The Search for Habitable Worlds

> There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system . . . The countless worlds in the universe are no worse and no less inhabited than our Earth.
>
> *Giordano Bruno*
> *De L'infinito Universo*
> *E Mondi, 1584*

Do Earth-like planets exist in the habitable zones of Sun-like stars within 20 pc?

What are the masses and mass distributions of exoplanets?

Are planetary orbits co-planar?

How do multiplanet systems evolve?

What is the frequency of planets for stars of different mass? Among binary stars? Stars with dust disks? Evolved stars and white dwarfs? Stars with planets found with radial velocity surveys?

Is a high abundance of heavy elements correlated with giant planet formation? With rocky planets?

Are multiple fragmentation events or core accretion in a dense disk responsible for the formation of planets?

1 Detecting Earth-Like Planets

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ABSTRACT

Astrometry is the only known technique for detecting planets of Earth mass in the habitable zone around solar-type stars within 20 pc. These Earths are close enough for follow-up observations to characterize both the planets and dust disks by infrared imaging and spectroscopy with planned future missions such as the James Webb Space Telescope (JWST) and the Terrestrial Planet Finder/Darwin. Employing a demonstrated astrometric precision of 1 µas and a noise floor under 0.1 µas, SIM Lite can make multiple astrometric measurements of the nearest 60 F,- G-, and K-type stars during a five-year mission to detect the ~0.3 µas amplitude induced by a benchmark Earth-mass planet orbiting in the habitable zone (1 AU) about a solar-mass star at 10 pc. SIM Lite can detect rocky planets in a broad range of masses and orbital distances, and it will measure their masses and three-dimensional orbital parameters, including eccentricity and inclination, to provide the properties of terrestrial planets in general. The masses of both the new planets and the known gas giants can be measured unambiguously, allowing a direct calculation of the gravitational interactions, both past and future. Such dynamical interactions inform theories of the formation and evolution of planetary systems, including the Earth-like planets. Thus, SIM Lite directly tests theories of rocky planet formation and evolution around Sun-like stars and identifies the nearest potentially habitable planets for later spaceborne imaging, e.g., with Terrestrial Planet Finder and Darwin. SIM was endorsed by the two recent Decadal Surveys and it meets the highest-priority goal of the 2008 AAAC Exoplanet Task Force.

1.1 Introduction to Exoplanets: Toward Rocky Worlds

The past decade has seen the discovery of over 300 exoplanets, found by precise Doppler measurements, transits, and microlensing. The known exoplanets have masses from ~10 M_{Jupiter} down to nearly 5 $M_{\oplus}$. The $M \sin(i)$ distribution of Doppler-detected exoplanets (Figure 1-1) reveals increasing numbers of planets with decreasing mass in the Jovian domain. But for lower masses, below a Saturn-mass (0.3 M_{Jup}), there is an apparent decline in the number of planets with decreasing mass. This apparent paucity of low-mass planets is almost certainly an artifact of sensitivity, as the Doppler technique struggles to detect lower-mass planets. Thus, we have reached a roadblock in planetary science and astrobiology. Without knowledge of the occurrence rate or properties of terrestrial planets, the confluence of geology, astrophysics, and biology remains poorly informed.

