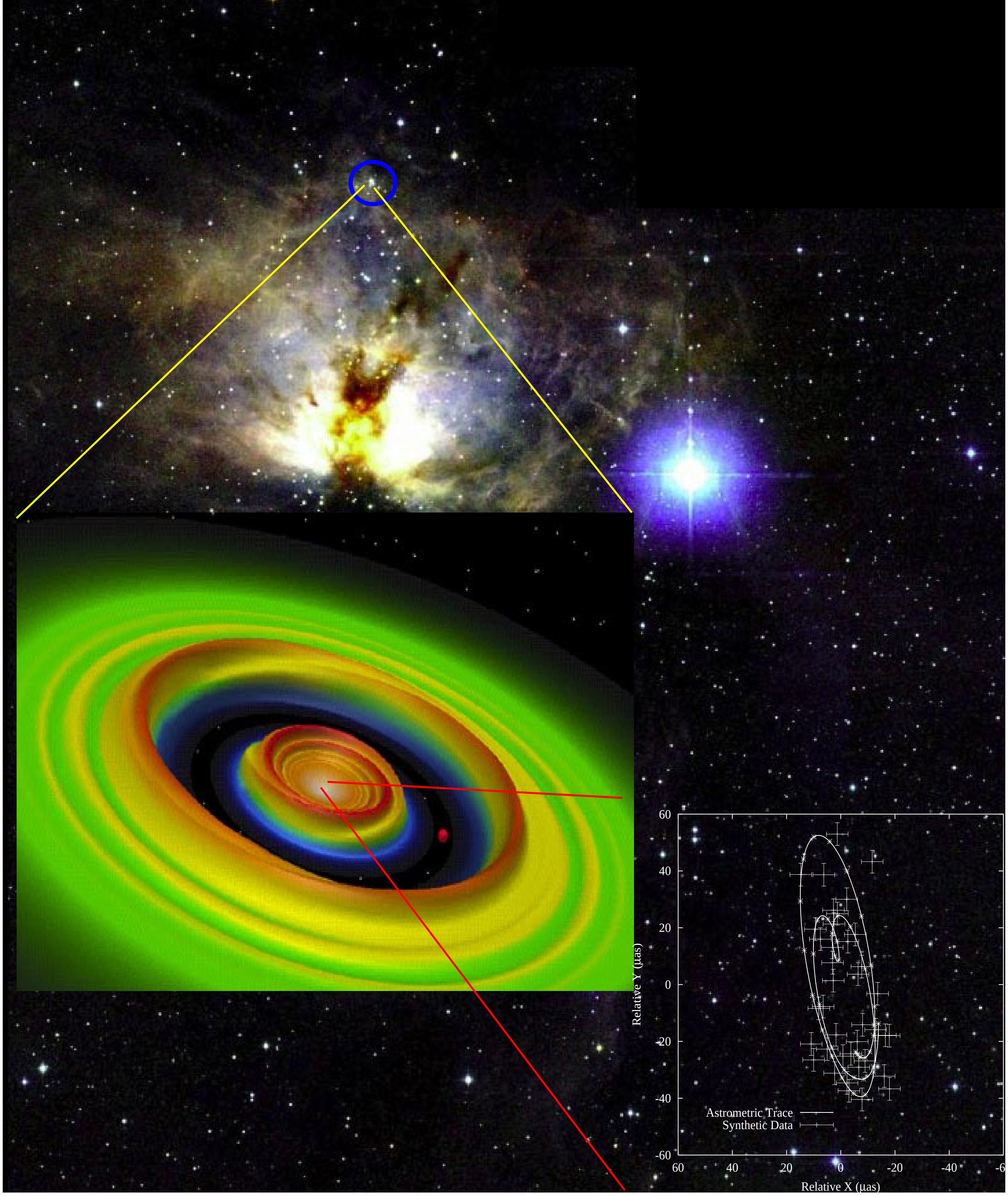
The Search for Young Planetary Systems and the Evolution of Young Stars: A Proposal to Observe with the Space Interferometry Mission

