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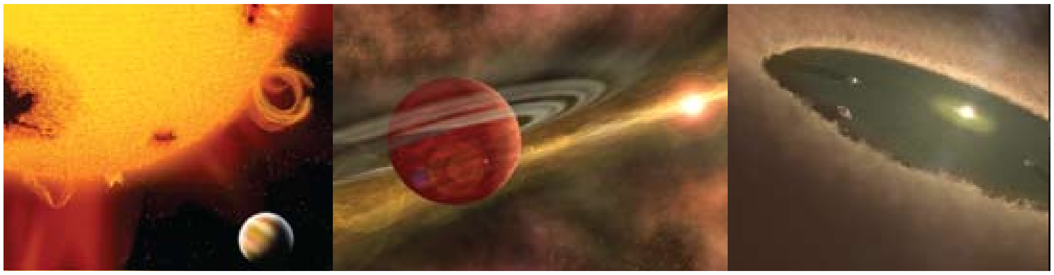
Young Planets and Star Formation



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ABSTRACT

Despite the revolution in the detection of planets around mature stars, we know almost nothing about planets orbiting young stars because rapid rotation and active photospheres preclude detection by radial velocities or transits. Thus, our knowledge about the formation and evolution of planetary systems is rudimentary at best. Astrometry with SIM Lite offers our best observational opportunity to find gas giant (100 to 300 $M_\oplus$), icy giant (10 to 100 $M_\oplus$) planets, and even a few rocky, super-Earths (~10 $M_\oplus$) orbiting stars ranging in age from 2 to 100 Myr. SIM Lite's astrometry can also address more general questions of star formation, including the physical properties of young low-mass objects whose masses and evolutionary tracks are highly uncertain.

2.1 Young Systems: Beyond the Reach of RV, Transit, and Imaging

An astrometric survey using SIM Lite of 200 stars with ages from 2 to 100 Myr will help us to understand the formation and dynamical evolution of gas-giant planets. The majority of the host stars of the more than 300 exoplanets found to date are mature main-sequence stars (and a few giants) chosen for having quiescent photospheres to enable the measurement of small Doppler velocities (≤10 m/s) or small photometric variations due to transits (millimagnitude precision). In this section, we contrast SIM Lite's astrometric capabilities with other techniques as well as with expectations for Gaia's performance.

2.2 The Challenge of RV

Many young stars are characterized by weak spectral features due to veiling, rotationally broadened line widths >> 1 km/s, large-scale radial velocity (RV) motions, and/or brightness fluctuations of many percent due to starspots (Carpenter et al. 2001). Thus, visible radial velocity measurements and photometric observations have been unable to detect planets around young stars. Setiawan et al. (2008) recently claimed an RV detection of a planet orbiting the young star TW Hya, but this claim has been called into serious question (Huélamo et al. 2008) as being due to large-scale photospheric variations. Similarly, Prato et al. (2008) initially identified potential "hot Jupiters" orbiting DN Tau and V836 Tau based on visible spectroscopy, but used follow-up IR spectroscopy to demonstrate that the RV variations were due to photospheric variability, not planets. While the near-IR is a promising wavelength region for RV and photometric searches of young stars due to the 2 to 5 times lower contrast between the photosphere and the starspots that are often the cause of the variability (Eiroa et al. 2002), there is no evidence that precisions less than 50 m s^{-1} will be possible. This limit precludes detections of all but the most massive, most closely orbiting "hot Jupiters" (<0.1 AU). As valuable as such detections would be, this technique cannot push into the interesting 1 to 5 AU area now well studied around main sequence stars and critical for understanding the formation of planetary systems.