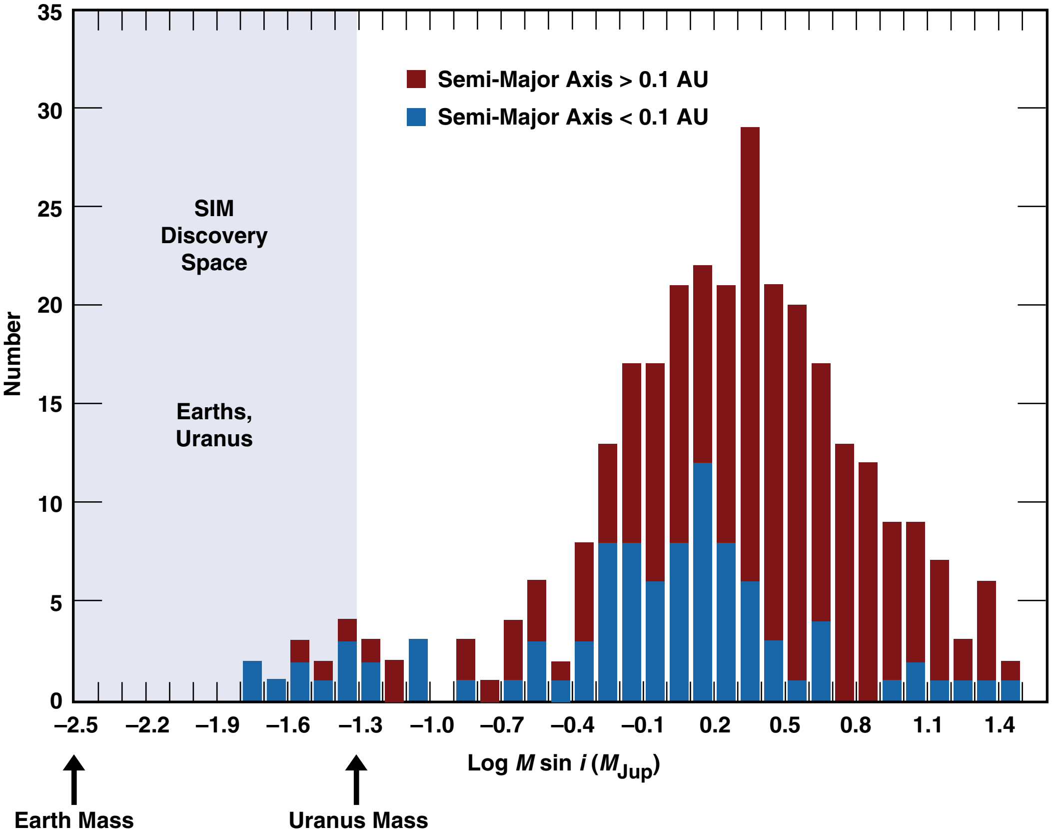


Figure 1-1. Distribution of minimum masses, $M \sin(i)$, for known exoplanets, on a log mass scale. The rise of jovians toward lower masses is real, implying more Saturns than super-Jupiters. But the decline in the sub-Jupiter domain toward lower masses is likely an artifact of the declining sensitivity to low-mass planets by the Doppler technique. Detecting Earth-like planets around nearby Sun-like stars requires a space-borne astrometric mission. Blue represents planets orbiting within 0.1 AU; red represents planets beyond 0.1 AU.

The study of exoplanets is driven in part by a fundamental question of the human desire to better understand life and our role in the Universe: is the phenomenon of life unique to Earth or frequent elsewhere? A reasonable starting point is to search for life similar to that found on Earth. Life as we know it appears to require a few crucial ingredients that guide this search, including liquid water on relatively small, rocky planets. Only a small range of star–planet separations result in planet temperatures suitable for liquid water; our search for candidate life-hosting planets requires the ability to find planets in the regime (near 1 AU for Sun-like stars). While some planets have been found at this separation around other stars, they are gas giants like Jupiter. Current techniques are insensitive to the smaller signatures that result from smaller Earth-like planets. Once candidate planets are found, the next logical step will be to confirm whether water (and other life-related chemicals) exists on those planets. This will require isolating the spectrum of the planet's light from that of the bright star it orbits. Only for the closest systems to the Sun will it be feasible for future missions to detect the light from a faint planet near a bright star. To reliably interpret the spectrum, it will be important to know the planet's mass. Thus, the path to finding candidate habitable planets requires a new observatory capable of simultaneously addressing four search criteria:

It must (1) search the stars closest to the Sun with enough sensitivity to (2) detect Earth-sized planets at (3) star–planet separations that allow for liquid water, and (4) measure their masses.

Existing techniques do not meet these four criteria. Only spaceborne astrometry is capable of detecting Earth-mass, rocky planets around nearby Sun-like stars while simultaneously measuring their masses, a key property of planets. The technology development of SIM Lite during the past decade has established an instrument architecture that is thoroughly tested and reviewed, demonstrating the crucial sub-μas astrometric precision to detect rocky planets. Having met all technology milestones, SIM Lite's historic search for other Earths can begin as soon as funding becomes available.

A recent 15-year strategy for detecting Earth-like planets was developed in a study conducted by the Astronomy and Astrophysics Advisory Committee's Exoplanet Task Force commissioned by NASA and NSF. The final report from the task force recommends that in the 6- to 10-year time frame, the U.S. should "Launch and operate a space-based astrometric mission capable of achieving 0.2 μas sensitivity to detect planet signatures around 60 to 100 nearby stars."

This recommendation agrees with the past three Decadal Surveys, notably the Field, Bahcall, and McKee-Taylor Reports, that have strongly promoted development of a μas astrometric program for detecting and characterizing extrasolar planets.

1.2 Basic Astrometric Physics and SIM Lite Detectability

The semi-amplitude of the angular wobble, α, of a star of a given mass, M_*, and distance, D, due to a planet of a given mass, M_p, orbiting with a semi-major axis, a, is given by:

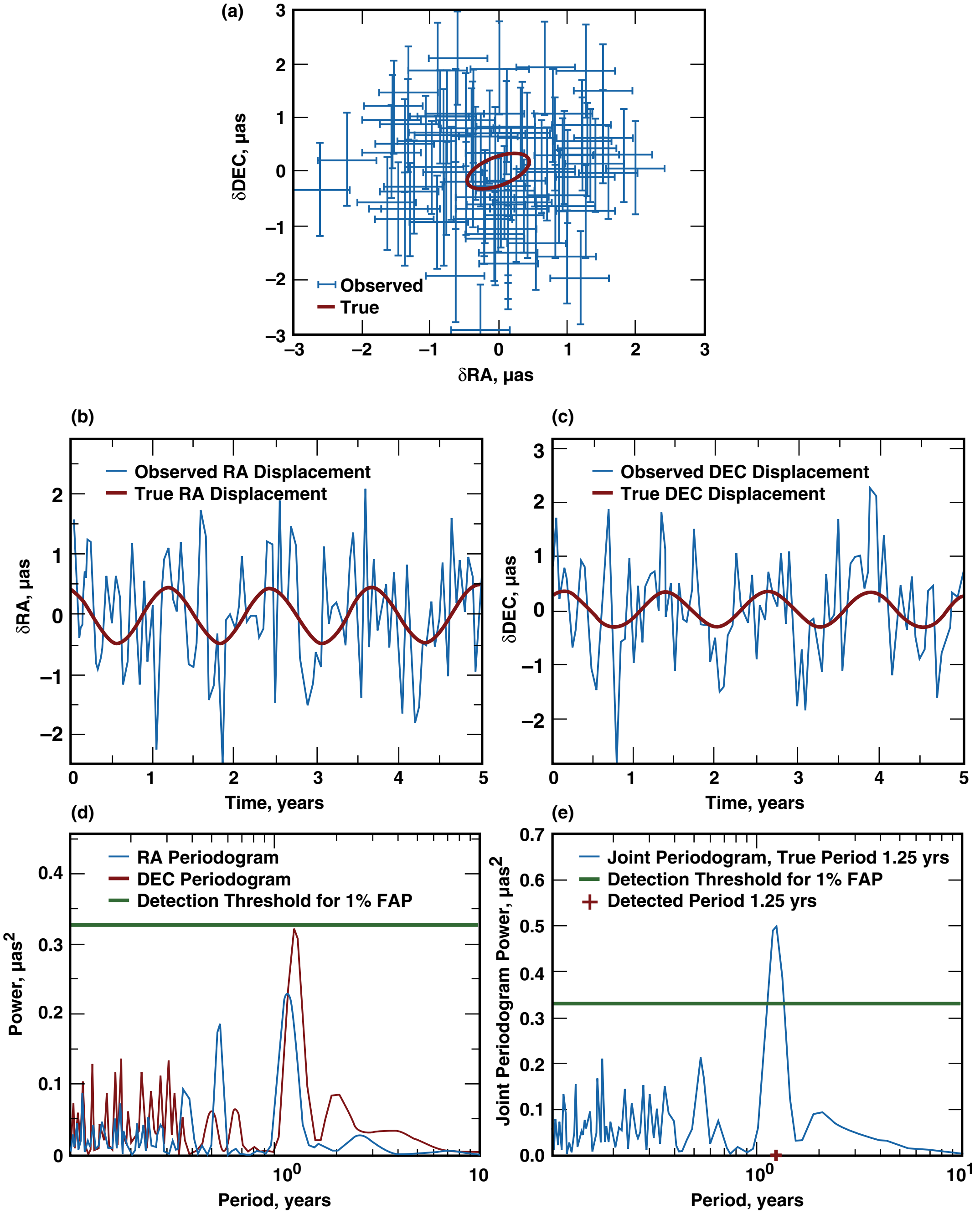
$$\alpha = 3.00 \frac{M_\odot}{M_*} \frac{M_p}{M_\oplus} \frac{a}{(1\ \mathrm{AU})} \frac{(1\ \mathrm{pc})}{D}\ \mu\mathrm{as}$$

The benchmark case is an Earth-mass planet orbiting 1 AU from a solar-mass star located 10 pc away. For such a planet, the astrometric semi-amplitude, α, is 0.3 μas. Using specially chosen and vetted reference stars located within a degree of the target star, SIM Lite achieves an astrometric precision of 0.82 μas per observation. (Note that this "narrow-angle" mode of SIM Lite yields higher astrometric precision than the "wide-angle" mode by using angularly nearby reference stars rather than generic grid stars for reference.) With SIM Lite's narrow-angle astrometric precision of 0.82 μas per observation, many observations are needed to detect the benchmark signal, as described below.

The intrinsic periodicity of the astrometric signals from planets greatly enhances their detectability. In contrast, errors, both photon-limited and systematic, are unlikely to be strictly periodic (except near 1.0 year). If any periodic errors did occur, they would be quickly revealed in the astrometry of the ensemble of target stars and reference stars, allowing such periodicities to be ignored (and perhaps removed). Thus, planet signals increase, relative to noise, with the square root of the number of observations because of the strict temporal coherence orbital motion obeys.

Standard time-series analysis provides a quantitative measure of the increasing signal-to-noise ratio (and decreasing false alarm probability) that accrues with an increasing number of observations. A periodogram analysis of simulated astrometric data from planets shows that the signal rises over the noise in Fourier space with the square root of the number of observations, as expected (Catanzarite et al. 2006). Figure 1-2 shows one such example in which the astrometric signature of a 1.5 $M_\oplus$ planet is inferred from 200 simulated SIM Lite observations. The periodograms of the simulated astrometry in both RA and DEC reveal the 1.5 $M_\oplus$ planet with a false-alarm probability (FAP) under 1 percent (Unwin et al. 2008).

Figure 1-2. Simulation of the astrometric detection of a planet with SIM Lite. The simulation assumes 100 measurements in RA and 100 in DEC over a mission of five years duration. The planet has a mass of 1.5 $M_\oplus$ orbiting at 1.16 AU from a 1.0 $M_\oplus$ star at a distance of 10 pc from Earth. This example was chosen to illustrate a system close to the limit of detectability with SIM Lite. (a) Sky plot showing the astrometric orbit (solid curve) and the individual SIM measurements with error bars. (b), (c) The same data as in (a) but shown as time series along with the astrometric signal projected onto RA and DEC. (d) Periodograms of the data plotted in (b) and (c). (e) Joint periodogram of data from (b) and (c). The horizontal lines in (d) and (e) show the level above which the false-alarm probability is less than 1 percent. The peak near $P = 1.2$ years is the astrometric signal of the 1.5 $M_\oplus$ planet. Note that the planet is not detected in RA or DEC alone, but is detected with a false-alarm probability of well below 1 percent in the joint periodogram.