AO-00-OSS-01



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The Search for Young Planetary Systems and The Evolution of Young Stars: A Proposal in Response to NASA Announcement of Opportunity

AO-00-OSS-01

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ABSTRACT

We propose a SIM Key Project to elucidate the processes of star and planet formation and to understand both the frequency of giant planet formation and the early dynamical history of such objects. By doing so we will gain deep insight into how common is the basic architecture of our solar system compared with recently discovered systems with close-in giant planets. To accomplish our goals we divide our observing resources into three parts. The bulk of our program is a planet search around 150 of the nearest (<150 pc) and youngest (0.5-100 Myr) solar-type stars. We expect to find 5-150 previously unknown planetary systems. We have set our sensitivity threshold to ensure the detection of Jupiter-mass planets in the critical orbital range of 1 to 5 AU. These observations, when combined with the results of planetary searches of mature stars from SIM and other facilities, will allow us to test theories of planetary formation and early solar system evolution. Second, we will measure distances and orbital properties of ~100 stars precisely enough to determine the masses of single and binary stars to an accuracy of 1%. This information is required to calibrate the pre-main sequence tracks that serve as a chronometer ordering the events that occur during the evolution of young stars and planetary systems. Third, we will obtain images with ~1 AU resolution of jets emanating from young stars to probe the physics of outflows. Since these young stars will evolve into stars like the Sun, the results of our investigation will be directly relevant to the origin, evolution, and ultimate habitability of solar systems like our own—a key goal of NASA’s Origins Program and a topic of broad scientific, public and educational appeal.

Cost to NASA: $6,404,00

I. *Executive Summary*

We propose to use SIM's unprecedented astrometric capabilities to address critical problems relating to the formation and early evolution of both planets and young, Sun-like stars. SIM will detect unseen stellar, brown dwarf, or planetary companions, determine precise distances to faint, young stars, and image disk-jet systems, allowing us to address the following questions:

- *What is the incidence of gas giant planets around young, solar-mass stars in the orbital range 1 AU to 5 AU? When and where do gas giant planets form?* By searching for planets around ~150 pre-main sequence stars carefully selected to span an age range from 0.5 to 100 million years, 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. This will provide insight into the physical mechanisms by which planets form and migrate from their place of birth, and about their survival rate. *As shown in Figure 1, astrometry with SIM is the only technique available to determine the distribution of planets shortly after their formation in this critical interval of mass and orbital distance.*

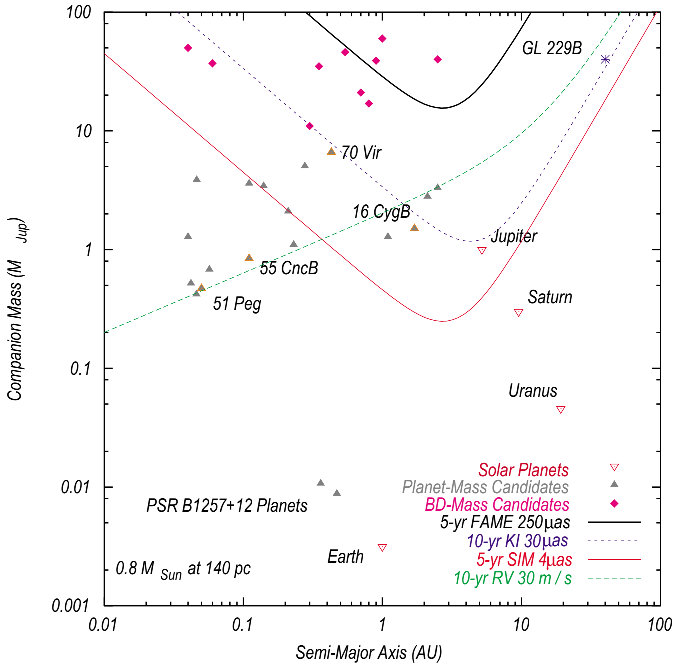

Figure 1. Comparison of our SIM survey, FAME, and the Keck Interferometer for the detection of planets around young stellar objects at a distance of 140 pc. We adopt single measurement accuracies of 4 µas for SIM, 250 µas for FAME (both for 5 yr missions), and 30 µas for the Keck-Interferometer (10 yr mission). We also show the sensitivity to planets for 30 m s^{-1} radial velocity measurements appropriate for YSOs (10 yr survey).