2.3 The Challenge of Transits

There is a long history of the variability of young stars, from outbursts of FU Ori objects to rotational modulation of a few percent in relatively quiescent T Tauri stars. These variations make transit detections of even gas giant planets (~1 percent transit depth) highly unlikely in the visible. Transit detections may prove possible in the near-IR where the variability is a factor of 2 to 5 times lower (Eiroa et al. 2002), but transits are likely to remain a marginal technique for young stars also because the surface density of suitable stars is so low that it is difficult to build up adequate samples. A survey of $\sim 10^4$ objects is necessary given the low probability of alignment and of having a planetary system in the first place, i.e., total probability of 10^{-3}.

2.4 The Challenge of Imaging

A few objects of potentially planetary mass have been detected at 25 to 100 AU from young (<10 Myr) host stars by direct, coronagraphic imaging, e.g., 2MASSW J1207334-393254 (Chauvin et al. 2005) and GQ Lup (Neuhauser et al. 2005) and most recently around the stars Fomalhaut and HR8799 (Marios et al. 2009; Kalas et al. 2009). However, these companions are only inferred to be of planetary mass by comparison to uncertain evolutionary models that predict the brightness of young Jupiters as a function of mass and age (Wuchterl and Tscharnuter 2003; Baraffe et al. 2002; Burrows et al. 1997). Since dynamical determinations of mass are impossible for objects on such distant orbits, it is difficult to be sure that these are planets and not brown dwarfs. Nor is it even clear that the origin of these distant young "Jupiters" is due to the same formation processes as planets found closer to their hosts. Multiple fragmentation events (Boss 2001), rather than core accretion in a dense disk (Ida and Lin 2005), may be responsible for the formation of these objects orbiting so far from their star.

Advanced coronagraphs on extremely large telescopes (~30 m) may one day explore as close to a host star as 3 AU (corresponding to an Inner Working Angle of 4 λ/D at 50 pc) down to a few M_{Jup} levels, and interferometers may probe comparable masses and regions in the youngest star forming regions (140 pc). But imaging cannot yield dynamical information, so even if objects can be detected by these instruments, critical information on masses will remain unknown in the absence of astrometry.

2.5 The Promise of Astrometry

As a consequence of the limits and selection biases of the radial velocity, transit, and direct imaging techniques, we know almost nothing about the incidence of planets around young stars, leaving us with many questions about the formation and evolution of gas giant planets. Astrometry with SIM Lite promises to remedy this situation. Table 2-1 gives typical astrometric signals for gas giants (Jupiter and Saturn) and icy giants (Uranus) at two orbital distances (1 and 5.2 AU), two distances from the Sun (140 and 30 pc [cf. Figures 2-1 and 2-2], representative of 2- to 10-Myr-old stars and 10- to 100-Myr-old objects, respectively), and orbiting 0.15 and 1.0 $M_{\odot}$ stars. The signatures cover a range of <1 to 1000 µas. The closest Jovian planets will be detectable by Gaia or ground-based interferometers (~50 µas), but most will require SIM Lite's precision.

