers of planets, will revolutionize our understanding of gas-giant and icy-planets. While less information will be available for smaller, rocky planets, a critical result of the transit surveys will be the frequency of Earth-sized planets in the habitable zone, $\eta_\oplus$ (*Beichman*, 2000). Since the angular resolution and collecting area needed for the direct detection of nearby planets are directly related to the distance to the closest host stars, the value of $\eta_\oplus$ will determine the scale and cost of missions to find and characterize those planets.

Subsequent to the transit surveys, we will embark on the search for and the characterization of nearby planets, and the search for a variety of signposts of life. We will ultimately require three complementary datasets: masses via astrometry (SIM PlanetQuest, Section 3); optical photons (TPF-Coronagraph, Section 4); and mid-IR photons (TPF-Interferometer/Darwin, Section 5). JWST will play an important role in follow-up activities looking at ground-based, COROT and Kepler transits; making coronagraphic searches for hot, young Jupiters; and studying proto-planetary and debris disks. The synergy between the planet finding missions, with an emphasis on studies of nearby, terrestrial planets and the search for life, is addressed in Section 6. Studies of potential target stars are ongoing but will need to be intensified and their results col-

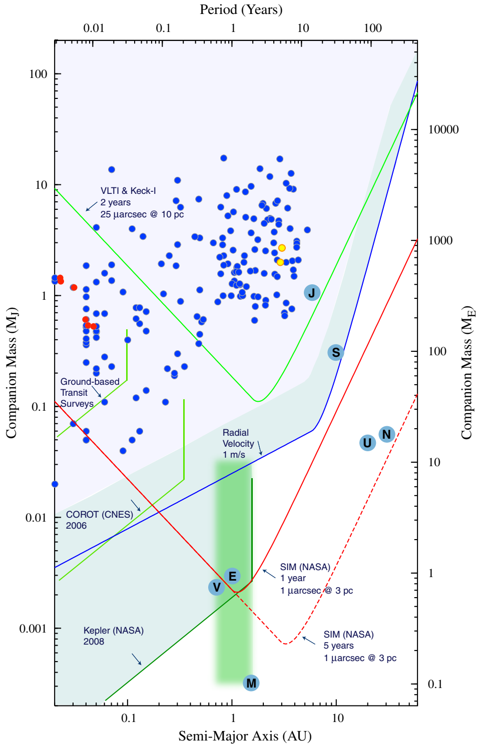

Fig. Plate 1.— A wide variety of space- and ground-based capabilities are summarized in this figure showing the detectability of planets of varying sizes and orbital locations. Space-based techniques become critical as one goes after terrestrial planets in the habitable zone. For a detailed description of this figure, see *Lawson et al.*, (2004).

lated to select the best targets (Section 7). The ordering of these missions will be the result of the optimization of a highly non-linear function incorporating technical readiness, cost, and political and scientific support on two or more continents (Section 8).

2. TRANSITING PLANETS

The age of comparative planetology is upon us with a growing number of transiting giant planets—nine and counting. As they pass in front of and behind their parent stars, the transiting planets' size—and hence density, transmission spectrum, and thermal emission and albedo can potentially be measured. This makes the group of transiting planets the ones that can best be physically characterized—before direct imaging is available; see chapters by *Udry et al.*, *Charbonneau et al.*, and *Marley et al.* for details on the recent planet transit discoveries, observations, and interpretations.

The dedicated, space-based, transit survey missions — Kepler and COROT — will build upon the exciting ground-based transit detections of giant planets. With very high-precision photometry enabled by the stable space environment and lack of day/night and weather interruptions, COROT and Kepler will push to planetary sizes as small as the Earth's. With long-duration observing campaigns they will extend transit planet discoveries to larger semi-major axes. JWST will similarly build on the pioneering HST and Spitzer measurements of planetary atmospheres. The legacy of Kepler and COROT combined with JWST will be to enable comparative planetology on a wide range of planet types, encompassing a range of planet masses, temperatures, and host stars, before direct imaging of solar-system-aged planets is possible.

2.1 Prospects for Planet Transit Discoveries

2.1.1 HST and MOST. The Hubble Space Telescope (HST) and the MOST (Microvariability and OScillations of STars) microsatellite of the Canadian Space Agency have shown the promise of space-based transit studies. HST monitored 34,000 stars in the globular cluster 47 Tuc (*Gilliand et al.*, 2000) continuously for 8.3 days. While 17 short-period giant planets were expected, none were found, suggesting that either low-metallicity or high stellar density interfere with planet formation or migration. More recently, HST ACS/WFC monitored a field of 160,000 main sequence stars in the Galactic bulge field for 7 days (*Sahu et al.*, 2005). Over 100 transiting planets were expected if the frequency of hot Jupiters in the Galactic bulge is similar to that in the solar neighborhood. MOST, launched in June 2003, is a 15 cm telescope with a 350-700 nm broadband filter and a part-per-million photometric accuracy capability for bright stars monitored for one month or more. MOST is not a transit survey instrument, but has monitored four stars hosting known hot Jupiters for 10 to 30 days. Of relevance to COROT and Kepler, MOST has put an upper limit on the albedo of HD209458b of 0.15 (1σ) (*Rowe et al.*, 2006) and is finding hints that host stars of the short-period planets (hot Jupiters) may be too variable to detect the illumination phase curve (*Walker et al.*, 2005).

2.1.2 COROT and Kepler. COROT (COnvection, ROtation and planetary Transit) and Kepler are wide-field survey space telescopes designed to detect small transiting planets via extremely high precision photometry. These telescopes will initiate the next generation of exoplanetary science by uncovering Neptune- (17 $M_\oplus$) to Earth-size planets around a range of stellar types. A large pool of this as yet unknown class of low-mass planets will provide the planet frequency and orbital distribution for insight into their formation and migration. The same group of planets will yield many objects suitable for follow-up physical characterization.

COROT is a CNES/ESA mission to be launched in October 2006 (*Baglin et al.*, 2003). COROT is a 27 cm telescope with a 3.5 deg^2 field of view. For the planet survey part of the program, five fields containing approximately 12,000 dwarf stars in the range $11 < V < 16.5$ mag will be continuously monitored for 150 days. COROT will detect over 10,000 planets in the 1 to 5 $R_\oplus$ range within 0.3 AU assuming all stars have one such planet (*Bordé et al.*, 2003). More realistic simulations show that COROT will detect about 100 transiting planets down to a size of 2 $R_\oplus$ around G0V stars and 1.1 $R_\oplus$ around M0V stars. See *Gillon et al.* (2005) and *Moutou et al.* (2005) for details including the radius and semi-major axis distribution of expected transiting planets around different star types.

Kepler is a NASA Discovery mission (*Borucki et al.*, 2003) to be launched in June 2008. Kepler has a 0.95 m diameter mirror and an extremely wide field of view—105 deg^2. Kepler will simultaneously monitor more than 100,000 main sequence stars (V <14 mag) for its 4-year mission duration. Kepler will find 50 transiting Earth-sized planets in the 0.5-1.5 AU range, if every star has 2 terrestrial planets (as the Sun does). This number increases to 650 planets if most terrestrial planets have a size of 2 $R_\oplus$. If Kepler finds few Earth-sized planets it will come to the surprising and significant conclusion that that Earth-size planets in Earth-like orbits are rare. Aside from detecting Earth-sized planets in the habitable zone, Kepler will advance the hot Neptune and hot Earth studies started by COROT, detecting up to hundreds of them down to a size as small as that of Mercury.

Both Kepler and COROT will produce exciting extrasolar giant planet science with tens of transiting giant planets with semi-major axes from 0.02-1 AU. Even giant planets in outer orbits—beyond 1 AU—can be detected with Kepler from single transit events at 8σ. Follow-up radial velocity observations are required to confirm that the photometric dips are really due to planetary transits, as well as to measure the planetary masses and in some cases to determine the orbital period.

2.2 Physical Characterization of Transiting Planets

The prospects for physical characterization of transiting planets first with Spitzer and then with JWST are truly astonishing. By the time JWST launches, one hundred or more transiting planets from Jupiter down to Earth-sizes should be available for observation. While the most favorable planets of all sizes will be at short semi-major axes, a decent number of larger planets out to 1 AU will also be suitable for density and atmosphere measurements. For transiting giant planets, their albedo, moons and rings (*Brown et al.*, 2001), and even the oblateness and hence rotation rate (*Seager and Hui*, 2002; *Barnes and Fortney*, 2003) can potentially be measured. Some specific possibilities of physical characterization are given below.