- *What are the masses of young solar type stars?* The current uncertainty of a factor of two or more in the masses of Young Stellar Objects (YSOs) results in comparable or larger uncertainties in determinations of mass functions, ages, circumstellar disk lifetimes, and star forming histories of young clusters. We will determine the distances, masses and luminosities of ~100 pre-main sequence stars in binary systems, covering a range of 3 in mass and 100 million years in age. With accurate distances and companion information from SIM we will be able to determine precise stellar masses and thus provide the most reliable calibrations of pre- main-sequence evolutionary tracks.
- *What is the origin of the apparent dearth of companion objects between planets and brown dwarfs seen in mature stars?* Our survey for young planets and observations of young binaries will determine whether the "brown dwarf desert" is the expression of two different kinds of formation mechanisms, or the result of dynamical evolution acting on bodies made via a common process.
- *To what extent do jets, winds, and outflows affect the planet forming regions of YSO disks?* We will demonstrate the power of interferometric synthesis imaging by

making high spatial resolution images in key spectral lines such as Hα and [O I] to determine the size scales on which jet acceleration and collimation occur.

Table1 summarizes an observational program requiring 2403 hours over a 5-year mission. We have focused our observational program on problems that only SIM can address, taking into account other planned astrometric facilities such as the Full-Sky Astrometric Explorer (FAME) and the Keck Interferometer. The program is robust against modest degradations in SIM's performance, particularly in the area of systematic errors in narrow angle astrometry.

Table 1. Summary of Observing Time Requested

Project	# of Stars	# of Hours
Planet Searches (Jupiters @1-5 AU)	146	2228
Fundamental Properties of YSOs	100	100
Disk/Jet Imaging	10	75
Total	256	2403

Our team is arranged in a "core-halo" structure in adherence with NASA's desire to limit team size. Nine co-Investigators will carry out the day to day responsibilities of the program and form the core of the team. They will draw upon the expertise of a "halo" of scientists (Associate Investigators) who have committed to helping the program as needed. Together the team has decades of experience in observational and theoretical aspects of the science of Young Stellar Objects (YSOs) and the reduction of interferometric and astrometric data.

Primary data products will include catalogs of distances and proper motions of over 250 stars, calibrated narrow angle astrometric measurements of over 150 stars; and images of 5-10 stars in multiple spectral bands. Secondary products will include derived properties such as masses and orbital properties of primary and companion objects. From these, a tertiary set of products will be developed including planetary initial mass function(s), inferences about formation mechanisms and dynamical loss processes at high and low mass ends of the planetary spectrum, the relationship between disk processes and the occurrence of planetary systems, and well calibrated evolutionary tracks for pre-main-sequence stars.

Team members have extensive experience with education and public outreach (EPO) activities. Working closely with the SIM and Origins EPO offices, we will develop material for grades K-14 that addresses concepts such as the formation and evolution of planetary systems and generally ensure that our results are conveyed to the broadest possible community.

II. Science Investigation and Technical Description

Our science focus is three-fold. The bulk of our program is a planet search around 150 of the nearest (<150 pc) and youngest (0.5-100 Myr) solar-type stars. We expect to find 5-150 previously unknown planetary systems. Second, we will determine distances to ~100 stars precisely enough to determine masses of single and binary stars to an accuracy of 1%. Third, we will obtain very high resolution images of jets emanating from young stars to probe the physics of outflows.

A. The Formation and Migration of Jupiter- Mass Planets

A long-term goal of NASA's Origins program is the search for habitable, terrestrial planets. The search for and characterization of giant planets is a crucial intermediate step in this program because the formation, survival, and ultimately the habitability of terrestrial planets are tied to the properties of giant planets, particularly in the critical orbital range from 1-5 AU.