For the benchmark case of an Earth-mass planet orbiting at 1 AU around a solar-mass star at 10 pc, roughly 500 measurements at 0.82 μas accuracy are needed to attain a signal-to-noise ratio (SNR) of 5.8, the approximate threshold for detection. In general, if σ is the one-axis RMS noise per differential measurement, N is the number of SIM Lite visits, and α_{THRESH} is the threshold astrometric amplitude detectable with a probability of 50 percent, we have:

$$\alpha_{THRESH} = SNR \times \sigma / N^{1/2}$$

SIM Lite offers the astrometric precision and duration (five years), along with a noise floor below 0.1 μas, to detect Earth-mass planets around the ~60 nearest FGK stars.

1.3 SIM Lite: Making the First Catalog of Earth-Like Planets

SIM Lite remains the only technically demonstrated method for identifying rocky, Earth-mass planets around Sun-like stars within 20 pc, during the 2010 to 2020 decade. A competitor, the Doppler technique, suffers from the intrinsic “jitter” of ~1 m/s due to photospheric spots, convection, and acoustic oscillations, preventing detection of the tiny radial velocity signature (0.1 m/s) of a habitable Earth-like planet around a Sun-like star. Another competitor, direct imaging, remains to be developed technically; and indeed, three architectures of the Terrestrial Planet Finder and the European counterpart, Darwin, remain to receive full technical vetting. Yet another approach, detecting transits of planets as they block starlight, works for the rare planets whose orbits are edge-on as seen from Earth. That probability is only 1 in 200 for planets in the habitable zones of Sun-like stars. Most nearby planetary systems would be missed. Other planet detection methods, such as microlensing, are not well suited for nearby stars. Figure 1-3 shows the detectability of rocky planets by a variety of techniques, none of which is competitive with SIM Lite in the domain of the habitable zone around solar-mass stars.

Nonetheless, a key long-term goal is to directly image and take spectra of Earth-like planets. The well-known challenge for imaging missions is to overcome the combination of the extreme contrast between, and the small angular separations of, the star and planet, along with the sheer intrinsic faintness of the planet. Rocky planets orbiting 1 AU from stars 10 pc away will have a V-band magnitude of V = 28 mag separated only 0.1 as from a magnitude 5 star. Astrometry is well optimized for discovering such low-mass planets around the nearest stars, to identify the best targets for later missions that can directly image the planets.

Indeed, the ExoPTF Report states on page 60, “The most promising way to mitigate the cost of space-based direct imaging is 1) to identify targets before the direct imaging mission is flown….” By first

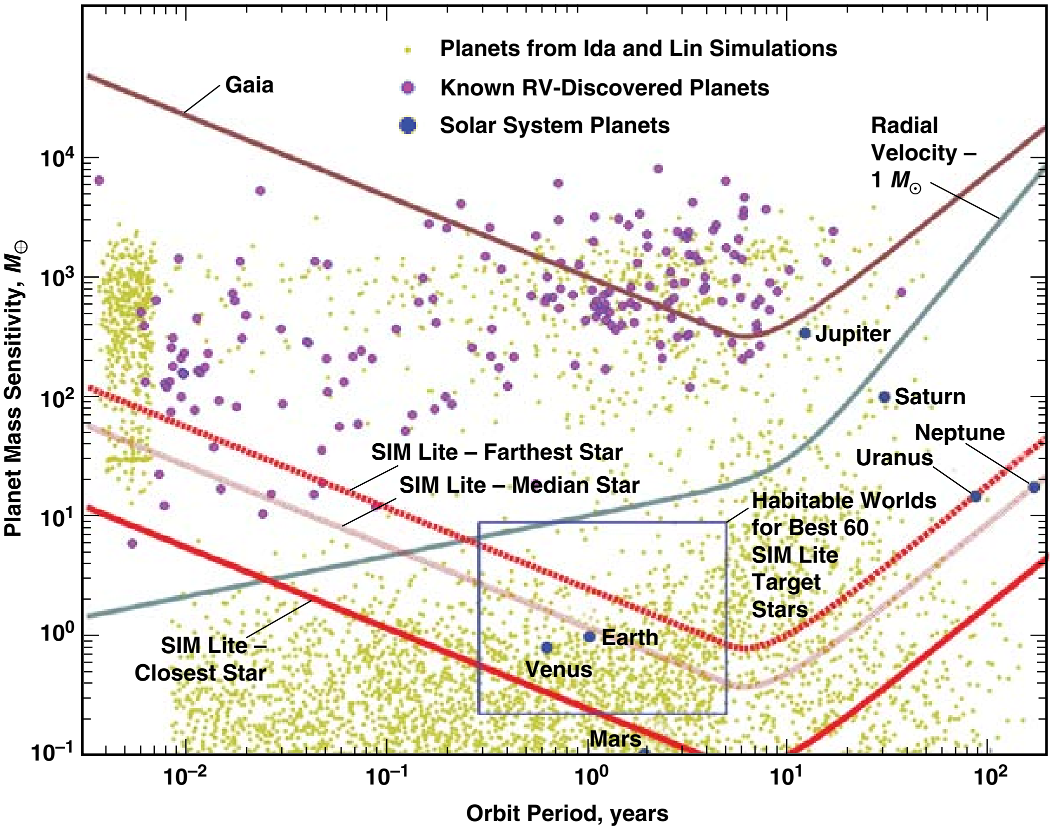


Figure 1-3. Detectability of planets by SIM Lite, Gaia, and radial velocity (RV). The regions above each curve are accessible to the respective mission/technique. The two red curves show the detection thresholds for the closest and farthest among the 60 FGK stars to be probed by SIM Lite. Small rocky worlds circling in the habitable zones of these stars will fall within the box near the bottom of the figure. SIM Lite offers excellent detectability of these planets. In contrast, RV (accuracy ≈ 1 m/s) and Gaia lack the sensitivity to probe this region. The pale green dots show predicted planets from planet formation theory (Ida and Lin 2004), the purple dots show known planets, mostly from RV work, and the blue dots show the planets of our Solar System.

deploying SIM Lite to find and characterize Earth-like planets around nearby stars, the cost of a future direct-imaging mission is reduced and the scientific output increased. Moreover, the risk of failure is greatly reduced, and the specifications of any imaging system and a spectrometer are definable, based on the orbit and expected size of the planet, all stemming from SIM Lite observations.