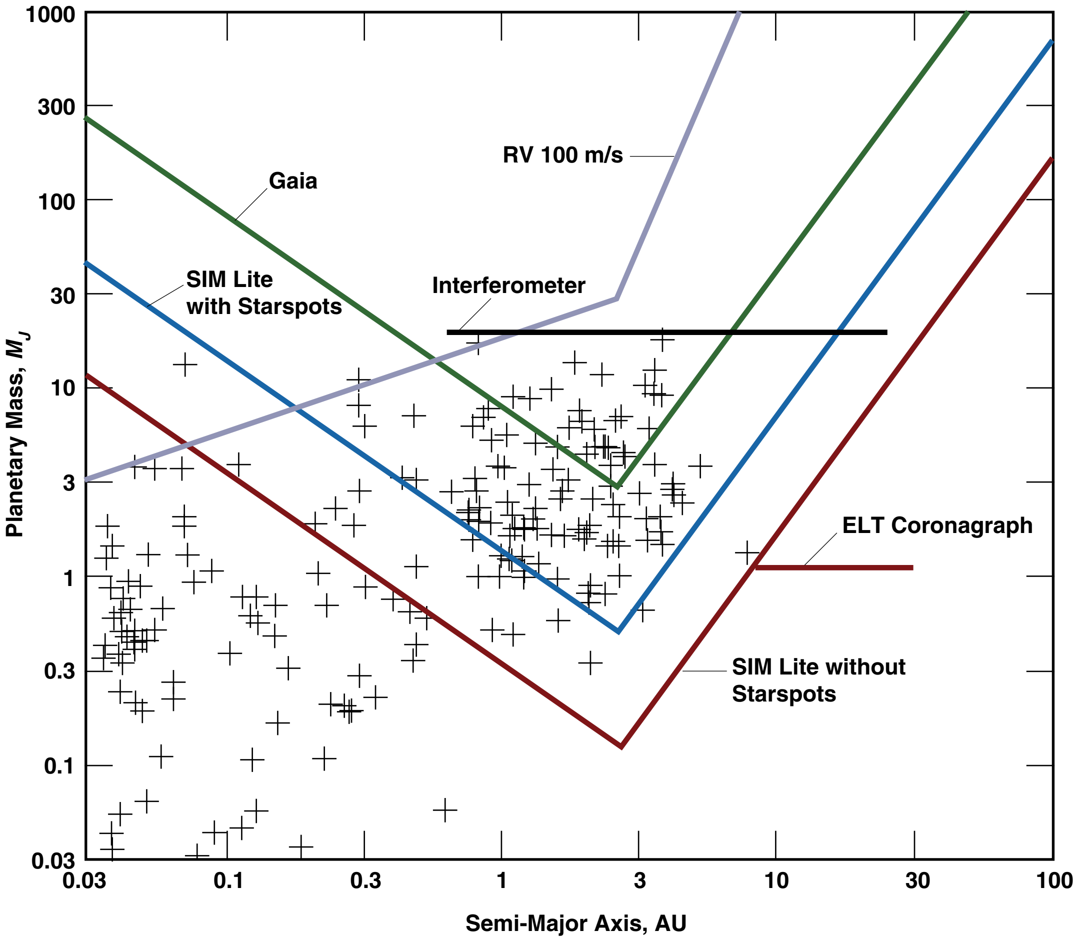
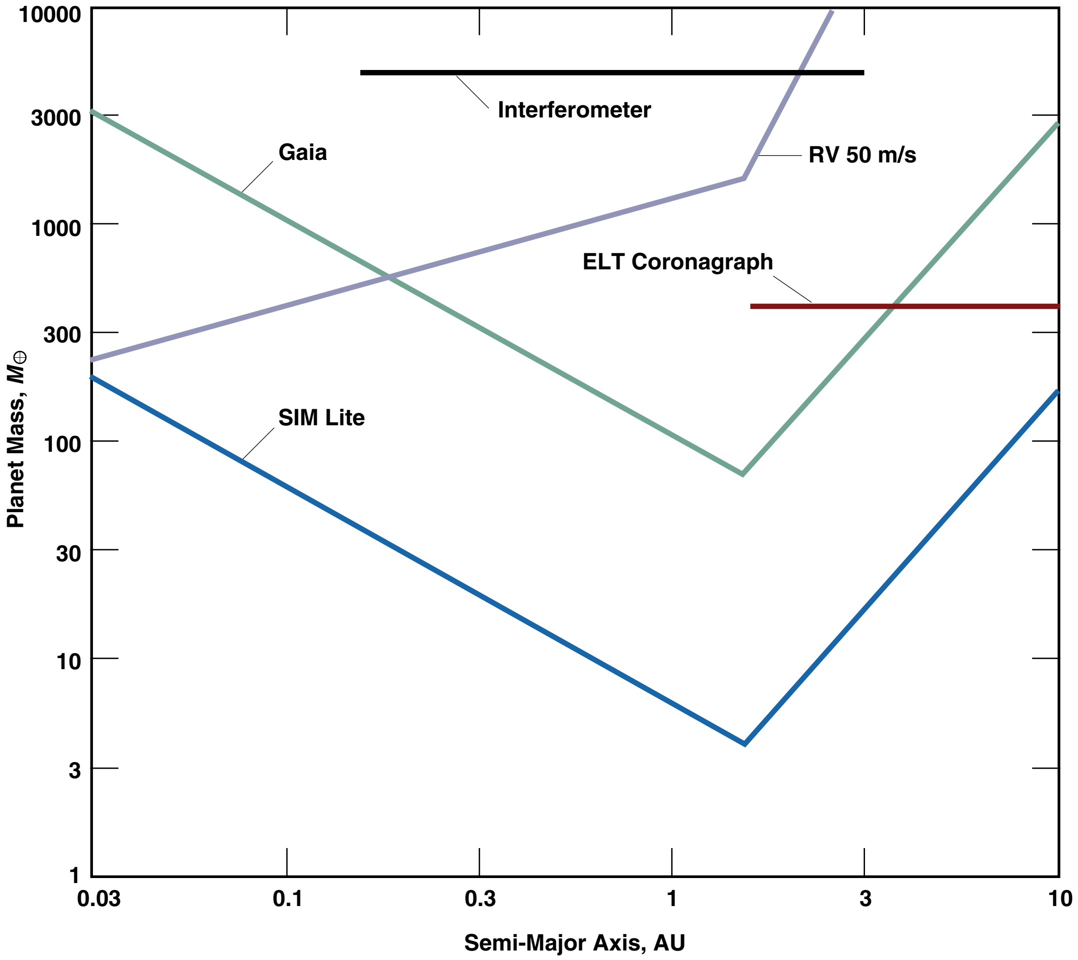