The formation of gas giants like Jupiter requires the presence of a substantial gaseous disk around the protostar and therefore must occur before that disk is dissipated, i.e. in 10^6-10^7 years (Skrutskie *et al*. 1990). Once formed, giant planets profoundly affect the long-term habitability of terrestrial planets through direct inward migration and through the scattering of solid planetesimals. In our own solar system this scattering led to a water-rich asteroid belt and the formation of large planetary embryos acting as sources of Earth's volatiles and perhaps of Earth's Moon as well (Morbidelli *et al*. 2000).

Is the situation in our own solar system typical, or just one of a large range of possible outcomes of disk evolution? Around 5% of sun-like stars, radial velocity surveys have discovered Jupiters and perhaps even Saturns (depending upon the actual—unknown—system inclinations) at orbital radii much smaller than those of our own giant planets, favoring the latter idea (Cumming, Marcy, Butler 1999). The diverse orbital properties of planets discovered to date imply that dynamical evolution determines the survival of many planetary systems (Lin and Papaloizou 1986; Lin *et al*. 2000). However, we cannot determine from existing data whether the radial velocity discoveries are the tail of a greater population of giant planets distributed over larger semi-major axes, or the preferred primordial arrangement (making our system the exception). Neither radial velocity surveys nor SIM's astrometric observations of mature planetary systems can answer this question if the majority of giant planets formed with initial Jupiter-Saturn type orbits (4-40 AU; Levison *et al*. 1998) and subsequently moved inward through dynamical processes. It is therefore a high scientific priority to establish the early distribution of planet masses and orbital properties by looking for planetary companions around a sample of young, pre-main-sequence (PMS) stars with ages from 0.5-100 Myr.

The future prospects for detecting planetary companions around young stars are summarized in Figure 1 which shows the sensitivity of radial velocity (RV) surveys and astrometric observations (SIM, FAME, and the Keck Interferometer) to planets around a 0.8 M_o star at the140 pc distance typical of nearby star-forming regions. Since lower mass YSOs are often rapid rotators with active chromospheres and strong sunspot activity, they are not well suited for planet searches via radial velocity methods because of the breadth and variability of their spectral lines. The dispersion of radial velocity measurements is typically ~10 times worse for YSOs than for solar-type, main sequence stars (30 m s^{-1} vs. 3 m s^{-1}) with corresponding increases in the masses of planets that the RV technique can detect (Saar *et al*. 1998). Astrometric measurements, *with SIM's level of precision*, are essential to detect Jupiter mass planets around YSOs. FAME's single measurement accuracy on faint (10<V<14 mag) stars will be 500 μas. The Keck Interferometer with a single measurement accuracy of 30 μas will be able to find planets of a few M_J only beyond 10 AU around young stars. Thus, only SIM with its <4 μas measurement capability will be able to detect Jupiter mass companions in nearby star forming regions over a broad range of orbital parameters.

1. *The Formation and Dynamical Evolution of Planets*

a) When and Where do Planets Form? Determining when and where giant gas planets form is a key goal of our project. Theoretical timescales for planet formation are very uncertain and depend sensitively on disk properties (Wuchterl *et al*. 2000). Since the formation timescale is closely related to the amount of disk dissipation which in turn affects the amount of planetary migration (Lin and Papaloizou 1986), the “where” and “when” of planetary formation are closely coupled properties.

Current theory indicates that gas giant planets should form most readily in the cooler, outer reaches of a circumstellar disk where the ices of volatile species such as water are stable, i.e. beyond a few AU (Pollack *et al*. 1996). These expectations seem contrary to the recent discoveries of planets at locations much closer to their parent stars (Marcy and Butler 2000 and refs. therein), but current observational techniques cannot detect Jupiters at radii >5 AU. SIM will be able to locate <1 M_J planets at distances >5 AU from young stars, limited only by SIM’s ability to observe over an appreciable part of an orbit during its lifetime (Figure 1). *The SIM observations proposed here will make a definitive test of the theory that giant planes form at and beyond the radius of water-ice condensation.* If indeed giant planets are found to be abundant at and beyond the water ice “snow-line”, there are two important implications. First, such planetary systems (if devoid of close-in Jupiters) could accommodate terrestrial planets in habitable zones, and could potentially resemble our own solar system. Second, the abundance of giant planets beyond the snowline, coupled with the RV results for close-in giant planets, will allow an estimate of the rate of migration and destruction of planets and provide crucial constraints on models of post-formation planetary migration.

