The Space Interferometer Mission (SIM) and The Search for Terrestrial Planets

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A major goal of the SIM mission is the search for Earth-like planets in the habitable zones of nearby stars. By Earth-like we mean a predominantly rocky planet with a mass greater than about 0.5 $M_\oplus$ and thus capable of retaining an atmosphere, but less than about 10 $M_\oplus$ which is the theoretically expected transition between gas/ice giants and rocky planets. By "habitable zone" we mean located in an orbit similar to that of the Earth such that there is the possibility of liquid water being found on the surface, i.e. 1 AU scaled by the square root of the stellar luminosity.

Other techniques, such as microlensing and transits, are statistical in nature and offer limited (if any) opportunities for follow-up, particularly for low mass planets. Radial velocity studies of extremely quiescent stars may push down to terrestrial mass range but only for small semi-major axes and even then with only limited orbital information. Only astrometry, and only with the single measurement accuracy of SIM, offers the chance of finding Earth-like counterparts in the habitable zones of our closest stellar neighbors. When a direct detection mission such as the Terrestrial Planet Finder eventually becomes a reality, the information from SIM will play a key role in advancing our knowledge of other Earths. (Beichman et al 2006; Traub et al. 2006).

If we combine the basic astrometric signal of a planet, θ, of mass m_p orbiting a star of mass m_* at a distance d with Period P(yr):

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

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

with the size of the habitable zone $(1\,AU(L/L_\odot)^{0.5})$ and a parameterized mass-luminosity function, we get that the minimum mass detectable by SIM. For SIM's sensitivity level of 1 μas single measurement accuracy this minimum mass is

$$M_{min}(SIM) = 0.33 M_\oplus d L^{-0.26} \qquad (2)$$

for a planet of orbiting a star at d pc of luminosity L ($L_\odot$) (Traub et al. 2006). While closer, lower mass stars maximize SIM's astrometric signal (cf. Eqn 1), more luminous stars have a larger habitable zone that offsets their higher mass and typically greater distance and eases the astrometric search for habitable planets in such systems.

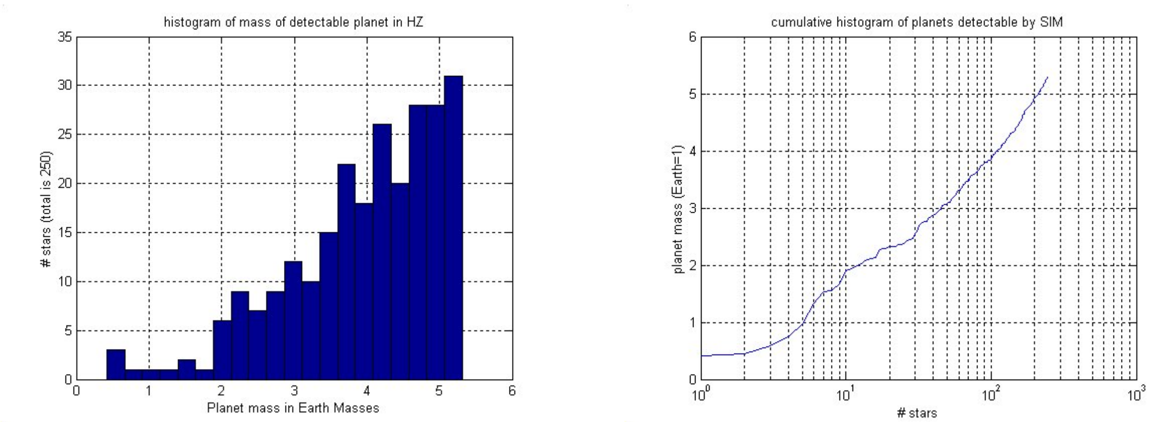

Fig. 1.— The number of stars for which terrestrial mass planets of a particular mass might be detected in specific mass bins (left) or cumulatively (right).

Figure 1 plots the number of stars around which a planet of mass M can be found assuming every star has 1 planet in the habitable zone. From the figure and Table 1 we can see that there are 45 stars around which SIM could detect a planet of $3M_\oplus$ or lower mass. SIM can easily detect a terrestrial planet ($< 10M_\oplus$) around every one of the 250 stars in the deep searches conducted by the Marcy and Shao key projects.

These numbers are based on 100 measurements per star over 5 years for the 250 stars on the search list. Simulations were carried out in which a detection is defined using a $2D$ periodogram with a threshold for detection set for a false alarm probability of 1%. The

Table 1. SIMs Planet Yield (Cumulative)

Number of Stars	Planet Mass Limit
5 stars	$< 1M_\oplus$
12 stars	$< 2M_\oplus$
45 stars	$< 3M_\oplus$
110 stars	$< 4M_\oplus$
250 stars	$< 5.3M_\oplus$

accuracy of each measurement is 1 μas, corresponding to 1.4 μas for the star's position relative to the reference frame defined by the reference stars. While the planetary signal varies with each star, all stars were searched to the same noise level. Thus, if we define the signal to noise ratio (SNR) as the ratio of the amplitude of a sine wave perturbation of 1 μas to a noise level of 1.4 μas (single measurement accuracy) divided by the square root of the number of observations (100), then the end of mission noise level is 0.14 μas, for a resulting SNR=7.

It is important to note that SIM's sensitivity for planets did not change appreciably after the recent redesign. First, the ultimate accuracy of $\sim 1\,\mu$as was not greatly affected by the change in baseline from 10 to 9 m due to margin in the system performance. Second, SIM planet search targets have been selected to be bright, $\sim$ 7 mag, stars. For these stars, astrometric accuracy is not dominated by increased photon noise in a given integration time due to the loss of collecting area. Before the redesign, however, the reference and target stars were both assumed to be about 10 mag and to take roughly the same amount of integration time. After the redesign, the planet search programs were re-optimized to take roughly the same amount of total integration time by observing 7 mag targets and 10 mag reference stars.

1. References

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