1.3.1 Earths Are Detectable Despite the Presence of Other Planets

A significant question is whether SIM Lite can detect Earth-mass planets despite the astrometric "noise" contributed by other planets, both other terrestrials and gas giants. Terrestrials and asteroids located both inward and outward of the habitable zone will create a forest in the power spectrum, making the detection of one Earth-mass planet difficult. Giant planets orbiting well outside 1 AU will cause an astrometric curvature partially absorbed (incorrectly) in the solution for proper motion. As part of a comprehensive double-blind simulation (described in Chapter 3), 12 mock planetary systems were generated containing Earth-mass planets in the habitable zone, to carry out a "double-blind test" of detectability. Four systems were single-planet systems with a terrestrial planet in the habitable zone, and eight were solar system analogs with planets and orbit parameters within 10 percent of the corresponding solar system planets. The corresponding astrometric data and radial velocity data were generated for each mock system with realistic errors and cadence. The astrometric and velocity data were analyzed by four competent teams without knowledge of the input planets. The teams "discovered" virtually all of the Earth-mass planets (masses 0.3 to 10 $M_\oplus$) that should have been detectable had they been alone. (Section 1.2 shows that planets with astrometric amplitude greater than $5.8\,\sigma / N^{1/2}$ are detectable, where σ is the single-measurement error and N is the number of observations.) A major conclusion of the double-blind study is that the presence of additional planets in a planetary system causes almost no degradation in the detectability of Earth-mass planets. This double-blind test showed that SIM Lite is capable of detecting Earth-like planets embedded in multiple-planet systems. (See Chapter 3 for a more complete treatment of multiple-planet systems.)

1.3.2 Earth Search Yields

The exact expenditure of SIM Lite time spent searching for other Earths remains open to discussion (cf. Figure 1-4). To survey the nearest 64 stars to a threshold of 1 $M_\oplus$ at 1 AU scaled to stellar luminosity takes 40 percent of the nominal SIM Lite mission time, with a lifetime of five years. Among the 64 stars, the most distant 10 of them require 25 percent of that time due to their distance and the 1 $M_\oplus$ detection goal. An alternative plan is to observe only 54 stars, which requires only 30 percent of SIM Lite mission time, while adhering to the 1 $M_\oplus$ threshold. The saved time can be used to observe an additional 37 stars at a lower threshold of 2 $M_\oplus$ (photon-limited errors twice as large are achievable with one-fourth the exposure time). Such a relaxed threshold offers useful statistical advantages gleaned from the 37 stars, over the gains of 10 more stars surveyed at the highest precision. Simulations of actual planetary systems are needed to optimize the use of SIM Lite observing time.

1.3.3 Earth-Analog Characterization Facilitated by SIM Lite

Splitting the discovery and characterization of other Earths between two sequential missions — namely an easier indirect discovery program, i.e., SIM Lite, and a later imaging and spectroscopy program, i.e., Terrestrial Planet Finder/Darwin — allows for technology to be developed for the latter with specified detection thresholds. Such a two-step approach offers methodical, cumulative, and complementary information about other Earth-like planets. It should be noted that SIM Lite stands on its own, providing