(i) Photometry. JWST's NIRSpec is a high-resolution spectrograph from 0.7 to 5 μm. With its spectral dispersion and high cadence observing NIRSpec will be capable of high-precision spectrophotometry on bright stars. NIRSpec data can then be used in the same way that the HST STIS spectral data for HD209458 was rebinned for photometry (*Brown et al.*, 2001). For example, at 0.7 μm JWST can obtain 35σ transit detection for two interesting cases: an Earth-sized moon orbiting HD209458b (3 hour transit time at 47 pc) and a 1 AU Earth-sized planet orbiting a sun-like star at 300 pc (*Gilliland*, 2005). Kepler stars are about 300 pc distant—meaning JWST will be capable of confirming Kepler Earth-size planet candidates.

Planetary density is the key to the planetary bulk composition. With precise radii from JWST and complementary radial velocity mass measurements, densities of many planets can be determined, even for super-Earth-mass planets close to the star. This will identify the nature of many Neptune-mass and super-Earth-mass planets. Are they ocean planets? Carbon planets? Small gaseous planets? Remnant cores of evaporated giant planets? Or some of each? In this way JWST + Kepler/COROT will be able to provide insight into planet formation and migration of the low-mass planets.

(ii) Spectroscopy. Planetary temperature is important for understanding planetary atmospheres and composition. Spitzer has initiated comparative exoplanetology by measuring transiting hot Jupiters in the thermal infrared using secondary eclipse (*Deming et al.*, 2005; *Charbonneau et al.*, 2005). Four transiting planets are being observed in 2005. Spitzer's broad-band photometry from 3-8 μm, together with photometry at 14 and 24 μm will help constrain the temperatures and compositions of hot Jupiters, including possibly their metallicity. The thermal infrared phase variation of 7 hot Jupiters may also be detected this year, providing clues about planetary atmospheric circulation in the intense irradiation environment.

The JWST thermal IR detection capability can be explored by scaling the Spitzer results. The 5-8 μm region is ideal for solar-type stars because the planet-star contrast is high and the exo-zodiacal background is low. For an estimate we can scale the TrES-1 5σ detection at 4.5 μm, taking into account that JWST has 45 times the collecting area of Spitzer, and assuming that the overall efficiency is almost 2x times lower, giving an effective collecting area improvement of $\sim$25 times. JWST will be therefore be able to detect hot Jupiter thermal emission at an SNR of 25 around stars at TrES-1's distance ($\sim$150 pc; a distance that includes most stars from shallow ground-based transit surveys). Similarly, JWST can detect a hot planet 5 times smaller than TrES-1, or down to 2 Earth radii, for the same set of stars *assuming instrument systematics are not a limiting factor*. Scaling with distance, JWST can detect hot Jupiters around stars 5 times more distant than TrES-1 to SNR of 5, which includes all of the Kepler and COROT target stars. Beyond photometry, JWST can obtain thermal emission spectra (albeit at a lower SNR than for photometry for the same planet). Rebinning the R=3,000 NIRSpec data to low-resolution spectra will enable detection of H_2O, CO, CH_4, and CO_2.

Transiting planets too cold to be observed in thermal emission can still be observed via transmission spectroscopy during primary planet transit. Such planets include giant planets at all semi-major axes from their stars. In visible and near-IR wavelengths, NIRSpec might detect H_2O, CO, CH_4, Na, K, O_2 and CO_2. With NIRSpec capabilities to a wavelength as short as 0.7 μm, JWST has the potential to identify molecular oxygen at 0.76 μm (a sign of life as we know it) in the outer atmosphere of a super-Earth-mass planet.

3. ASTROMETRY

3.1 Why Astrometry?

The principle of planet detection with astrometry is similar to that behind the Doppler technique: the presence of a planet is inferred from the motion of its parent star around the common center of gravity. In the case of astrometry one observes the two components of this motion in the plane of the sky; this gives sufficient information to solve for the orbital elements without the $\sin i$ ambiguity plaguing Doppler measurements. In addition, the astrometric method can be applied to all types of stars (independently of their spectral characteristics), is less susceptible to noise induced by the stellar atmosphere, and is more sensitive to planets with large orbital semi-major axes. From simple geometry and Kepler's Laws it follows immediately that the astrometric signal θ of a planet with mass m_p orbiting a star with mass m_* at a distance d in a circular orbit of radius a is given by

$$\theta = \frac{m_p}{m_*}\,\frac{a}{d} = \left(\frac{G}{4\pi^2}\right)^{1/3} \frac{m_p}{m_*^{2/3}}\,\frac{P^{2/3}}{d}$$

$$= 3\,\mu\mathrm{as}\cdot\frac{m_p}{M_\oplus}\cdot\left(\frac{m_*}{M_\odot}\right)^{-2/3}\left(\frac{P}{\mathrm{yr}}\right)^{2/3}\left(\frac{d}{\mathrm{pc}}\right)^{-1} \qquad (1).$$

This signature is represented in Plate 1 which shows astrometric detection limits for a ground-based and space-based programs.

3.2 Astrometry from the Ground

The best prospects for astrometric planet detection from the ground will be offered by the development of narrow-angle dual-star interferometry (*Shao and Colavita*, 1992; *Quirrenbach et al.*, 1998; *Traub et al.*, 1996), which is being pursued at the Palomar Testbed Interferometer (PTI; *Muterspaugh et al.*, 2005), the Keck Interferometer (KI) and at ESO's Very Large Telescope Interferometer (VLTI; *Quirrenbach et al.*, 2000). While the Earth's atmosphere imposes limits on ground-based interferometers, in favorable cases where a suitable reference star is available within $10''$, a precision of $10\,\mu$as can be reached. While adequate for gas giant planets, this limit excludes the use of ground-based facilities for searches for Earth analogues (cf. Plate 1). The scientific goals of ground-based projects thus include determining orbital inclinations and masses for planets already known from radial-velocity surveys, searches for giant planets around stars that are not amenable to high-precision radial-velocity observations, and a search for large rocky planets around nearby low-mass stars.

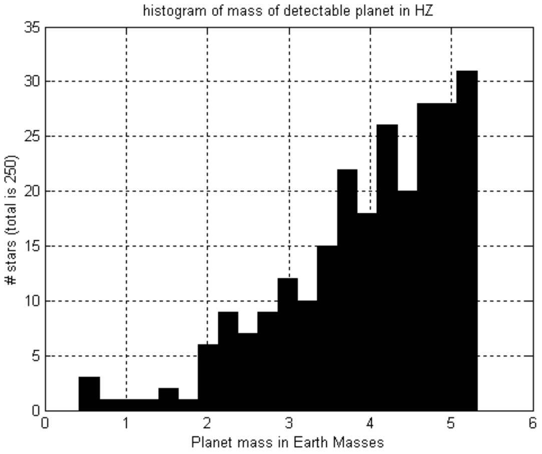

Fig. 1.— The histogram shows the number of terrestrial planets in different mass ranges that SIM Planetquest could find in the habitable zones surrounding 250 nearby solar type stars assuming 100 visits with 1 μas accuracy over 5 years.

3.3 SIM PlanetQuest: Nearby Terrestrial Planets

NASA's Space Interferometry Mission (SIM PlanetQuest) will push the precision of astrometric measurements far beyond the capabilities of any other project currently in existence or under development. SIM, to be launched in 2012, will exploit the advantages of space to perform a diverse astrometric observing program, e.g., *Unwin* (2005) and *Quirrenbach* (2002). SIM consists of a single-baseline interferometer with 30 cm telescopes on a 9 m baseline. SIM is a pointed mission so that targets can be observed whenever there is a scientific need, subject only to scheduling and solar exclusion angle constraints. Additionally, the integration time can be matched to the desired signal-to-noise ratio enabling observation of very faint systems.

In its "narrow-angle" mode (i.e., over a field of about $1°$), SIM will provide an accuracy of $\sim 1\,\mu$as for each measurement. SIM PlanetQuest will carry out a high-precision survey of 250 nearby stars reaching down to 1 to 3 $M_\oplus$ (depending on stellar mass and distance) and a less sensitive survey of some 2,000 stars establishing better statistics on massive planets in the Solar neighborhood. In addition, SIM will observe a sample of pre-main-sequence stars to investigate the epoch of planet formation.