Figure 2-1. Sensitivity of SIM Lite to planets in the mass–semi-major axis plane for young stars (<5 Myr) at a distance of 140 pc. A representative population of planets seen around nearby mature stars (data from a variety of RV surveys of main sequence stars, e.g., http://exoplanet.edu/) is shown to indicate what SIM Lite might find when looking at young (1 $M_{\odot}$) stars for the first time. SIM Lite sensitivity estimates are given for worst-case and best-case scenarios for starspot noise. Sensitivity estimates for Gaia, RV studies, a coronagraph on a 30-m Extremely Large Telescope (ELT) operating at 1.6 µm, and the 85-m Keck Interferometer operating in direct imaging mode are shown for comparison. To date there are no credible detections of young planets located within <25 AU of their parent stars, highlighting the need for SIM Lite.

Table 2-1. Astrometric signal (μas) from planets at various distances, orbital locations, and stellar host mass. Entries indicated in blue (≥ 50 μas) would be detectable with Gaia or ground-based interferometers. Entries indicated in green require SIM Lite's sensitivity in either narrow- or wide-angle modes.

		1 $M_\odot$ Star				0.15 $M_\odot$ Star			
		Distance, pc				Distance, pc			
		30		140		30		140	
		Orbit, AU		Orbit, AU		Orbit, AU		Orbit, AU	
Planet	M_{Jup}	1	5.2	1	5.2	1	5.2	1	5.2
Jupiter	1	32	170	7	36	214	1110	46	240
Saturn	0.28	9	47	2	10	60	311	13	67
Uranus	0.023	0.7	4	0.2	0.8	5	26	1.1	6

Figure 2-2. Same as Figure 2-1, except for a planet orbiting a 0.15 $M_\odot$ star at a distance of 30 pc. Such stars have ages between 10 and 100 Myr.