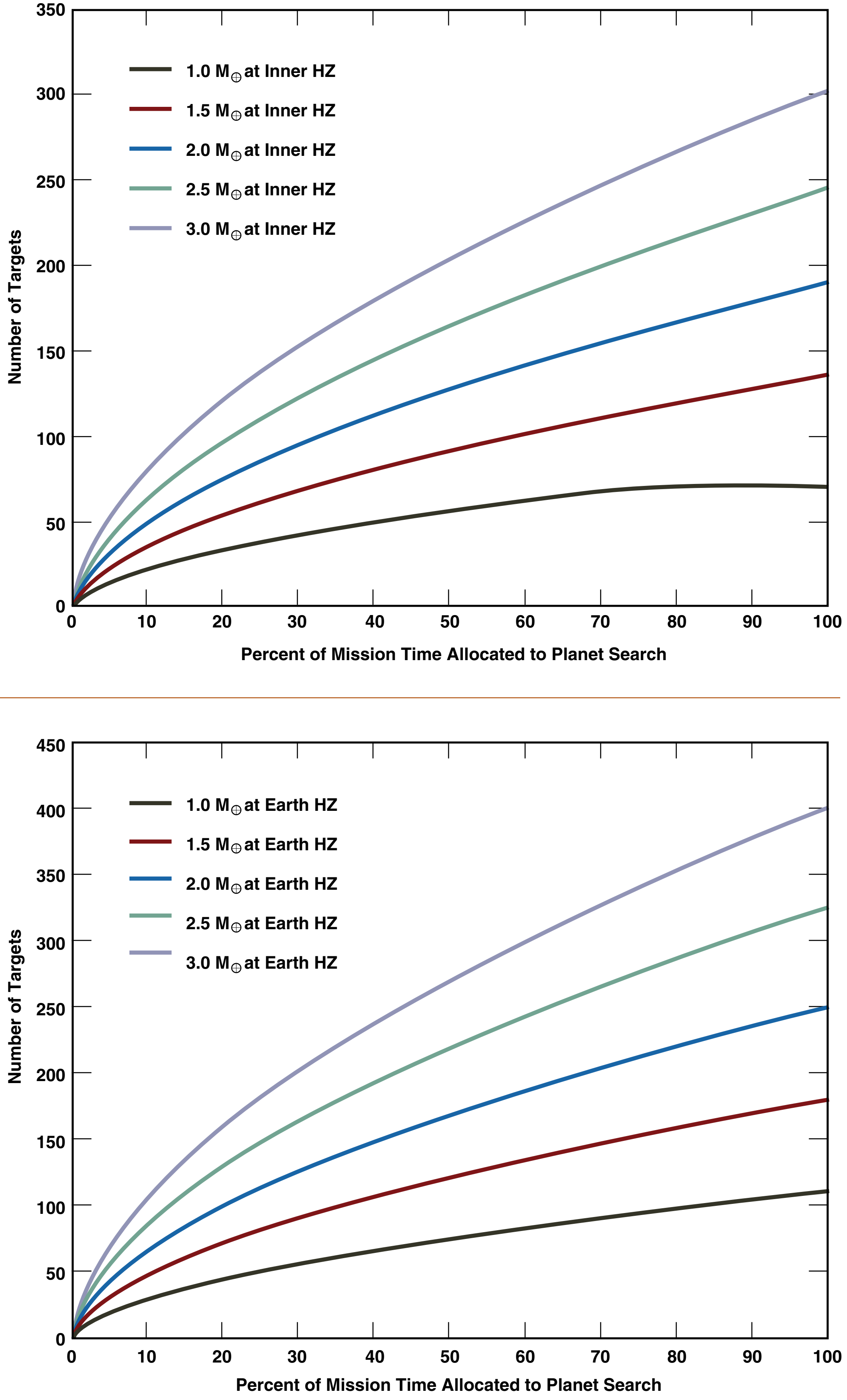


Figure 1-4. The number of stars that can be searched for Earth-analogs depends strongly on the planet mass threshold adopted by SIM Lite. Top: Mass sensitivities are presented at the Inner Habitable Zone (IHZ), which is 0.8 AU scaled to the square root of luminosity. The flat plateau in the black curve exists because there are no more target stars that can be measured to 1 $M_\oplus$ in fewer than the maximum number of measurements set by the instrument noise floor. Bottom: Mass sensitivities are at the Earth Habitable Zone (EHZ), which is 1.0 AU scaled to the square root of luminosity. A differential measurement error of 1.4 µas for a 900 s "standard visit" and a mission lifetime of five years are assumed. Note that the ordinates have different scales. (Charts prepared by Joseph Catanzarite.)

the detections of rocky planets, their masses, and their full, three-dimensional orbits in the habitable zone (1 AU) of the host star. Moreover, in combination with Doppler observations (see Chapter 3), SIM Lite data will permit the full characterization of all planets, rocky and giant, out to about 5 AU. This is an especially intriguing prospect, given that many of the stars that SIM Lite will examine are already known from Doppler measurements to have one or more giant planets. If archival Hipparcos data are also included, it may be possible to infer the presence of giant planets beyond 5 AU, although with less-complete characterization. Such an inventory of rocky and giant planets around individual nearby stars will offer valuable constraints on the formation and dynamical evolution of planetary systems in general.

1.4 Measuring Masses: A First Step Toward Characterizing Exoplanets

Determining planet mass by space-based astrometry is clearly necessary in conjunction with direct imaging. Because mass is a fundamental property of planets, the science return of a direct imaging mission would be reduced without SIM Lite and would suffer significant ambiguities. A dot does not a planet prove, and even a spectrum that reveals some particular molecular constituent (such as methane or carbon dioxide) cannot securely distinguish between rocky planets and ice giants. Using either transits (that provide radius) or spectroscopy (offering chemical assays of the atmosphere), the distinction between ice giants and rocky planets may not be solid. The uncertain albedos of ice giants and rocky planets will prevent a secure mapping of reflected light fluxes to planet radius, leaving the planetary masses even less secure. Thus, measuring a planet's mass will remain crucial for interpreting any spectrum of the planet's atmosphere, and certainly bears on its habitability. Only by measuring the gravitational effect of the planet on its host star can the planet's mass be measured, and only astrometry can do the job. A µas astrometric mission is required to empirically characterize Earth-like planets.

A precise measurement of the planet mass is important when attempting to understand the formation and dynamical evolution of any individual planetary system. Only with accurate measurements of mass, unencumbered by sin (*i*) ambiguities, can dynamical models be attempted securely. Not only may planet masses correlate with the mass or chemical composition of the host star, the mass of a particular planet having unexpected properties can spur theoretical research into its formation mechanisms (e.g., orbital migration, eccentricity excitation). Theorists will watch for planets having intriguing combinations of properties of their mass, orbits, and host star. Table 1-1 illustrates some of the possibilities for Earth-like planets. Thus, SIM Lite's ability to characterize individual planet systems, rather than just statistical averages, will help reveal the physical processes by which they formed.

