SIM Lite Detection of Habitable Planets in P-type Binary-Planetary Systems

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ABSTRACT

Close binary stars like spectroscopic binaries create a completely different environment than single stars for the evolution of a protoplanetary disk. Dynamical interactions between one star and protoplanets in such systems provide more challenges for theorists to model giant planet migration and formation of multiple planets. For habitable planets the majority of host stars are in binary star systems. So far only a small amount of Jupiter-size planets have been discovered in binary stars, whose minimum separations are 20 AU and the median value is about 1000 AU (because of difficulties in radial velocity measurements). The SIM Lite mission, a space-based astrometric observatory, has a unique capability to detect habitable planets in binary star systems. This work analyzed responses of the optical system to the field stop for companion stars and demonstrated that SIM Lite can observe exoplanets in visual binaries with small angular separations. In particular we investigated the issues for the search for terrestrial planets in P-type binary-planetary systems, where the planets move around both stars in a relatively distant orbit.

1. INTRODUCTION

Since 1990's the search for exoplanets has concentrated on single stars, and all binary stars have been excluded from the observation lists. The reason for this is the technical difficulty of discerning the stellar companion's perturbations in precision radial-velocity measurements. It is well known, however, that more than 50% of F, G, and K stars in the solar neighborhood are binary or multiple star systems. Close binary stars represent a unique class of targets to harbor exoplanets, in particular to host habitable planets. A big argument is whether the stellar binarity inhibits or promotes formation of planets. Are there further restrictions on how close the planets are located in close binaries? More important, planets in binary stars provide critical constraints for different theories on formation and evolution of exoplanets. Beginning in the 21st century some observation programs have started to use so-called two-dimensional correlation technique to probe exoplanets in binary stars. Also, several projects systematically look for companions of existing planets' host stars. The number of exoplanets orbiting one of the components of a binary or a multiple star system grows rapidly. It is important, however, to notice that several important scientific issues have not been addressed.

First, the orbital inclinations of planet-host binary stars are unknown for most of the planets determined by radial velocity measurements. Also, the inclinations of exoplanet orbits are unknown. More important, for all exoplanets in binaries, we don't know if the planets and stellar companions in the same system are coplanar, or perpendicular. This has never been emphasized enough for the study of the formation and evolution mechanisms of exoplanets. Second, so far only S-type binary-planetary systems, wherein planets orbit only the primary, or the secondary star, have been probed by precision RV and imaging. No circumbinary planet, i.e. one revolving around both components of a binary star system (so-called P-type binary-planetary system), has been discovered. Third, current spectroscopic searches are successful for SB1 (only the primary's spectral lines can be seen) binary stars only. The sizes of planets in binary systems are all as big as that of Jupiter. That's why a –20 AU limit" to the presence of planets in close binary systems has been accepted and discussed. If micro-arcsecond astrometry with the SIM Lite mission can be applied, many Neptune or Earth mass planets can be discovered. It is important to determine accurate masses of planets, not the minimum masses. In that case the –20AU limit" may be meaningless and a new theory will be developed.

In this work we calculate the spectral responses of the science interferometer of SIM Lite and estimate impact of its field stop in the instrument design. We investigate detection of exoplanets in close visual binary stars with SIM Lite, and discuss the estimates of astrometric errors. Secondly, we concentrate on detection of terrestrial planets in P-type binary-planet systems. The period distribution of possible candidate binary stars for detection of exoplanets is calculated. The modeling of physical and dynamical parameters for such binary-planetary systems is studied. Finally we summarize the unique capability of the SIM Lite mission for detection of exoplanets in P-type binary-planet systems.

2. SIM Lite field stop and observation of exoplanets in visual binaries

The SIM Lite instrument includes a science interferometer for astrometric observation and a guide interferometer and a guide telescope in roughly orthogonal directions to determine the orientation of the baseline of the science interferometer. Two siderostats separated by a baseline in the science interferometer determine the radius of the primary beam (~λ/D) and the delay beam (~ (λ /Δλ)*(λ /B)). For SIM Lite the aperture of siderostats is 0.5 m and the baseline is 6 m, the primary beam and the delay beam are about 0.”26 and 0.”03, respectively. The siderostats of the science interferometer, however, are not filled aperture mirrors. Each has a central hole of 30 cm where a big corner-cube is used for the SIM Lite metrology system. Thus the throughput has been reduced and spectral responses have been changed. Although the SIM Lite instrument has one fixed baseline only, the large wavelength range covers a factor of two for wavelengths from red to blue. So a single measurement of SIM Lite covers a large range of spatial frequencies. SIM Lite’s spectrometer has good sensitivity for light from 0.45 μm to 0.95 μm, and detected fringes are spread on 80 spectral channels. Such a chromatic instrument with variable orientation of the baseline provides an opportunity for bandwidth synthesis. For the current annular aperture of outer diameter of 50 cm and inner diameter of 30 cm the fraction of the total energy verses different radius of field stops for various wavelengths are presented in Figure 1. It can be seen that throughputs at long wavelengths are significantly reduced for small field stops.