A Jupiter orbiting 5.2 AU away from a 1 $M_\odot$ star at the distance of the youngest stellar associations (1 to 10 Myr) such as Taurus (140 pc) and Chamaeleon (100 pc) would produce an astrometric amplitude of 36 μas. At the 25 to 50 pc distance of the nearest young stars (10 to 50 Myr), such as members of the β Pic and TW Hya groups, the same system would have an astrometric amplitude in excess of 100 μas. Moving a Jupiter into a 1 AU orbit would reduce the signal by a factor of 5.2, to 40 μas for a star at 25 pc and 7 μas for one in Taurus.

In its narrow-angle mode, SIM Lite will have a planet search accuracy of 2 to 3 μas with SNR = 5.8 at relevant magnitudes, V ~ 6 to 13 mag, and for reasonable integration times (cf. §2.6). A search for gas and icy giant planets, and even large rocky planets orbiting the closest, lowest-mass stars, falls well within SIM Lite's capabilities and forms the basis of the SIM–YSO Key Project (Beichman, PI; Beichman 2001; Tanner et al. 2007). Figure 2-1 and Figure 2-2 show SIM Lite's expected astrometric accuracy for the SIM–YSO survey as a function of planet mass and semi-major axis at distances of 140 and 30 pc. Also plotted is the expected RV accuracy achievable with infrared echelle spectrometers subject to the RV limitations ($100\ \mathrm{m\ s^{-1}}$ for the youngest stars, $50\ \mathrm{m^{-1}}$ for somewhat older stars, >10 Myr) discussed in the preceding section. RV surveys will be limited to Jupiter-mass planets located very close to the star and coronagraphic imaging will be limited to planets located very far from the star. SIM Lite can detect planets throughout the critical distances of 1 to 5 AU around the snowline where gas giant planets are thought to form.

2.6 The Challenge of Astrometry

The photospheric activity that affects radial velocity and transit measurements also affects astrometric measurements, although to a lesser degree consistent with the secure detection of gas giant and smaller planets. From measurements of photometric variability (Bouvier and Bertout 1989; Bouvier et al. 1995) plus Doppler imaging (Strassmeier and Rice 1998), T Tauri stars are known to have active photospheres with large starspots covering significant portions of their surfaces (Schussler et al. 1996) as well as hot spots due to infalling accreting material (Mekkaden 1998). These effects can significantly shift the photocenter of a star. Using a simple model for the effect of starspots on the stellar photocenter (Beichman 2001; Tanner et al. 2007), the astrometric jitter for a typical T Tauri star at 140 pc with radius 3 $R_\odot$ is less than 3 μas (1 σ) for R-band variability less than 0.05 mag. Thus, the search for Jovian planets is plausible for young stars less variable than ~0.05 mag in the visible, even without making any assumption that the star spot noise will average down. If the spot noise averages down over many stellar rotational periods (typically of a few days, short compared with the observing sequence) with the square root of the number of observations, the mass detection limit will drop well below the gas giant limit.

If the Key Project survey is carried out with instrumental noise of 2.5 to 4 μas (single-measurement accuracy, depending on target brightness) and with astrophysical jitter of 3 μas (depending on stellar variability), then the limiting astrometric amplitude for reliable detection is given by a combination of instrumental and astrophysical noise sources:

$$\text{Amplitude} \sim 5.8 \sqrt{(\sigma^2(\text{SIM}) + \sigma^2\,(\text{astrophysical}))\,/\,N_{epoch}}\ \mu\text{as}$$

For σ (SIM Lite) = 3 μas (single-measurement accuracy), σ (Astrophysical) = 3 μas and N_{epoch} = 62 (125 one-dimensional measurements), the minimum detectable amplitude is 3 μas. For N_{epoch} = 125 (250 one-dimensional measurements), the minimum amplitude is 2 μas. In either case, SIM Lite's performance is consistent with detection of Saturns and Jupiters throughout nearly the entire the 1 to 5 AU region at 140 pc (Table 2-1). The value of 5.8 has been shown by extensive Monte Carlo simulations to be the correct value to ensure reliable detection (<1 percent false alarm probability; §1.2). If the astrophysical jitter does not scale with the square root of the number of observations, i.e., due to unfavorable "1/f" noise in the power spectrum of the astrometric noise, the SIM Lite limit will be astrophysical rather than instrumental, roughly $3(R_*/3\ R_\odot)$(D/140 pc) μas. Even at this pessimistic limit, SIM Lite will be able to detect Jupiters and possibly Saturns in most of the 1 to 5 AU region. If, as expected, the astrometric jitter scales favorably, then much lower masses (discussed below) will be detected.