It is very likely that SIM PlanetQuest will discover the first planets in the habitable zone around nearby stars. True Earth analogues are just within reach. With 200 visits at a single-measurement precision of 1 μas, astrometric signatures just below 1 μas constitute secure planet detections, with a false-alarm probability of only 1%. This means that planets with 1 $M_\oplus$ in 1 AU orbits can be discovered around seven nearby G and K dwarfs; planets twice as massive would be found around 28 G and K stars. Assuming $\eta_\oplus = 0.1$, SIM would have a $\sim 50\%$ chance of finding at least one 1 $M_\oplus$ / 1 AU planet, and a $\sim 95\%$ chance of discovering at least one 2 $M_\oplus$ planet in a 1 AU orbit. Fig. 1 summarizes the number of terrestrial planets of various masses that SIM might find in the habitable zones ($\sim 1AU(L/L_\odot)^{0.5}$) surrounding 250 nearby solar type stars (Section 6, 7).

One should note that the astrometric signature of the Earth, 450 km or 1/1,500 $R_\odot$, is several times larger than the motion of the photocenter of the Sun induced by spots. Starspots are not expected to contribute significantly to the noise for planet searches around Sun-like stars. Although starspots are a cause for concern for more active types of star, their effects are less than the radial velocity noise associated with young stars. SIM astrometry will be able to find gas giant planets within a few AU of T Tauri stars for the first time.

3.4 GAIA: A Census of Giant Planets

The European Space Agency is planning to launch an astrometric satellite, GAIA, in roughly the same time frame as SIM. GAIA's architecture builds on the successful Hipparcos mission (*Lindegren and Perryman*, 1996; *Perryman et al.*, 2001). Unlike SIM, GAIA will be a continuously scanning survey instrument with a large field of view, which will cover the whole sky quite uniformly, observing each star hundreds of times over its 5 year mission. Among the many scientific results of the GAIA mission will thus be a complete census of stellar and sub-stellar companions down to the accuracy limit of the mission. This limit depends on the magnitude and color of each star: for a G2V star the expected accuracy, expressed as the parallax error at the end of the mission is 7 μas at $V = 10$ mag and 25 μas at $V = 15$ mag. Very roughly, the corresponding *single measurement accuracy* relevant to planet detection will be 70 μas at $V = 10$ mag and 250 μas at $V = 15$ mag, assuming

100 measurements per star over the course of the mission. GAIA is thus expected to detect some 10,000 Jupiter-like planets in orbits with periods ranging from 0.2 to 10 years, out to a typical distance of 200 pc. Around nearby stars, the detection limit will be about 30 $M_\oplus$. In addition, over 4,000 transiting "hot Jupiters" will be detected in the GAIA photometry. GAIA will thus provide complementary information to SIM, on the incidence of planetary systems as a function of metallicity, mass and other stellar properties.

4. CORONAGRAPHY

4.1 Ground-based Coronagraphy

The search for faint planets located close to a bright host star requires specialized instrumentation capable of achieving contrast ratios of $10^{-9} - 10^{-10}$ at subarcsecond separations. The most common approach is a Lyot coronagraph, where direct starlight is occulted at a first focal plane; diffraction from sharp edges in the entrance pupil is then suppressed with a Lyot mask in an intermediate pupil plane; and finally, imaging at a second focal plane occurs with greatly reduced diffraction artifacts. In addition to diffraction control, good wavefront quality (Strehl ratio) and wavefront stability are needed to achieve high image contrast.

Future extremely large ground-based telescopes will complement space coronagraphy through studies of young or massive Jovian planets. Contrast levels of 10^{-7} or perhaps 10^{-8} may be achievable at subarcsec separations through future developments in extreme adaptive optics. However, achieving the higher contrasts needed to detect Earths would require working at levels of 10^{-3} and 10^{-4} below the level of the residual background, many orders of magnitude greater than has been demonstrated to date (*Dekany et al.*, 2006; *Chelli* 2005; see chapter by *Beuzit et al.*). As discussed below, the TPF-Coronagraph will greatly reduce the residual stellar background by taking advantage of a stable space platform and the absence of a variable atmosphere. Furthermore, the study of weak atmospheric features (including key biomarkers) on distant planets will be straightforward from space, but could be compromised by observing at relatively low spectral resolution through the Earth's atmosphere.

4.2 High Contrast Imaging from Space

Ground-based adaptive optics systems and three Hubble Space Telescope (HST) instruments using simple coronagraphs have achieved valuable results on circumstellar disks and substellar companions at moderate image contrast (see chapters by *Beuzit et al.* and *Ménard et al.*; *Schneider et al.*, 2002; *Krist et al.*, 2004, and references therein). However, only by taking full advantage of stable, space-based platforms can the necessary starlight rejection ratios be achieved. To date, no space astronomy mission has been designed around the central goal of very high contrast imaging to enable detection of extrasolar planets. The HST coronagraphs were low priority add-ons to general-purpose instruments, and achieved only partial diffraction control and image contrasts of 10^{-4}-10^{-5}.

JWST, expected to launch in 2013, will offer coronagraph modes for its two infrared imaging instruments. Even though JWST's segmented primary mirror is poorly suited to high contrast coronagraphy, JWST's coronagraphs can access the bright 4.8 μm emission feature expected in the spectra of giant planets and brown dwarfs enabling the detection of substellar companions at contrast ratios of 10^{-5}-10^{-6}. Detailed performance estimates show that JWST should be able to detect warm planets in nearby young stellar associations at radii $> 0.7''$, and perhaps even a few old (5 Gyr) Jupiter-mass planets around nearby, late-M type stars (*Green et al.*, 2005).

The key to achieving such high contrasts is precision wavefront sensing and control. After a coronagraph suppresses the diffracted light in a telescope, the detection limits are governed by how much light is scattered off surface imperfections on the telescope primary mirror. In HST, these imperfections produce a background field of image speckles that is more than $1000\times$ greater than the expected brightness of a planet in visible light. At the time HST was designed, the only way to reduce these imperfections would have been to polish the primary mirror to 30× better surface accuracy - infeasible then and now. But during the 1990s, another solution became available: use deformable mirrors (DMs) to actively correct the wavefront. The needed wavefront quality can be achieved by canceling out primary mirror surface figure errors with a DM - exactly as Hubble's spherical aberration was corrected, but now at higher precision and higher spatial frequencies.

Over the past 5 years, the community has been developing deformable mirror technology, innovative pupil masks, and instrument concepts to enable very high contrast imaging (*Green et al.*, 2003; *Kuchner and Traub*, 2002; *Vanderbei et al.*, 2004; *Guyon et al.*, 2005; *Traub and Vanderbei*, 2005; *Shao et al.*, 2004). At the Jet Propulsion Laboratory, the High Contrast Imaging Testbed (HCIT) has been developed and consists of a vacuum-operated optical bench with a Lyot coronagraph and a 64×64 format deformable mirror. New wavefront control algorithms have been developed. As of mid-2005, HCIT had *demonstrated* 10^{-9} contrast in 785 nm narrowband light, at a distance of 4λ/D from a simulated star image (*Trauger et al.*, 2005) — a huge improvement over the previous state of the art. While additional progress is needed to achieve the requirement of 10^{-10} contrast in broadband light, these results are extremely encouraging evidence that a coronagraphic version of the Terrestrial Planet Finder mission (TPF-C) is feasible. NASA is now defining a TPF-C science program and mission design concept.

4.3 TPF-C Configuration

The configuration of the TPF-C observatory is driven by the specialized requirements of its high contrast imaging mission (Plate 2). To enable searches of the habitable zone in at least 100 nearby FGK stars an 8 meter aperture is needed. A monolithic primary mirror is essential to achieving the needed wavefront quality and maximizing throughput, but a conventional circular 8 m primary cannot be accommodated in existing rocket launcher shrouds. The unconventional solution is an 3.5 m × 8 m elliptical primary, tilted on-end within the rocket shroud for launch, with a deployed secondary mirror. The telescope has an off-axis (unobscured) design, to minimize diffraction effects and maximize coronagraph throughput. To provide very high thermal stability, the telescope is enclosed in a multi-layer V-groove sunshade and will be operated in L2 orbit. The large sunshade dictates a solar sail to counterbalance radiation pressure torques on the spacecraft. Milliarcsec-level pointing will be required to maintain alignment of the bright target star on the coronagraph occulting spot.