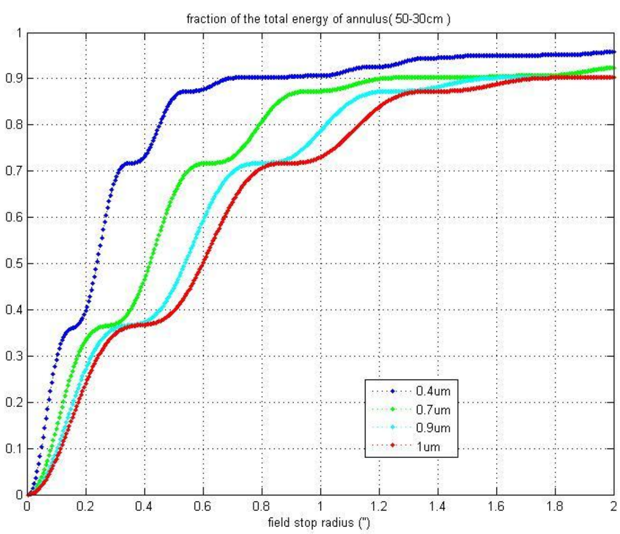

Figure 1 Fraction of the total energies vs. radii of the field stops (arc sec)

Science observations with SIM Lite assume that only the target star, as a single point source, will produce fringes on the detector. In such case measured position changes are all referred to its space motion. In practice, background objects will cause significant shift of the photo center and produce systematic position errors relative to its true positions. In addition the reduced signal-noise ratio will decrease measurement precisions. That’s why the SIM Lite instrument applies a field stop to limit the field of view (FOV) to about 2”—4” in diameter. It is obvious that the smaller the field stop is, the better the astrometry accuracy is. If the diameter of the field stop reaches 2.”4 or bigger, the fraction of the total energies in Figure 1 has small changes of a few percent for wide wavelengths.

Figure 2 shows the transmission efficiency of science interferometer verses wavelength for different sizes of the field stop. It can be seen that efficiencies at the red end of the spectrum are much worse than that at the blue end. Also, the quantum efficiencies of the CCD detector are lower in the red even for a red-enhanced device. In order to observe GKM stellar types of targets large field stops are preferred, in particular for faint objects. With respect to other SIM Lite science projects which have targets in crowded fields in the sky, small sizes of the field stop are required.

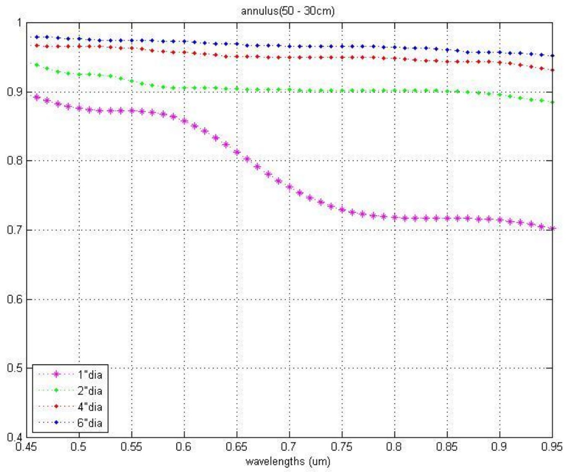

Figure 2 Fraction of total energy vs. wavelength for different sizes of field stops

In order to search for exoplanets in binary stars, the companion's influences cannot be ignored. Figure 3 demonstrates how flux ratios of a companion which has the same brightness as the target changes with separation between target and companion for different sizes of field stops. For a field stop of 2" in diameter, if a binary star with magnitude difference of 1 mag has a semi-major axis of 2" or larger, the flux ratio can be reduced to 0.002, and for a binary with 2 magnitude difference the flux ratio is as small as 0.0008.

The SIM Lite instrument has two sets of instrument parameters for selection: one set has annular apertures of 35/18 cm with a field stop of 4"; another is 50/30 cm annular with a 2."4 field stop. The flux ratios of the two designs are shown in Figure 4. For 35/18 cm apertures the flux ratio has a sharp drop at angular separation of 3", and for 50/30 cm apertures the big drop of flux ratio happens around 2". For the currently adopted field stop of 2."4 in diameter it is obvious that the SIM Lite mission can comfortably observe exoplanets in visual binaries with separation of 2" or larger.