Note that since both the astrometric signal and the astrometric jitter scale inversely with distance, there is no advantage (from the jitter standpoint) to examining nearby stars despite their larger absolute astrometric signal — although the measurements will be easier for SIM Lite since the nearer targets will be brighter and the signal larger. Other astrophysical noise sources, such as offsets induced by the presence of nebulosity and stellar motions due to non-axisymmetric forces arising in the disk itself, are negligible for appropriately selected stars.

For searches for the lowest-mass planets around nearby low-mass stars, one can scale the astronomical jitter directly with the distance to the star and the stellar activity and inversely with the stellar radius. A 40-Myr-old star at a distance of 30 pc, with radius 0.28 $R_\odot$ and mass of 0.15 $M_\odot$, displays astrometric jitter at <0.5 μas, assuming that the stellar activity decreases from its level at ~3 Myr in Taurus to 40 Myr according to the Skumanich relation $\propto t^{-0.5}$ for calcium plage activity (Skumanich 1972). If this estimate for the astrometric noise of spotted stars is correct, then planets of super-Earth to Uranus masses will be detectable over the semi-major axis range of 1 to nearly 5 AU for these young, but not infant, stars.

2.7 The YSO Sample

The observational strategy of the existing SIM–YSO project is a compromise between the desire to extend the planetary mass function as low as possible and the essential need to build up sufficient statistics on planetary occurrence. About half of the sample will be used to address the where and when of planet formation. SIM Lite will study classical T Tauri stars (cTTs), which have massive accretion disks, as well as post-accretion, weak-lined T Tauri stars (wTTs). Preliminary studies suggest the sample will consist of ~30 percent cTTs and ~70 percent wTTs, driven in part by the difficulty of making accurate astrometric measurements toward objects with strong variability or prominent disks. The second half of the sample will be drawn from the closest young clusters with ages starting around 5 to 10 Myr, thought to mark the end-stage of prominent circumstellar disks, through targets of ~100 Myr, when theory suggests that the properties of young planetary systems should become indistinguishable from those of mature stars. The characteristics of the planets found around stars in these later age bins will be used to address the effects of dynamical evolution and planet destruction (Lin et al. 2000). Since we will also measure accurate parallaxes, we will have reliable luminosities for the host stars which can be used to help estimate ages.

The youngest stars in the sample will be located in well-known star-forming regions such as Taurus, the Pleiades, Scorpius-Centaurus, and TW Hydrae (Tanner et al. 2007). Somewhat older stars, such as those in the β Pictoris and TW Hydrae Associations, are only 25 to 50 pc away and can be observed with less mission time to the accuracy needed to identify Saturn- and Jupiter-mass planets. We have adopted the following criteria in developing our initial list of candidates: (a) stellar mass between 0.2 and 2.0 $M_\odot$; (b) $R < 12$ mag for reasonable integration times; (c) distance less than 140 pc to maximize the astrometric signal to be greater than 6 μas; (d) no companions within 2" or 100 AU for instrumental and scientific considerations, respectively, (e) no nebulosity to confuse the astrometric measurements; (f) variability $\Delta R < 0.1$ mag; and (g) a spread of ages between 1 and 100 Myr to encompass the expected time period of planet–disk and early planet–planet interactions. The variability program proved to be the most stringent filter with roughly 50 percent of the sample showing photometric dispersion in excess of 0.1 mag. A fully validated list of 75 stars meeting all of the above criteria now exists. More stars will be added to the precursor program to bring the total up to the desired number of ~200 stars.