The combination of SIM’s detections of planets and the improved ages of young stars, made possible by the combination of SIM and ground-based observations (§II.B), will allow us to test directly the hypothesis that giant planets form beyond the ice condensation radius in a few million years or less.

b) What is Initial Mass Distribution Of Planetary Systems around Young Stars? The opening of gaps in a protostellar disk may provide a natural upper limit to the masses of planets formed by the accretion of solids and gases in a stable disk. However, radial velocity surveys cannot detect planetary mass objects around young stars to ascertain whether the mass function of planets at the time of their birth is consistent with this or any other theory. *SIM can establish a mass function for the young planets over a decade in mass (from 1 M_J to the putative 10-20 M_J planetary cutoff) prior to the end of the epoch of dramatic orbital evolution.*

Although our main focus is on finding planetary mass objects, our survey will also define the *ab initio* incidence of brown dwarf companions by finding >10M_J brown dwarfs in orbits ranging from below 1 AU to well beyond 20 AU (Figure 1). Radial velocity measurements toward mature stars suggest a “brown dwarf desert” between 10 and 50 M_J (Marcy and Butler 2000; Mazeh *et al*. 1998; Mazeh 1999). If this effect is present as we look at progressively younger stars, then formation processes, not dynamical mechanisms, are likely to be the cause.

c) How Might Planets Be Destroyed? Other SIM programs will target the closest stars which are, by accident of our solar neighborhood, mature stars. However, mature stars are surrounded by only those planets that survive. Young stars, on the other hand, offer a snapshot of the initial properties of planetary systems. A comparison of the percentages of planets found around YSOs and mature stars would *provide an estimate of the rate of destruction of planets due to inward migration*. Trilling *et al*. (1998, 2000) suggest that as many as three times as many gas giant planets form around stars as ultimately survive in older planetary systems. These planets are lost as a result of inward migration onto the star due to planet-disk and planet-planet interactions. Other models involving different migration, stopping, or ejection mechanisms, e.g., Murray *et al*. (1998), may yield different predictions that can be compared with the results of our survey.

d) What is the Origin of the Eccentricity of Planetary Orbits? The current RV surveys show that a large fraction of extrasolar planets have eccentric orbits. If planets are formed through gravitational instability in the disk, they should have large initial eccentricities. Even if they are formed through gas accretion onto solid cores, protoplanets may acquire eccentricity as a consequence of their interaction with the disk or other migrating protoplanets. The existence of single or multiple eccentric planets around these stars will provide useful clues *to the dominant eccentricity excitation mechanisms*. The comparative statistics of orbital parameters for different age cohorts will provide valuable insights into the genesis and dissipation of eccentric orbits.

2. *Sample Selection*

Our fundamental goal is to test mechanisms of planet formation and dynamical (orbital) evolution by surveying ~150 stars of different ages in search of planets of a Jupiter mass (1 M_J) and larger in the orbital range between 1-5 AU. We have optimized the strategy to search for Jupiter mass planets as 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. Our strategy will allow us, however, to find sub-Jupiter mass planets at and beyond 5 AU. About half of the sample will be used to address the “where” and “when” of planet formation. We will study classical T Tauri stars (cTTs) which have massive accretion disks and post-accretion, weak-lined T Tauri stars (wTTs). Preliminary estimates suggest the sample will consist of ~30% cTTs and ~70% wTTs, driven in part by the difficulty of making accurate astrometric measurements toward objects with strong variability (§II.A.4).