Table 1-1. Planet properties enabled by SIM Lite plus visible and infrared spectra.

Parameter	Planet Property Derived	Planet Property Implied
Planet Mass	Density, Surface Gravity, Atmosphere	Likelihood of plate tectonics; atmospheric mass, scale height, lapse rate, and surface pressure and temperature
Orbit Semi-Major Axis	Temperature	Potential habitability, liquid water
Orbit Eccentricity	Variation of Temperature	Thermal time constant of the atmosphere, mass of the atmosphere
Orbit Inclination	Co-planar Planets?	
Orbital Period		

1.5 SIM Lite Contributions to the Theory of Rocky Planet Formation

The theory of the formation of rocky planets and super-Earths, along with their subsequent dynamical evolution, has been developed by Ida and Lin (2008) and Kennedy and Kenyon (2008) (and references therein). They start with a collection of thousands of rocky planetesimals having kilometer sizes similar to modern asteroids and comets. They simulate the collisions and sticking of these objects, allowing them to grow and gravitationally perturb each other until final planets emerge. The dynamical effects of the gas (drag, density inhomogeneities) and the condensation of ice are included in the calculation. Gas serves both as a dissipative medium to exchange angular momentum and energy with the planet (often causing inward migration) and also as the reservoir of material that can accrete onto the rocky cores, making ice and gas giants. Ice condensation also creates density discontinuities in the dust component of the disk, causing reversals in density and ionization gradients that can trap planetesimals.

Figure 1-5 shows the result of a recent simulation by Ida and Lin (2008), displaying the distribution of final planets in a two-parameter space of planet mass and orbital distance. Remarkably, planets of mass 1 to 30 $M_{\oplus}$ are predicted to be rare within 1.5 AU. That is, super-Earths and Neptunes are expected to be rare, largely because once inside the ice line they migrate inward quickly, destined to be lost in the star (or parked in a close-in orbit). More-massive rocky cores accrete gas quickly, becoming gas giants. Thus, this theory makes a remarkable prediction that planets in a decade range larger than Earth may be rare. Indeed, our Solar System has no such super-Earths. This remarkable prediction may be directly tested by SIM Lite, as planets orbiting within 0.5 to 1 AU, with masses of 5 to 30 $M_{\oplus}$, will be detected easily.

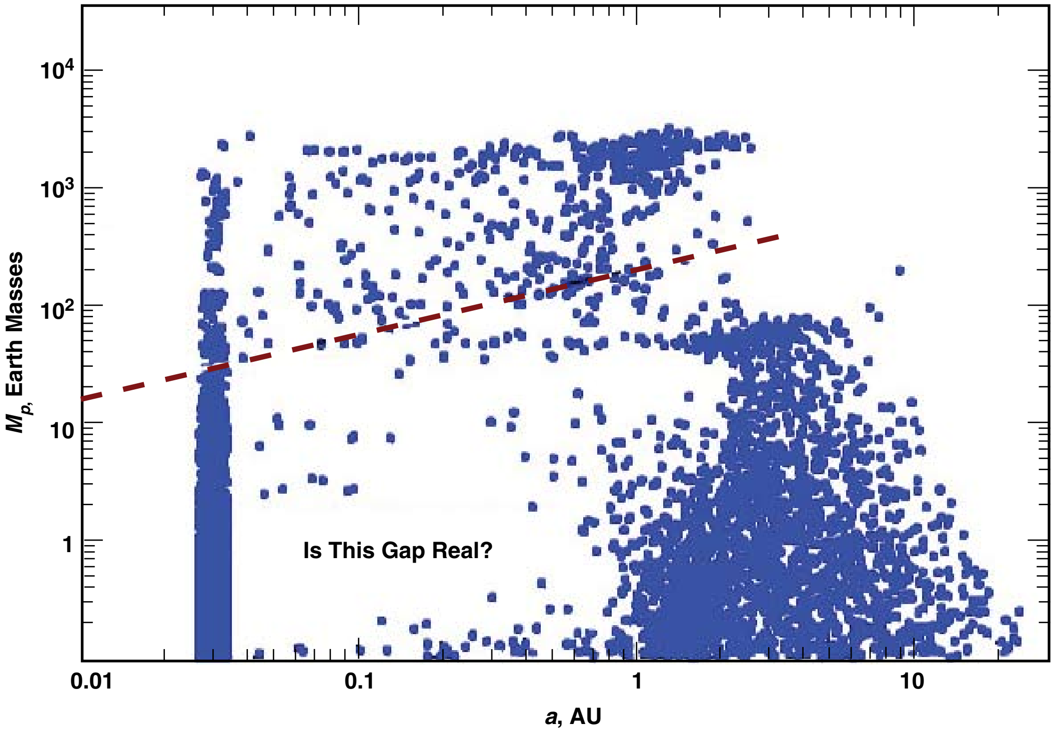


Figure 1-5. Predicted masses and orbital distances of planets from a Monte Carlo simulation of planet formation, from Ida and Lin (2008). The calculation includes growth of planetesimals and effects of gas drag. Note the predicted planet "desert" between 1 to 30 $M_{\oplus}$ within 1.5 AU. SIM Lite will test such predictions.