SIM Lite will also look for the lowest-mass planets around the closest, lowest-mass young stars. More and more young stars (10 to 100 Myr) are being found in the vicinity of the Sun as members of the "nearby young moving groups (NYMGs)," associations of stars moving in the same approximate direction (Zuckerman and Song 2004). The stars in the NYMGs are much closer than those in the intensely studied Taurus and Ophiuchus star-forming regions. Hence, the NYMGs enable study of the processes of planet formation at higher resolution than has been possible. To date, the identified members of the NYMGs consist mostly of stars of spectral type F, G, or K; only a few low-mass stars of spectral type M have been confirmed as members. One would, however, expect the groups to contain many more low-mass members simply because the local field mass function strongly favors them. A program is presently underway (Lepine and Simon 2008) to identify new low-mass members in the β Pic and AB Dor groups.*

Figure 2-3 shows the distance distribution of the stars in these groups identified by Zuckerman and Song (2004). The median distances are similar, 35 pc for the ~12-Myr-old β Pic group, and 30 pc for the older, ~40-Myr-old, AB Dor group. Of the 14 candidates for membership in the β Pic NYMG, 11 are bona fide members of which eight are new identifications. Of the 14, eight are M stars, including two M4s. The one AB Dor candidate is also a new member. Even lower-mass group members should be observable in the β Pic and AB Dor moving groups.

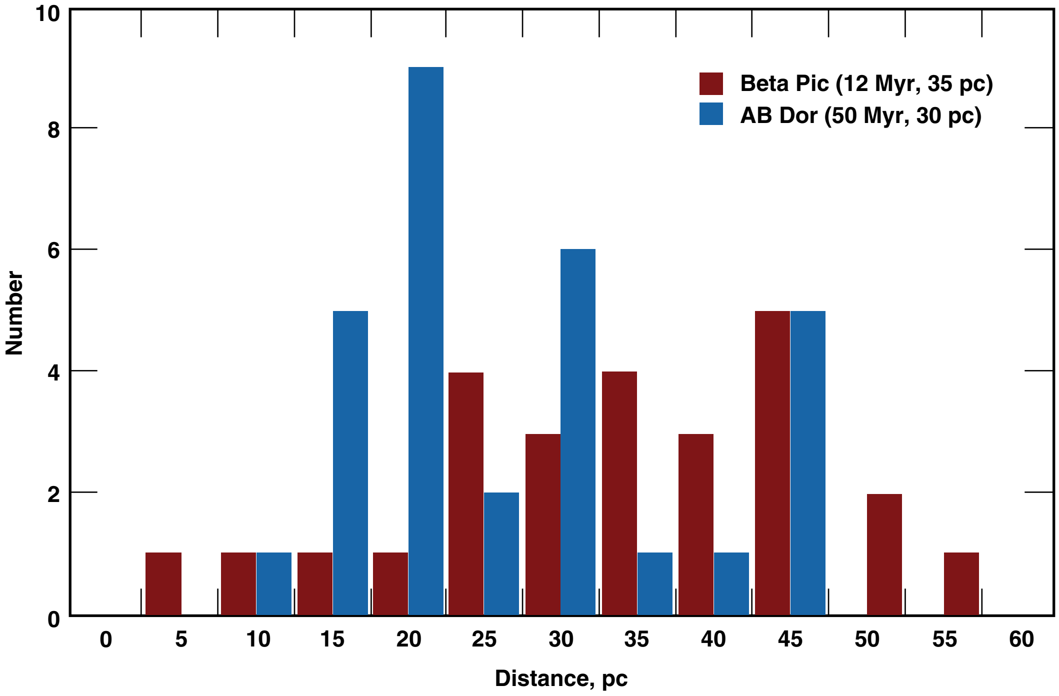


Figure 2-3. Nearby moving groups (<35 pc) contain stars as young as 12 to 50 Myr that could be targets for SIM searches for very young, very low-mass planets.