TPF-C's main instrument will be a coronagraphic camera/spectrometer operating over the wavelength range 0.4 $< \lambda <$ 1.1 μm. It will have a very modest field of view, perhaps $20''$ in diameter, with a corrected high contrast dark field extending to a radius of $\sim 1''$ from the bright central star. The science camera will also serve as a wavefront sensor to derive the adaptive correction settings for the DM which must be set and maintained to sub-angstrom accuracy to achieve the required contrast. The camera will provide multispectral imaging, at resolutions from 5-70, in order to separate planets from residual stellar speckles, and to characterize their atmospheres. Spectral features of particular interest for habitability are the O_2 A band at 0.76 μm, an H_2O band at 0.81 μm, and the chlorophyll red edge beyond 0.7 μm.

Terrestrial exoplanets are very faint targets, with typical $V> 29$ mag. Even with a collecting area five times greater than HST's, exposure times of order a day will be needed to detect them. Repeat observations at multiple epochs will be needed to mitigate against unfavorable planetary elongations or illumination phases. Each of the target stars must therefore be searched for roughly a week of cumulative integration time. In systems where candidate planets are detected, follow-up observations to establish common proper motion, measure the planet's orbital elements, and spectroscopic characterization would add weeks of additional integration time per target. Accompanying giant planets and zodiacal dust should be readily detected in the systems selected for terrestrial planet searches.

5. INTERFEROMETRY

While COROT and Kepler will tell us about the general prevalence of terrestrial planets, we need to study planets in their habitable zones around nearby (25 pc) solar type stars in a large enough sample (150 to over 500) to make statistically significant statements about habitable planets and the incidence of life. In order to cover a range of spectral types, metallicities, and other stellar properties, we would like to include many F, G, K and some M dwarfs. As described in Section 4, the angular resolution of a space-based coronagraph is limited to about 60 mas ($4\lambda/D$ at 0.7 μm) by the size of largest monolithic telescope one can launch (roughly an $\sim$ 8 m major axis). Beyond about 15 pc such a coronagraph will be limited to searches of the habitable zones around more luminous F-type stars. An interferometer with each telescope on a separate spacecraft suffers no serious constraints on angular resolution and would be able to study stars over a large span of distances and luminosities with a consequently larger number and greater variety of potential targets.

Nulling (or destructive) interferometry uses an adaptation of the classical Michelson interferometry currently being developed at ground based sites like the Keck Interferometer and ESO's Very Large Telescope Interferometer. Interferometers operating in the mid-infrared offer a number of advantages over other systems:

(i) Inherent flexibility which allows the observer to optimize the angular resolution to suit a particular target star.

(ii) A star-planet contrast ratio that is only $10^{-6} - 10^{-7}$ at 10 μm, roughly a factor of 1,000 more favorable than at visible wavelengths.

(iii) A number of temporal and spatial chopping techniques to filter out optical and mechanical instabilities, thereby relaxing some difficult requirements on the optical system.

(iv) The presence of deep, broad spectral lines of key atmospheric tracers that can be observed with low spectral resolution.

There are, of course, disadvantages to a mid-IR system, including the need for cryogenic telescopes to take advantage of low space background; the complexity of multi-spacecraft formation flying; and the complexity of signal extraction from interferometric data compared to more direct coronagraphic imaging.

ESA and NASA are investigating interferometric planet finding missions and investing heavily in key technologies to understand the tradeoffs between different versions of the interferometer and, more generally, with coronagraphs.

5.1 Nulling Interferometry

In a nulling interferometer the outputs of the individual telescopes are combined after injecting suitable phase differences (most simply a half-wavelength) so that the on-axis light is extinguished while, at the same time, slightly off-axis light will be transmitted. By rotating the interferometer or by using more than two telescopes in the system one can sweep around the optical axis with high transmission while constantly obscuring the central object. In this manner, first proposed by *Bracewell* (1978), one can achieve the very high contrast ratios needed to detect a planet in the presence of its parent star. The depth and the shape of the null in the center depend critically on the number of telescopes and the actual configuration (*Angel and Woolf*, 1997). While better angular resolution is desirable to probe closer to the star, at high enough resolution the central stellar disk becomes re-

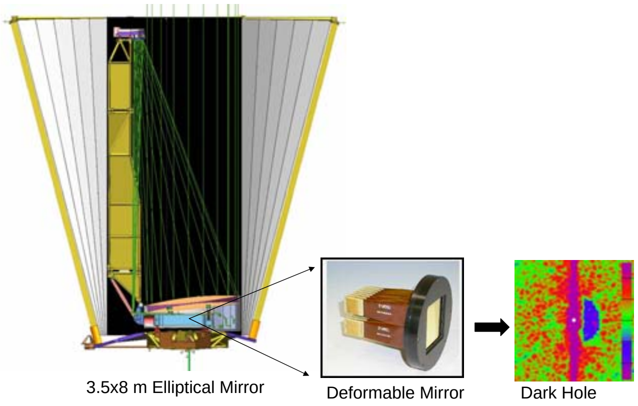

Fig. Plate 2.— Left) An artist's concept for TPF showing the sunshield surrounding the 3.5x8 m primary mirror; middle) a picture of the deformable mirror which is the key development for wavefront control; right) a "dark hole" is created when the deformable mirror is adjusted to take out wavefront errors in the optical system. In this rectangular area the contrast demonstrated in the laboratory has reached 10^{-9} starting at a field angle of $4\lambda/D$, within a factor of 10 of that needed to detect planets.

solved and light leaks out of the central null. This leakage is one of the noise sources in a nulling interferometer designed to search for terrestrial planets. When full account is taken of the leakage and other noise sources including local zodiacal emission, telescope background, and zodiacal light from dust orbiting the target star, the performance of a nulling interferometer using 3-4 m telescopes is well matched to the study of terrestrial planets around hundreds of stars (*Beichman et al.*, 1998; *Mennesson et al.*, 2004).

Excellent technical progress has been made in both the US and Europe on the key "physics" experiment of producing a broad-band null. Depths less than 10^{-6} have been achieved in a realistic 4 beam configuration in the laboratory (*Martin et al.*, 2003). Operational nulling systems are being deployed on both the Keck and Large Binocular Telescope Interferometers (*Serabyn et al.*, 2004; *Herbst et al.*, 2004).

5.2 Darwin and the Terrestrial Planet Finder

ESA's Darwin and NASA's TPF-I are currently foreseen to be implemented on 4-5 spacecraft flying in a precision formation. The system would consist of 3 or 4 telescopes each of 3-4 m diameter and flying on its own spacecraft. An additional spacecraft would serve as a beam combiner. When searching nearby stars out to 25 pc, the distance between the outermost telescopes would be roughly 100 m. The operating wavelength would be 6 to 17 μm (possibly as long as 20 μm) where the contrast between parental star and Earth-like planet is most favorable and where there are important spectral signatures characterizing the planets. ESA and NASA are collaborating on TPF-I/Darwin under a Letter of Agreement that calls for joint science team members, conferences and workshops as well as for periodic discussions on technology and the various configurations under study individually by the two space agencies. The common goal is to implement one interferometric mission, since complexity and cost indicate the necessity for a collaborative approach. Systems utilizing 1-2 m telescopes could also be considered if it were known in advance, e.g. from COROT and Kepler, that Earths in the habitable zone were common so that one could limit the search to 10 pc instead of 25 pc to detect a suitable number of planets.

6. SYNERGY AMONG TECHNIQUES FOR NEARBY PLANETS

The major missions discussed in this chapter approach the search for terrestrial planets from different perspectives: COROT and Kepler for transits (Section 2); SIM using astrometry (Section 3); TPF-C directly detecting visible photons (Section 4); and TPF-I/Darwin directly detecting mid-infrared photons (Section 5). In this section we argue that all these perspectives are needed to determine habitability and search for signs of life. The synergy between the transit missions and JWST has already been discussed (Section 2). In this section we focus on investigations of nearby stars and the potential for SIM, TPF-C, and TPF-I/Darwin to determine important physical parameters either individually or in combination (Table 2). *The cooperative aspects are discussed below in italics.* We anticipate that the strongest, most robust statements about the characteristics of extrasolar planet will come from these cooperative measurements.