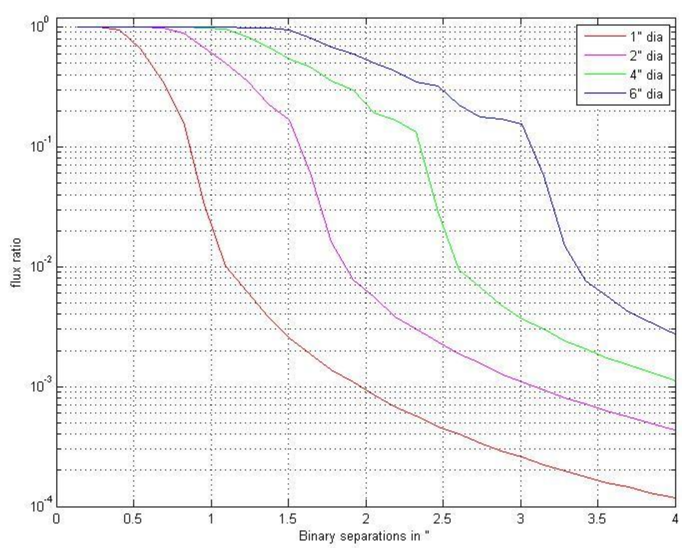

Figure 3 Flux ratios for an equal brightness binary vs. binary separations for different sizes of field stops

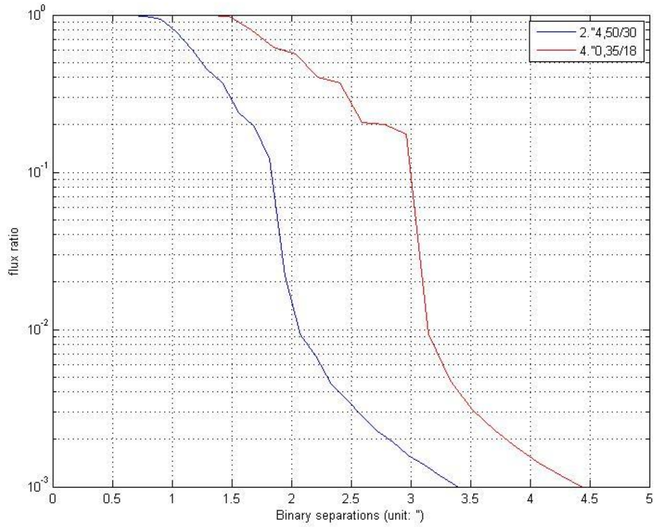

Figure 4 Flux ratio comparisons between two sets of instrument designs. One has smaller field stop and larger annular aperture in blue; another has larger field stop and smaller annular aperture in red.

SIM Lite's measurement error (ζ) can be described as follows:

$$\sigma = \frac{c\lambda}{B * Vis(\lambda) * \frac{S(\lambda)}{N(\lambda)}}$$

$$S(\lambda) = \int Star * Mirrors * Coating * BS * FS * CCD * d\lambda$$

$$N(\lambda) = N_{photon} + N_{read} + N_{dark} + N_{sky}$$

where B is the baseline, Vis(λ) represents visibility losses, signal S(λ) is the integral of star photons and the attenuations of mirrors, AR coatings(Coating), beam spread (BS), field stop (FS), and CCD detector over the whole wavelength range. Noise, N (λ), includes photon noise, read noise, dark current of the CCD detector, and sky background noise. It is important to keep in mind that the field stop cannot fully obstruct the photons from the companion star which is outside of the field of view of the science interferometer. The intensity on the fringe detector for different instrument parameters as shown in Figure 3 and 4 will increase the noise N (λ) and reduce the visibility Vis (λ). Calculations made using the formulas above indicate that for typical visual binaries with separation of 2" or larger and magnitude difference $\Delta m > 1$ mag, the astrometric error from the companion star is negligible. It is easy for the SIM Lite mission to detect exoplanets in visual binary stars with either larger separation, or larger magnitude difference, or both.

3. Modeling of P-type binary-planetary systems

Many candidate P-type binary-planetary systems are spectroscopic binaries. Only these binaries have semi-major axis of < 1 AU and may possibly have terrestrial planets around 1 – 4 AU from their primary star. For such spectroscopic binaries the angular separations are 10 mas or less. So far no spectroscopic techniques can search for exoplanets in such kind of targets simply because there is no way to extract precision radial velocities for both stellar components (km/s level) and planets (tens of m/s) simultaneously.