The second half of the sample will be drawn from the closest, young clusters with ages starting around 5 Myr, to the 10 Myr thought to mark the end of prominent disks, and ending around the100 Myr age at which theory suggests that the properties of young planetary systems should become indistinguishable from those of mature stars. The properties of the planetary systems 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). We will supplement stars drawn from these young clusters with young, nearby field stars either selected from the literature or from a ground-based spectroscopic program we intend to conduct (Table 9 and §II.A.7).

3. *Sensitivity and Sampling Strategy*

On the basis of our own analysis as well of that of Brown, Sozzetti, and Casertano (1999), we set the sensitivity of our program to ensure a 2σ *single-measurement* detection of 1 M_J at 1 AU around a 0.8 M_o star (an astrometric amplitude of 8 μas); SIM will take 40 such measurements over the course of 5 yrs to ensure that Jupiter mass planets can be detected with high reliably and completeness over at least the 1-5 AU range of orbital distances. This accuracy level is also robust against the expected level of astrometric jitter produced by starspots, by variable scattered light from a disk (§II.A.4), *and/or possible degradations in SIM's astrometric accuracy.* In many cases we will be able to detect single planets with signatures x2 smaller than this value, i.e. 0.5 M_J at 1 AU or 1 M_J at 0.5 AU as well as sub-Jupiter mass planets beyond 5 AU. An illustrative sample of clusters, observing time estimates, and specific stars are given in Tables 2 and 3 (§II.A.6, 7).

Our sampling strategy (§II.A.5) is consistent with finding up to 3 planets orbiting a star with unknown periods between 100 and >2000 days, although we will be able to derive only limited information on planets

Table 2. A Survey For Jupiter's at 1-5 AU*

Region	*Age (Myr)*	*Dist (pc)*	*Observing Mode*	*Time per star*	*# Stars*	*Total Time for 40 samples and 2 axes*
Taurus, CrA, Lupus, Ophiuchus	1-2	140	Single star, Narrow angle**	10 stars (<13 mag) at 0.5 hour per star.	10	10*0.5hr*N_{axis} *N_{sample}=400 hour
			Cluster mode. Narrow angle**	6 groups of 5 stars (<13 mag) at 1.2 hr per group	30	6*1.2hr*N_{axis} *N_{sample}=576 hr
Chamaeleon	1-2	180	Cluster mode; narrow angle**	4 groups of 4 stars (<13 mag) in 1.2 hr per group	16	4*1.2hr*N_{axis} *N_{sample}=384 hr
Sco-Cen	2-20	160	Cluster mode. Narrow angle**	2 groups of 5 stars (<13 mag) in 1.2 hr per group	10	2*1.2hr*N_{axis} *N_{sample}=192 hr
TW Hya, and other nearby young stars	3-50	~50	Wide Angle observations @ ~8 µas repeated 40 times	2-6 hours (10-14 mag) for two axes	40	15*2.6hr (V ~10 mag) +25*6.3hr (V~14 mag)=196 hr
Eta Cha	8	100	Narrow angle, cluster mode**	10 stars in 1 cluster (<13 mag) in 1.2 hr (1 axis).	10	1*1.2hr*N_{axis} *N_{sample}=96 hr
IC 2391	50	160	Narrow angle, cluster mode**	5 stars in 1 cluster (<13 mag) in 1.2 hr (1 axis).	5	1*1.2hr*N_{axis} *N_{sample}=96 hr
α Per	85	175	Narrow angle, cluster mode**	5 stars in 1 cluster (<13 mag) in 1.2 hr (1 axis).	5	1*1.2hr*N_{axis} *N_{sample}=96 hr
Pleiades	100-125	125	Narrow angle, cluster mode**	2 groups of 10 stars (<12 mag) in 1.2 hr per group	20	2*1.2hr*N_{axis} *N_{sample}=192 hr
Total					**146**	**2228 hr**

*Minimum 2σ single measurement detection of 1 M_J at 1 AU.
**Choose 1-2 (grid) stars within 4° as reference.

with periods longer than about twice the duration of the SIM mission.