If the Ida and Lin prediction of a mass desert is contradicted by SIM Lite observations, the theory must be significantly modified with new physics. Successful theories will have to determine orbital stability of all planets over long time periods, include orbital resonances, and determine the interactions in multiple planet systems. The chemistry of both the gaseous and dust components will also require considerable care.

Indeed, theoretical work on planet formation mechanisms for the entire range of planet masses, from terrestrial planets, to ice giants, to gas giants, is necessary in order to place the exoplanet discoveries in the context of planetary system formation theories. Terrestrial planet formation is strongly influenced by gas giant planet formation and orbital evolution. A complete theory of planet formation is needed in order to understand the formation of any one component.

1.6 Other Exoplanet Research

1.6.1 Lifting the Mass-Inclination Ambiguity in RV Planets

The large majority of known exoplanets have ambiguous masses: their unknown inclination angles permit only lower-limit mass estimations. This mass ambiguity disappears in the astrometric determinations of dynamical mass, since astrometry determines the system inclination angles. Specific targets of interest where unambiguous masses are important include those with multiple planets where planet–planet interactions might become significant. The inclination ambiguity does not strongly affect the derived distributions of planet masses (i.e., Figure 1-5). However, for individual planetary systems, it is important to know the full specification of masses and orbits to compare with the structure of the systems predicted by theorists. Ida and Lin et al. (2004) demonstrate how the knowledge of the unambiguous dynamical masses guides the development of the theory. Unknown inclination angles (and hence masses) degrade the quality of the comparison between observation and theory, especially when planet–planet interactions are significant.

1.6.2 Follow-up of Kepler Candidate Earths

The candidate Earth-like planets revealed by Kepler will raise the question: Are they really Earths? Instead, they could be grazing-incidence eclipsing binaries with a brighter third star that dilutes the photometric dimming. SIM Lite offers a valuable way to check some of these potential false-positives. SIM Lite can detect the astrometric motion of the photocenter of the triple-star system, or indeed detect the confused interference fringes from the three stars. With a resolution of 10 µas, SIM Lite can also interferometrically resolve binaries in the Kepler field. The fractional dimming corresponding to an Earth-sized planet is 1 part in 10,000 around a Sun-sized star. If instead, the dimming is caused by a diluted, eclipsing binary, the astrometric shift will be 1 part in 10,000 of the angular separation between the eclipsing binary and the brighter, third star. Ground-based work will detect such “third” stars unless they are within ~0.5 as. For separations of ~0.5 as, the displacement will be 50 µas, easily detectable by SIM Lite. For separations of 0.1 as, the displacement will be 10 µas, still detectable by SIM Lite. Thus, SIM Lite offers one of the very few methods to determine the false-positive rate of the Kepler mission.

1.7 Future Research: Imaging Earths

Astrometric observations not only identify which stars host Earth-like planets but also yield the full orbital ephemeris of the planet, specifying the angular position of the planet relative to the star at all times. Knowing the angular position and separation of the planet as a function of time specifies the optimal observation times for any direct imaging programs. One would attempt imaging and spectroscopy of rocky planets only when the planet is well outside the direct imaging instrument's inner working angle for the star. (The inner working angle is the radius within which the glare of the star, caused by diffraction and mirror microroughness, prevents detection of the planet.) This optimization is not possible without prior SIM Lite observations.

Such optimization can be quite valuable. A benchmark Earth-like planet resides only 0.1 as from the host star at maximum elongation. The inclination of the orbital plane flattens the apparent trajectory of the planet relative to the star. For a typical inclination of ~45 deg, the planet spends most of its time located well within 0.1 as of the star, only briefly poking out to ~0.1 as. There is no way to know when those favorable moments of maximum elongation occur without prior SIM Lite observations. For Earth-like planets 10 billion times fainter than the star, a high premium is placed on timing the imaging and spectroscopic effort to those moments when the elongation of the planet from the star is maximum.

SIM Lite will establish the planet orbital ephemeris, allowing imaging efforts to be timed when the planet is widely separated from the star. Indeed, the technical requirements of a direct imaging mission may be reduced because it need only detect planets when they are in optimal configurations relative to the star. Similarly, SIM Lite will establish the orientation of the orbit in space. This provides an additional increase in efficiency for any direct imaging mission that achieves its highest contrast for a limited range of angles and orientations. Such a mission could choose an observation time and roll-angle that would maximize the SNR for detecting the planet.

1.8 The Impact of Gaia

Gaia is a European astrometry mission with launch planned for 2011. It will achieve a precision of ~100 μas per measurement (to V = 15) on 30 million stars (and reduced precision for up to a billion fainter stars), with each star revisited 1 to 250 times (typically ~90 one-dimensional measurements) over the course of the mission. It is a survey mission without the capability of pointing at a particular object at a particular time. Thus, neither the timing nor cadence of revisits can be controlled for a high-priority target. Gaia will saturate for very bright stars ($V \lesssim 6$), including the stars closest to Earth that are highest priority when looking for Earth-like planets.

Thus, Gaia will fall short of discovering Earth-like planets due to its limited precision and cadence. The 100× better precision, and the pointing optimization of SIM Lite, are required to achieve this goal. Furthermore, the number of repeated measurements for a given target is much larger for SIM Lite, with 200 to 500 (two-dimensional) measurements on high-priority targets, which yield higher sensitivity to lower mass planets, and better coverage of orbital phase to accurately measure the orbit. Good orbital coverage is necessary to adequately characterize a planet's orbit well enough to inform a future direct imaging mission about the optimal observing time.

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