6.1 Stable Orbit In Habitable Zone

Table 2: Measurement Synergy for TPF-C, TPF-I/Darwin and SIM

	SIM	TPF-C	TPF-I
Orbital Parameters			
Stable orbit in habitable zone	**Measurement**	**Measurement**	**Measurement**
Characteristics for Habitability			
Planet temperature	Estimate	Estimate	**Measurement**
Temperature variability due to eccentricity	**Measurement**	**Measurement**	**Measurement**
Planet radius	*Cooperative*	*Cooperative*	**Measurement**
Planet albedo	*Cooperative*	*Cooperative*	*Cooperative*
Planet mass	**Measurement**	Estimate	Estimate
Surface gravity	*Cooperative*	*Cooperative*	*Cooperative*
Atmospheric and surface composition	*Cooperative*	**Measurement**	**Measurement**
Time-variability of composition		**Measurement**	**Measurement**
Presence of water		**Measurement**	**Measurement**
Solar System Characteristics			
Influence of other planets, orbit coplanarity	**Measurement**	Estimate	Estimate
Comets, asteroids, and zodiacal dust		**Measurement**	**Measurement**
Indicators of Life			
Atmospheric biomarkers		**Measurement**	**Measurement**
Surface biosignatures (red edge of vegetation)		**Measurement**	

Each mission can measure an orbit and determine if it lies within the habitable zone (where the temperature permits liquid water on the surface of the planet). SIM does this by observing the wobble of the star and calculating where the planet must be to cause that wobble. TPF-C and TPF-I/Darwin do this by directly imaging the planet and noting how far it appears to be from the star. The missions work together and separately to determine orbital information:

(i) SIM detections of planets of a few Earth masses would provide TPF-C and TPF-I/Darwin with targets to be characterized and the optimum times for observing them, thus increasing the early-mission characterization yield of TPF-C or TPF-I/DARWIN.

(ii) Where SIM finds a planet, of any mass, in almost any orbit, TPF-C and TPF-I/Darwin will want to search as well, because we expect that planetary multiplicity may well be the rule (as in our Solar System). Thus SIM will help TPF-C and TPF-I/Darwin to prioritize likely target stars early in their missions.

(iii) For stars where SIM data suggest that planets exist below SIM's formal detection threshold, TPF-C or TPF-I/Darwin could concentrate on those stars to either verify or reject the detection. Such verification would lower the effective mass detection threshold for planets with SIM data.

(iv) All three missions can detect several planets around a star, within their ranges of sensitivity. Thus there may be a planet close to the star that SIM can detect, but is hidden from TPF-C. Likewise there may be a distant planet that TPF-C or TPF-I/Darwin can detect, but has a period that is too long for SIM. For the more subtle issue of whether the planets have orbits in or out of the same plane, SIM will do the best job. *In general, each of the three missions will detect some but not necessarily all of the planets that might be present in a system, so the combination will deliver a complete picture of what planets are present, their masses, their orbits, and how they are likely to influence each other over the age of the system, including co-planarity.*

6.2 Gross Physical Properties of Planets

(i) Planet temperature. A planet's effective temperature can be roughly estimated by noting its distance from its star and assuming a value for the albedo. TPF-C can estimate the temperature by noting the distance and using planet color to infer its albedo by analogy with planets in our Solar System. TPF-I/Darwin can observe directly the thermal infrared emission continuum at several wavelengths (i.e., infrared color) and use Planck's law to calculate the effective temperature. For a planet like Venus with a thick or cloudy atmosphere, the surface temperature is different from the effective temperature, but might still be inferred from a model of the atmosphere. *With all three missions combined, the orbit, albedo, and greenhouse effect can be estimated, and the surface temperature as well as temperature fall-off with altitude can be determined cooperatively and more accurately than with any one mission alone.*

(ii) Temperature Variability due to Distance Changes. Each mission alone can observe the degree to which the orbit is circular or elliptical, and thereby determine if the temper-

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[1] **“Measurement”** indicates a directly measured quantity from a mission; “Estimate” indicates that a quantity that can be estimated from a single mission; and *“Cooperative”* indicates a quantity that is best determined cooperatively using data from several missions.

ature is constant or varying. In principle TPF-C and TPF-I/Darwin can tell whether there is a variation in color or spectrum at different points in the planet's orbit due, perhaps, to a tilt of the planet's axis which would lead to a seasonal temperature variability. *The measurement of a terrestrial planet's orbital eccentricity using combined missions (SIM plus TPF-C and/or TPF-I) can be much more accurate than from any one mission alone, because complementary sensitivity ranges in planet mass and distance from star combine favorably. SIM gives eccentricity data that aids TPF-C and TPF-I/Darwin in selecting optimum observation times for measuring planet temperature, clouds, and atmospheric composition.*

(iii) Planet Radius. SIM measures planet mass from which we can estimate radius to within a factor of 2 if we assume a value for the density (which in the Solar System spans a factor of 8). TPF-C measures visible brightness, which along with an estimate of albedo, can give a similarly rough estimate of radius. A TPF-C color-based estimate of planet type can give a better estimate of radius. TPF-I/Darwin measures infrared brightness and color temperature which, using Planck's law, gives a more accurate planet radius. *Planet radius and mass, or equivalently density, is very important for determining the type of planet (rocks, gas, ice, or combination), its habitability (solid surface or not; plate tectonics likely or not), and its history (formed inside or outside of the ice-line). With SIM's mass, and one or both TPF brightness measurements, we can dramatically improve the estimate of planet radius.*

(iv) Planet Albedo. The albedo controls the planet's effective temperature which is closely related to its habitability. SIM and TPF-C combined can estimate possible pairs of values of radius and albedo, but cannot pick which pair is best (see above). We can make a reasonable estimate of albedo by using TPF-C to measure the planet's color, then appealing to the planets in our Solar System to convert a color to an absolute albedo. By adding TPF-I/Darwin measurements we can determine radius (above), then with brightness from TPF-C we can compute an accurate albedo. *SIM and TPF-C together give a first estimate of planet albedo. Adding TPF-I/Darwin gives a conclusive value of albedo, and therefore effective temperature and potential habitability.*

(v) Planet Mass. SIM measures planet mass directly and accurately. TPF-C and TPF-I/Darwin depend entirely on SIM for a true measurement of planet mass. If TPF-C and TPF-I/Darwin do not have a SIM value for planet mass, then they will use theory and examples from our Solar System to estimate masses (see above). *SIM plus TPF-C and TPF-I/Darwin are needed to distinguish among rock-, ice-, and gas-dominated planet models, and to determine with confidence whether the planet could be habitable.*

(vi) Surface Gravity. The planet's surface gravity is calculated directly using mass from SIM and radius from TPF-C and TPF-I/Darwin (see above). *Surface gravity governs whether a planet can retain an atmosphere or have plate tectonics (a crucial factor in Earth's evolution). Cooperative measurements are the only way to obtain these data.*

(vii) Atmosphere and Surface Composition. The TPF missions are designed to measure a planet's color and spectra from which we can determine the composition of the atmosphere and surface. For the atmosphere, TPF-C can measure water, molecular oxygen, ozone, the presence of clouds for a planet like the present Earth, and in addition it can measure carbon dioxide and methane for a planet like the early Earth or a giant planet. For the surface TPF-C can measure vegetation using the red edge effect (see below). TPF-I/Darwin will add to this suite of observations by measuring carbon dioxide, ozone, water, methane, and nitrous oxide using different spectroscopic features, and in general probing a different altitude range in the atmosphere. SIM is important to this interpretation because it provides planet mass, crucial to interpreting atmospheric measurements.

Both TPF-C and TPF-I/Darwin are needed in order to determine whether a planet is habitable, because they make complementary observations, as follows (assuming an Earth-like planet). Ozone has a very strong infrared (TPF-I) feature, and a weak visible (TPF-C) one, so if ozone is abundant, both can be used to extract the abundance. If ozone is only weakly present, then only the TPF-I/Darwin feature will be useable. Water as seen by TPF-C will be in the lower atmosphere of the planet, but as seen by TPF-I/Darwin it will be in the upper atmosphere; together both give a more complete picture of the atmosphere. Methane and carbon dioxide could be detected by TPF-I/Darwin at levels similar to present day concentrations in the Earth's atmosphere. Methane and carbon dioxide, in large amounts (as for the early Earth), can be detected by TPF-C. For large amounts of methane or carbon dioxide, TPF-I/Darwin will see mainly the amount in the upper atmosphere, but TPF-C will see mainly the amount in the lower atmosphere, so both are needed for a complete picture. In addition to these overlap topics, only TPF-C can potentially measure oxygen, vegetation, and the total column of air (Rayleigh scattering); likewise only TPF-I/Darwin can measure the effective temperature. TPF-I's wavelength coverage includes a spectral line of nitrous oxide, a molecule strongly indicative of the presence of life. Unfortunately, there is only a small hope of detecting this biomarker at low spectral resolution. *In short, SIM is needed for planet mass, TFP-C and TPF-I/Darwin are needed to characterize the atmosphere for habitability, and all three are needed to fully characterize the planet.*