The current design of the SIM Lite instrument uses a baseline of 6 m. This determines its angular resolution of about 22 mas. In this case spectroscopic binaries with separation of 20 mas or less can be treated as a single point source. Of course, the photo center of the system moves around the system's center of mass and this has to be accounted for.

Table 1 SIM Lite candidate binary targets' period distribution (days)

Mass / Distance (pc)	1	1.5	2	2.5	3	4
1	1.222	0.996	0.863	0.772	0.704	0.61
2	3.451	2.818	2.440	2.182	1.992	1.725
5	13.640	11.137	9.645	8.627	7.875	6.820
10	38.581	31.501	27.281	24.401	22.275	19.290
20	109.123	89.099	77.162	69.016	63.002	54.562

First, we calculate periods (in days) of possible candidate P-type binary-planet systems as shown in Table 1. For FGK primary stars the total mass of the system may change from 1 to 4 solar masses. For angular separations < 20 mas the period is less than $\sqrt{(da")^3}/\sqrt{M}$, where d is the distance, a" is the semi major axis and M is the total mass. Since the candidate stars for a search for exoEarths are at distances of 10 pc or less, the periods of such systems are about 1 – 30 days. This will make the selection of P-type binary-planets targets much easier. In fact many spectroscopic binaries have periods of 30 days or less.

Here we show that we can model the motions of both stellar components and determine the physical parameters of planets simultaneously. For a spectroscopic binary which has semi-major axis less than the angular resolution of the SIM Lite instrument, its photo center rotates around the center of mass of the system. The measured positions of the photo center in R.A. and Decl. (Pr and Pd respectively) can be computed as:

$Pr = BX + GY,$

$Pd = AX + FY,$

where X and Y are elliptical rectangular coordinates in unit orbit. The Thiele-Innes constants B, G, A, F contain the semi major axis ρ" and the three orientation elements. The important issue here is that ρ" is not the semi major axis of relative orbits of the binary star, and has to be calculated as:

$$\rho" = \frac{q - r}{(1+q)*(1+r)} * a",$$

where q is the mass ratio between the companion and the primary (q < 1), r is the brightness ratio between the companion and the primary(r < 1), and a" is the semi-major axis of the relative orbit of the binary star.

The science interferometer of SIM Lite combines measurements from all of 80 spectral channels and determines the fringe delays. The reflex motions of the photo center are calculated in the following formulas. The differential delay ΔD is described as $\Delta D = u\Delta\alpha\cos\delta + v\Delta\delta$, where u and v are the projected baseline in the sky plane, Δα and Δδ are differential star positions in R.A.(α) and Decl. (δ), respectively. Here Δα and Δδ are expressed as:

$\Delta\alpha = BB * UU + GG * VV + (\mu \sin\varphi)/\cos\delta + \pi"/\cos\delta * (YY * \cos\alpha - XX * \sin\alpha) + Ca$

$\Delta\delta = AA * UU + FF * VV + \mu\cos\varphi + \pi" * (ZZ\cos\delta - XX\cos\alpha * \sin\delta - YY\sin\propto * \sin\delta + Cd$

$XX = \cos\lambda, \qquad YY = \sin\lambda * \cos\epsilon, \qquad ZZ = \sin\lambda * \sin\varepsilon.$

In the formula above AA, BB, GG and FF are Thiele-Innes constants for a planet, and ε and λ are obliquity of the ecliptic and true longitude of the Sun, respectively. By using delay measurements from SIM Lite at different epochs the orbital elements of both stellar and planetary objects, stellar parallax, and proper motions can be determined by the least squares method.

4. Conclusions

The SIM Lite instrument applies a small field stop of 2.”4 to limit the interference of background objects. For binary stars we analyzed spectral responses of the instrument and calculated flux ratios of a companion star with different brightness at different angular separations. Our analysis indicates that the SIM Lite mission can detect exoplanets in visual binary stars of 2” or larger easily. For the science interferometer of SIM Lite the delay beam is about 30 mas. Many spectroscopic binaries with periods of 1—30 days have angular separations of less than 30 mas, and the photo center of the system can be treated as one single object. The motion of photo-center of such a binary-planet system can be modeled and determined.

We demonstrate that SIM Lite mission can be used to search for exo-Earths in P-type binary-planetary systems. This is just the beginning of modeling and making precision estimates for the detection of exoplanets in binary stars by using SIM Lite. Further studied are planned for the case where both the primary and stellar companion have separate fringes in the SIM Lite spectrometer.

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