Figure 2-2 (Section 2.5) shows the sensitivity of SIM Lite (~4 μas in a single measurement) to planets with masses much less than Jupiter orbiting an AB Dor group member of M4 spectral type (0.15 $M_\odot$) at distance 30 pc. If the astrometric signal is not contaminated by positional jitter (or if, as expected, the noise averages down with square root of the number of visits), then planets with a few Earth masses might be detected at semi-major axes of ~1-5 AU. Certainly, Uranus-mass planets could be detectable.

** Low-mass members of the NYMG are also important targets for exoplanet surveys by high-resolution imaging techniques in the near-IR because, at ages of a few tens of Myr, the gas giants are still bright from their gravitational contraction.*

2.8 The Young Planets Observing Program

With the nominal performance of SIM Lite, the observing time allocated to the SIM–YSO program (1600 hr), will suffice to make 62 two-dimensional visits to each of 200 stars (Table 2-2). Spread over five years, this would be enough to identify and characterize one or more planets per star, with periods of 1 to 2.5 years. With additional observations during a 10-year extended mission, it will possible to find planets out to 5 AU. The instrumental limit for appropriate observing parameters (http://mscws4.ipac.caltech.edu/simtools/portal/login/) is 2 to 3 µas in narrow-angle mode and 12 µas in wide-angle mode for the closer stars.

Table 2.2. Representative search for planets around young stars (observing estimates from SIM Lite time-estimation simulator).

Observing Mode	Scientific Goal	V Range	5.8σ Limiting Amplitude	No. Stars	Time, hr
Narrow Angle	Jupiter/Saturn search around youngest stars (1–2 Myr, 140 pc, e.g. Taurus) AND Lowest-mass planets around nearby, low-mass stars (10–50 Myr, 30–50 pc, e.g., Beta Pic, AB Dor groups)	6–13 mag	2–3 µas	100	1373
Wide Angle	Jupiter/Saturn search around nearby stars (10–50 Myr, 30–50 pc, e.g., Beta Pic, AB Dor groups)	6–13 mag	12 µas	100	227
Total (equal to allocation for Young Stars Key Project of 1600 hours)				200	~1600

In a SIM Lite survey of 200 young stars, we expect to find anywhere from 20 (assuming that only the presently known fraction of stars, 10 ~15 percent, have planets; Cumming et al. 2008) to 200 (all young stars have planets) planetary systems. We have set our sensitivity threshold to ensure the detection of Jupiter- and Saturn-mass planets in the critical orbital range of 1 to 5 AU. Depending on how well astrometric jitter due to starspots averages down with increasing number of observations, the mass limits could be significantly lower.

These observations, when combined with the results of planetary searches of mature stars, will allow us to test theories of planetary formation and early solar system evolution. By searching for planets around pre-main-sequence stars carefully selected to span an age range from 1 to 100 Myr, we will learn at what epoch and with what frequency giant planets are found at the water-ice “snowline” where they are expected to form (Pollack et al. 1996). This will provide insight into the physical mechanisms by which planets form and migrate from their place of birth, and about their survival rates.

With SIM Lite we will have the data to investigate a series of important questions: What processes affect the formation and dynamical evolution of planets? When and where do planets form? What is the initial mass distribution of planetary systems around young stars? How might planets be destroyed? What is the origin of the eccentricity of planetary orbits? What is the origin of the apparent dearth of companion objects between planets and brown dwarfs seen in mature stars? How might the formation and migration of gas-giant planets affect the formation of terrestrial planets? With a sample of 200 stars, perhaps increased by additional observing programs in an extended 10-year mission, SIM Lite will address directly these and many other questions.

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