(viii) Temporal Variability of Composition. Both TPF-C and TPF-I/Darwin potentially can measure changes in color and the strengths of spectral features as the planet rotates. These changes can tell us the length of day on the planet, and can indicate the presence of large oceans or land masses (with different reflectivities or emissivities, by analogy to Earth). Superposed on this time series of data could be random changes from weather patterns, possibly allowing the

degree of variability of weather to be measured. *The TPF missions can potentially measure variability of composition over time, which we know from our Earth to be an indicator of habitability.*

(ix) Presence of Water. Both TPF-C and TPF-I/Darwin have water absorption features in their spectra, so if water vapor is present in the atmosphere, we will be able to measure it. However habitability requires liquid water on the surface, which in turn requires a solid surface as well as a temperature that permits the liquid state; only with the help of a value of mass from SIM will we be able to know the radius, and when TPF-I/Darwin is launched, the temperature. *To know whether liquid water is present on the surface of a planet, we need mass data from SIM, and spectroscopic data from TPF-C or TPF-I/DARWIN.*

6.3 Biomarkers

The simultaneous presence of an oxidized species (like oxygen or ozone) and a reduced species (like methane) is considered to be a sign of non-equilibrium that can indicate indirectly the presence of life on a planet. The presence of a large amount of molecular oxygen, as on the present Earth, may also be an indirect sign of life. In addition since water is a prerequisite for life, as we consider it here, the presence of liquid water (indicated by water vapor and an appropriate temperature) is needed. Together these spectroscopically-detectable species are our best current set of indicators of life on a planet. *These markers will be measured exclusively by TPF-C and TPF-I, but to know that we are observing an Earth-like planet will require SIM data on mass. If we do (or do not) find biomarkers, we will certainly want to know how this is correlated with planet mass.*

The "red edge" of vegetation is a property of land plants and trees whereby they are very good reflectors of red light just beyond the long-wavelength limit of our eyes. This is a useful feature for measuring plant cover on Earth. If extrasolar planets have developed plant life like that on Earth, and if the planet is bright, has few clouds, and a lot of vegetated land area, then we may use this feature to detect living vegetation. *As for other biomarkers (above), we will want to correlate the presence of vegetation with the planet mass, requiring SIM as well as TPF-C.*

Table 3: Key Target Star Properties

Stellar Age	Evolutionary Phase
Spectral Type	Mass
Variability	Metallicity
Distance	Galactic Kinematics
Multiplicity	Giant Planet Companions
Exozodiacal Emission	Background Confusion
Position in Ecliptic	Position in Galaxy

7. TARGET STARS

7.1 Stars Suitable for SIM, TPF-C and TPF-I/Darwin

Table 3 suggests just a few of the considerations that will go into choosing the best targets for SIM, TPF-C and TPF-I/Darwin. Some of these are of a scientific nature, e.g. age, spectral type, and metallicity (which seems to be highly correlated with the presence of gas giant planets), while other constraints are more of an engineering nature: zodiacal emission, ecliptic latitude, binarity, variability, or the presence of confusing background objects. An extensive program of observation and data gathering must be an essential part of preparation for the planet finding program. A report entitled *Terrestrial Planet Finder Precursor Science* (*Lawson et al.*, 2004) describes a complete roadmap for the acquisition and assessment of relevant data. NASA has begun development of the Stellar Archive and Retrieval System (StARs) to provide a long term repository and network accessible database for this effort. A parallel and complementary effort is currently being developed in Europe.

The science teams for SIM, TPF-C and TPF-I/Darwin have developed preferred lists of 100-250 stars optimized for their particular instrumental capabilities as described in (*Traub et al.*, 2006):

(i) While closer, lower mass stars maximize SIM's astrometric signal (cf. Eqn 1), more luminous stars have a larger habitable zone (scaling as $L_*^{0.5}$) that offsets their higher mass and typically greater distance and eases the astrometric search for habitable planets in such systems. Assuming a 1 μas sensitivity limit, the minimum mass planet in the habitable zone detectable by SIM is given by $M_{min}(SIM) = 0.33 M_\oplus d L^{-0.26}$ for a planet at d pc of orbiting a star of luminosity L ($L_\oplus$) (*Traub et al.*, 2006).

(ii) With its limited angular resolution, TPF-C favors the closest stars with the larger habitable zones. Assuming a limiting contrast ratio of 10^{-10} or 25 mag, the minimum mass planet in the habitable zone detectable by TPF-C is given by $M_{min}(TPF-C) = 0.81 M_\oplus L^{1.5}$ (*Traub et al.*, 2006).

(iii) With its nearly unlimited angular resolution but more limited sensitivity, TPF-I/Darwin is best suited to the study of later spectral types with smaller habitable zones.

Table 4 lists the top 25 stars suitable for joint observation by TPF-I/Darwin, TPF-C, and SIM based on information gathered from the science groups of each mission. These stars have no known companions within $10''$ and an inner edge to their habitable zones (roughly the orbit of Venus) larger than 62 mas. Stars with ecliptic latitudes in excess of 45^o are excluded due to the need to shade the TPF-I/Darwin telescopes from the sun. Also included in the table is the angular extent of the inner edge of the habitable zone (the orbit of Venus scaled by the square root of the stellar luminosity) and any indication of an infrared excess from exo-zodiacal dust as determined by IRAS or Spitzer. This information is also portrayed graphically in Plate 3 which shows stars observable in common between SIM, TPF-C, and TPF-I/Darwin.

7.2 Zodiacal Dust and Planet Detection

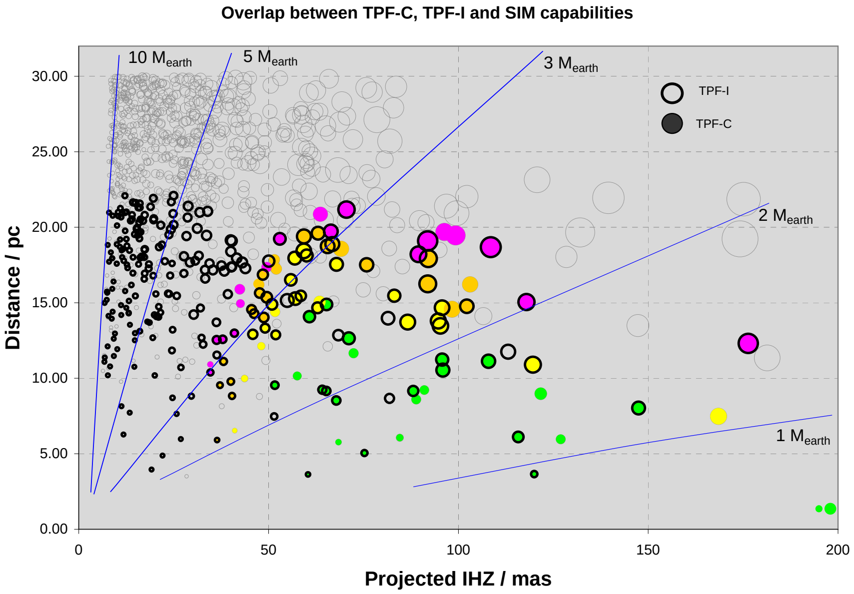

Fig. Plate 3.— Potential targets for SIM, TPF-C, and TPF-I/Darwin are shown in terms of stellar distance versus the angular extent of the inner edge of the habitable zone (IHZ, which is set to be the orbit of Venus scaled by the square root of the stellar luminosity). Stellar diameter is indicated by size of the symbol. High priority TPF-C targets are shown with filled symbols shaded to denote different probabilities of completeness (*Brown*, 2005) in a survey for Earth-sized planets in the center of the habitable zone (green denotes highest completeness ($> 75\%$); purple is lowest ($< 25\%$); yellow is intermediate). TPF-I/Darwin targets are shown as black open circles. The loci of minimum masses detectable by SIM in 125 2-Dimensional visits are also shown. Table 4 gives a subset of the most favorable targets.

Table 4: Likely Targets for TPF-C, TPF-I/Darwin and SIM

Hip	HD	Name	Spec Type	Dist. (pc)	Inner HZ (mas)	SIM Mass Limit ($M_\oplus$[1])	Zodiacal Emission
8102	10700	τ Ceti	G8V	3.65	120	0.97	Yes, IRAS
19849	26965	DY Eri	K0/1V	5.04	75	1.43	No 24/70, Nearby[2]
99240	190248	δ Pav	G6/8IV	6.11	116	1.29	No 24/70, FGK[2]
64924	115617	61 Vir	G5V	8.53	68	1.99	Strong 70, FGK
64394	114710	β Com	G0V	9.15	88	1.81	No 24/70, FGK
15457	20630	κ Cet	G5V	9.16	65	2.1	N/A, FGK
108870	209100	ϵ Ind	K4/5V	3.63	60	1.35	N/A, FGK
57443	102365	GL 442A	G3/5V	9.24	64	2.13	No 24/70, SIMTPF[2]
14632	19373	ι Per	G0V	10.53	96	1.88	N/A, FGK
12777	16895	13 Per	F7V	11.23	96	1.95	No 24/70, SIMTPF
53721	95128	47 UMa	G0V	14.08	61	2.72	No 24/70, FGK
47592	84117	GL 364	G0V	14.88	65	2.72	No 24/70, FGK
56997	101501	61 Uma	G8V	9.54	52	2.4	No 24/70, FGK
22449	30652	π^3 Ori	F6V	8.03	147	1.34	N/A, FGK
78072	142860	γ Ser	F6V	11.12	108	1.83	No 24/70, FGK
25278	35296	GL 202	F8V	14.66	63	2.74	No 24/70, FGK
16852	22484	GL 147	F8V	13.72	87	2.27	N/A, FGK
80337	147513	GL 620.1A	G3/5V	12.87	52	2.8	No 24/70, SIMTPF
57757	102870	β Vir	F9V	10.9	120	1.73	No 24/70, FGK
7513	9826	υ And	F8V	13.47	95	2.15	N/A, FGK
3909	4813	GL 37	F7V	15.46	59	2.91	No 24/70, SIMTPF
116771	222368	ι Psc	F7V	13.79	95	2.19	N/A, FGK
71284	128167	σ Boo	F3V	15.47	83	2.49	N/A, Dirty Dozen[2]
86796	160691	μ Ara	G3IV/V	15.28	57	2.93	No 24/70, FGK
40843	69897	χ Cnc	F6V	18.13	60	3.13	N/A, FGK

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[1] Assumes 125 2-Dimensional Visits

[2] Zodiacal emission at 24 or 70 μm in Nearby Stars MIPS Survey, *Gautier et al.*, (2006) in preparation; FGK survey (*Beichman et al.*, 2005a, 2006); *Bryden et al.*, 2006); or the SIMTPF Comparative Planetology survey (*Beichman et al.* 2006, in preparation); MIPS/IRS survey of the "Dirty Dozen", bright, potentially resolvable disks, *Stapelfeldt et al.* (2006) in preparation. N/A denotes data not yet available in a given survey.

Planetary systems include many constituents: gas-giant planets, ice-giant planets and rocky planets as well as comet and asteroid belts. Understanding the interrelated evolution of all these constituents is critical to understanding the astronomical context of habitable planets and life. For example, the presence of a large amount of zodiacal emission from the debris associated with either a Kuiper Belt of comets or a rocky zone of asteroids may indicate conditions hostile to the habitable planets due to a potentially high rate of bombardment. At the same time, the transfer of water and other volatile (organic) species from the outer to the rocky planets in the habitable zone may be an essential step in the formation of life. Thus, from a scientific standpoint, we want to gather information on disks at all stages in the evolution of planetary systems, including debris disks surrounding nearby stars. TPF-C, TPF-I/Darwin, and JWST will work in conjunction to make images and spectra of scattered light and thermally emitted radiation from a large number of targets, spanning distant stars (25-150 pc) with bright disks where planets may still be forming to nearby systems with zodiacal clouds no brighter than our own.

From an engineering standpoint, zodiacal dust is a critical factor for direct detection of planets due to increased photon shot noise and potential confusion with zodiacal structures. Sensitivity calculations for various TPF-I/Darwin and TPF-C designs suggest that the integration time needed to reach a certain level increases by a factor of 2-3 for zodiacal levels roughly 10 times the solar system's. Spitzer is carrying out a number of programs to assess the level of exo-zodiacal emission. Initial results suggest that only 15% of solar type stars have more than 50 times the solar system's level of zodiacal emission at 30 μm, corresponding to material just outside the habitable zone, beyond about 5 AU (*Beichman et al.*, 2006; *Bryden et al.*, 2006). This result is encouraging, but must be expanded to more TPF target stars using Spitzer and Herschel, and to lower levels of zodiacal emission using interferometric nulling at 10 μm on the Keck and LBT interferometers. The combination of these results will yield the "luminosity function" of disks for statistical purposes and allow us to screen potential targets. As an example of the sort of problem that can arise is the remarkable star HD 69830, a 2-4 Gyr old K0 star at 14 pc that might be a TPF target except for a zodiacal dust level in the habitable zone that is 1,400 times higher than seen in the solar system (*Beichman et al.*, 2005b). While SIM may be able to identify planets around this star astrometrically, no direct searches of the habitable zone will be possible.

8. DISCUSSION AND CONCLUSIONS

The exploration of extrasolar planetary systems is a rich and diverse field. It calls for measurements with many kinds of instruments, as well as theoretical studies and numerical modeling. To discover and characterize extrasolar planets that are habitable and to be sure beyond a reasonable doubt that we can detect life, we need to measure the statistical distribution of planet diameters, the masses of nearby planets, and the spectra at visible and infrared wavelengths. Each of the missions listed in Table 1 is a vital element of the program. Not only does each mission by itself produce its own compelling science, but the ensemble will provide a coherent set of data that will advance our understanding better than could any single mission.

The exciting scientific promise described in preceding sections will not happen cheaply or overnight. The Great Observatories program for astrophysics spanned more than a decade between the first and last launches — HST in 1990 and Spitzer in 2003 — and was still longer in gestation. While the transit missions COROT and Kepler are being readied for flight, the "Great Observatories" for planet finding will take a generation of scientific and political advocacy: SIM PlanetQuest has completed its technology development, has been endorsed repeatedly by the US science community, and awaits final NASA approval; TPF-C and TPF-I/Darwin are well along in their programs of technology development and will need strong endorsement by US and European scientific communities in coming years. Interest is TPF goals is growing in Japan as well (*Tamura and Abe* 2006). JWST is moving into its construction phase and will provide many observations useful to the planet finding endeavour.

While the study of extrasolar planets is a new field of research with a relatively small number of (young) practitioners, our field is growing rapidly. We will fare well in any assessment of the importance of our field to progress in astronomy and of the great interest our program holds for the general public. We will also fare well in any assessment of the value of these planet finding facilities for general astrophysical investigations: SIM has already allocated a significant amount of observing time to a broad suite of general astrophysics; TPF-C will provide wide-field optical imaging with unprecedented sensitivity and angular resolution to complement JWSTs mid- and near-IR capabilities; TPF-I/Darwin will break new ground with milliarcsecond mid-IR imaging and micro-Jy sensitivity.

Near-term political considerations must not discourage us as we plan this new era of planetary exploration. *While these proceedings were going to press, information about the NASA budget suggested the possibility of long delays for SIM, the possible cancellation of TPF-C/I, and a reduction in a variety of grants programs*. Yet Kepler and COROT are still going ahead, so that some of the exciting new data discussed in this paper will become available in the next few years. Despite delays and reverses, the remainder of the program outlined above will one day be carried out since it is grounded in fundamental scientific principles.

To accomplish our goals, we must demand from the funding agencies the budgets needed to nurture young scientists and senior researchers, to prepare the difficult technologies of nulling, large space optics, and formation flying, and eventually to build these "Great Observatories." With our colleagues, we must argue forcefully for a balanced program based on scientific priorities free from parochial considerations of individual facilities or institutions. 20^{th} Century cosmologists expanded our conception of the Universe with the discovery of galaxies, the expanding universe, and dark matter. 21^{st} Century planet finders will expand our conception of humanity's place in the Universe with the discoveries of other habitable worlds and possibly of life itself.

Acknowledgments. We would like to thank Peter Lawson for creating Figure Plate 1 and Oliver Lay for his work on putting together Plate 3 and Table 4. The science teams of SIM, TPF-C, and TPF-I, and in particular Jim Kasting, Mike Shao, and Ken Johnston, helped develop the synergy arguments presented in Section 6. Steve Unwin, who has been unstinting in his efforts on behalf of SIM and TPF over many years, helped to organize this special session on planet finding from space. We are grateful to Bo Reipurth for his heroic efforts in putting together this wonderful meeting. Some of the research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

Angel J. R. P. and Woolf N. 1997, *Astrophys. J., 475*, 373.

Baglin A. (2003) *Adv. Space Res, 31*, 345.

Barnes J. W. and Fortney J. J. (2003) *Astrophys. J., 588*, 545.

Beichman C. A. (1998) In *Exozodiacal Dust Workshop*, (Dana Backman and Larry Caroff, eds.), pp. 149-159. (NASA Technical Report).

Beichman C. A. (2000) In *Planetary Systems In The Universe: Observation, Formation And Evolution*, (Alan Penny, Pawel Artymowicz, Anne-Marie LaGrange and Sara Russell, eds.), in press.

Beichman C. A. *et al.* (2005a) *Astrophys. J., 622*, 1160-1170.

Beichman C.A., Bryden G., Gautier T.N., Stapelfeldt K.R., Werner M.W. *et al.* (2005b) *Astrophys. J., 626*, 1061-1069.

Beichman C. A., Tanner A., Bryden G., Stapelfeldt K.R., Werner M. W., and Rieke G. H., *et al.* (2006) *Astrophys. J., 639*, 1166-1176.

Bordé P., Rouan D. and Léger A., 2003, *Astron. Astrophys., 405*, 1137-1144.

Borucki W.J., Koch D.G., Lissauer J.J., Basri G.B., Caldwell J.F., *et al.* (2003), *Proc. SPIE, 4854*, 129-140.

Bracewell R. (1978) *Nature, 274*, 780-781.

Brown R. A. (2005) *Astrophys. J., 624*, 1010-1024.

Brown T. M. and Charbonneau D., Gilliland R. L., Noyes R. W. and Burrows A. (2001) *Astrophys. J., 552*, 699-709.

Bryden G., Beichman C.A., Trilling D.E., Rieke G.H., and Holmes E.K. *et al.* (2006) *Astrophys. J.,636*, 1098-1113.

Charbonneau D., Allen L.E., Megeath S.T., Torres G., Alonso R., and Brown T.M., *et al.* (2005), *Astrophys. J., 626*, 523-529.

Chelli A. (2005) *Astron. Astrophys., 441*, 1205-1210.

Dekany R., Stapelfeldt K., Traub W. Macintosh B., Woolf N., Colavita M., Trauger J. and Ftaclas, C. (2006) *PASP*, submitted.

Deming D. and Seager S. and Richardson L. J. and Harrington J. (2005) Nature, *434*, 740-743.

Gilliland R.L., Brown T.M., Guhathakurta P., Sarajedini A., and Milone E.F., *et al.* (2000) *Astrophys. J., 545*, L47-51.

Gilliland R., (2005) in *Astrobiology and JWST. A Report to NASA* http://www.dtm.ciw.edu/seager/NAIAFG/JWST.pdf.

Gillon M., Courbin F., Magain P., and Borguet B. (2005) *Astron. Astrophys., 442*, 731-744.

Green J.J., Basinger S.A., Cohen D., Niessner A.F., Redding D.C., Shaklan S.B., and Trauger J.T. (2003) *Proc. SPIE, 5170*, 38-48.

Green J.J., Beichman C. A., Basinger S.A., Horner S., Meyer M., Redding D.C., Rieke M., and Trauger J.T. (2005) *Proc. SPIE, 5905*, 185-195.

Guyon O., Pluzhnik E.A., Galicher R., Martinache F., Ridgway S.T., and Woodruff R.A. (2005) *Astrophys. J., 622*, 744-758.

Herbst T.M. and Hinz P.M. (2004) *Proc. SPIE, 5491*, 383-384.

Krist J. E. (2004) *Proc. SPIE, 5487*, 1284-1295.

Kuchner M.J. and Traub W.A. (2002) *Astrophys. J., 570*, 900-908.

Lawson P., Unwin S., and Beichman C. A. (2004) *Terrestrial Planet Finder Precursor Science*, JPL Tech. Rpt., #04-014, http://planetquest.jpl.nasa.gov/documents/RdMp273.pdf

Lindegren L. and Perryman M.A.C. (1996) *Astron. Astrophys (S), 116*, 579-595.

Marcy G. W., Butler R. P., Fischer D. A., Laughlin G., Vogt S. S., Henry G. andPourbaix D. (2002) *Astrophys. J., 581*, 1375-1388.

Marcy G. W., Butler R. P., Fischer D., Vogt S., Wright J. T., Tinney C. G. and Jones H. R. A. (2005) *Progress of Theoretical Physics Supplement, 158*, 1

Martin S. R., Gappinger R. O., Loya F. M., Mennesson B. P., Crawford S. L., and Serabyn E. (2003) *Proc. SPIE, 5170*, 144-154.

Mennesson B. P., Johnston K. J., and Serabyn, E. (2004) *Proc. SPIE, 5491*, 136-137.

MoutouC., PontF., BargeP., AigrainS., AuvergneM.,and BlouinD., *et al.* (2005) *Astron. Astrophys., 437*, 355-368.

Muterspaugh M. W., Lane B.F., Konacki M., Burke B.F., Colavita M.M., and Kulkarni S.R., Shao M. (2005) *Astron. J., 130*, 2866-2875.

Perryman M. A. C., de Boer K. S., Gilmore G., Høg E., Lattanzi M. G., et al. (2001) *Astron. Astrophys., 369*, 339-363.

Quirrenbach A. (2000) In *From Extrasolar Planets to Cosmology: The VLT Opening Symposium*, (J. Bergeron and A. Renzini, eds.), pp. 462-467. Berlin/Heidelberg: Springer-Verlag.

Quirrenbach A. (2002) In *From Optical to Millimetric Interferometry: Scientific and Technological Challenges.* (Surdej J., Swings J. P., Caro D., and Detal A., eds.), pp.51-67. Université de Liège,

Quirrenbach A., Coudé du Foresto V., Daigne G., Hofmann K. H., and Hofmann R., *et al.* (1998) *Proc. SPIE Vol., 3350*, 807-817.

Rivera E., Lissauer J., Butler R. P., Marcy G. W., Vogt S. Fischer D. A., Brown T., and Laughlin G. (2005) *Astrophys. J., 634*, 625-640.

Rowe J.F., Matthews J.M., Seager S., Kuschnig R., Guenther D.B., (2006) *Bull. Am. Astr. Soc, 207*, 110.07.

Sahu K., *et al.* (2005) HST Proposal ID#10466, http://adsabs.harvard.edu/cgi-bin/nph-bib_query? bibcode=2005hst..prop.6787S&db_key=AST

Schneider G. (2002) *Domains of Observability in the Near-Infrared With HST NICMOS and Large Ground-based Telescopes*, http://nicmos.as.arizona.edu:8000/REPORTS/

Seager S. and Hui L. (2002) *Astrophys. J., 574*, 1004-1010.

Serabyn E., Booth A. J., Colavita M.M., and Creech-Eakman M.J., *et al.* (2004) *Proc. SPIE, 5491*, 806-807.

Shao M. and Colavita M.M. (1992) *Astron. Astrophys., 262*, 353-

358.

Shao M., Wallace J.K. Levine, B.M., and Liu D.T. (2004) *Proc. SPIE, 5487*, 1296-1303.

Tamura M. and Abe L. (2006), in IAU Colloquium #200, Nice, France, in press.

Traub W. A., Carleton N. P., and Porro I. L. (1996) *Journal of Geophysical Research*, *101*, 9291-9296.

Traub W. A. and Vanderbei R.J. (2005) *Astrophys. J.*, *626*, 1079-1090.

Traub W.A, Kasting J., Shao M., Johnston K. J., and Beichman C. A. (2006) in IAU Colloquium #200, Nice, France, in press.

Trauger J.T., Burrows C., Gordon B., and Green J.J., *et al.* (2004) *Proc. SPIE, 5487*, 1330-1336.

Unwin S. C. (2005) In *Astrometry in the Age of the Next Generation of Large Telescopes*, ASP Conference Series, Vol. 338, (P. Kenneth Seidelmann and Alice K. B. Monet, eds.) pp. 37-42. San Francisco: Astronomical Society of the Pacific.

Vanderbei R. J., Kasdin N. J., and Spergel D. N. (2004) *Astrophys. J.*, *615*, 555-561.

Walker G. *et al.* (2005) *Astrophys. J.*, *635*, L77-L80.