4. Astrophysical Limits To Sensitivity

SIM’s astrometric accuracy for YSOs may ultimately be limited by astronomical noise sources that induce shifts in the observed photocenter. These noise sources can include starspots, starlight scattered by circumstellar disks, disk hot spots, and variable disk extinction. Since many of these attributes are characteristics of the youngest stars with the densest disks, there is an unavoidable tension between minimizing these effects by rejecting sources and keeping the most interesting objects. In this section we try to quantify the effect of some of these processes on the astrometric data and show how, by prudent source selection and careful data analysis, we can make observations at the precision needed to find planets at the desired levels.

a) Astrometric Shifts due to Starspots

Starspots can cause changes in the position of the photocenter of a star that can mask the astrometric signal from a planet. In the past decade a number of groups have used photometric variability and Doppler imaging to investigate the surface structures on both cTTs and wTTs. The data can be interpreted in the following ways: relatively few, large, cool, long-lived starspots in both cTTs and wTTs (~ 10-40% of a projected hemisphere vs. few millionths for the Sun); cool polar caps in rapidly rotating wTTs; hot spots in cTTs that may represent regions of accretion impact at the stellar surface; and a marked decrease in spot activity for stars approaching 1 M_o (Shevchenko and Herbst, 1998; Bouvier *et al*. 1995; Bouvier and Bertout 1989; Schussler *et al*. 1996; and refs. therein).

We have developed a numerical model to calculate the photometric and astrometric effects of a distribution of spots over the surface of rotating stars (Figure 2). The model incorporates a broad range of spot and star parameters as derived from the references cited above. A variety of runs were made for 100 evenly spaced observations over a 5 year period at wavelengths from 0.4-0.95 µm. *The key result of the numerical analysis (Figure 2) is that a V-band photometric variation of $\Delta F/F=10\%$ (rms) corresponds to an astrometric variation of ~3 µas (rms) in the position of a 2 R_o pre-main sequence star at the distance of Taurus.*

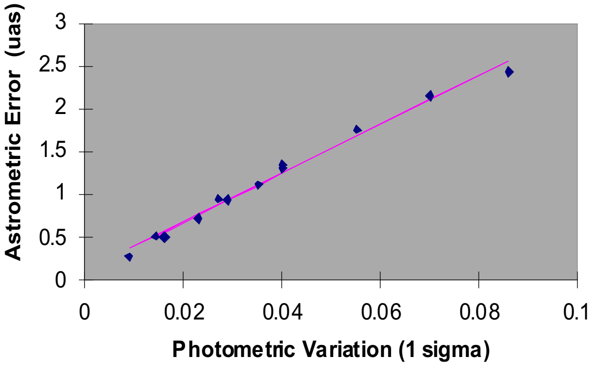

Figure 2. The relationship between the photometric variation ($\Delta F/F$) in V-band and photocenter shift due to sunspots on a T Tauri star at 140 pc.

These values are to be compared with the 8 µas signal of a Jupiter in a 1 AU orbit around a 0.8 M_o star at 140 pc. Because both photocenter excursions and the astrometric amplitude scale inversely with stellar distance, this noise source may ultimately set a distance-independent limit to our ability to find planets smaller than ~0.1 M_J around young stars. The fact that the photocenter excursions are well correlated with the intensity excursions will be critical for masking or modeling, and removing, the effects of starspots. We will compensate for the photocenter variation due to starspots in a number of ways:

1. Minimize this effect by selecting stars with relatively small photometric variations attributable to starspots ($\Delta V<0.2$ mag, $\Delta R<0.1$ mag; Figure 3; §II.A.7).
2. Use longer wavelength data where the contrast between the spot and the photosphere is typically 1.5-2 times more favorable than at shorter wavelengths.
3. Use SIM to mask out periods of large photometric variation which might be correlated with astrometric shifts, and/or model simple starspot distributions to reduce their effects. Simulations of one and two large spots at 7 different wavelengths from 0.4-0.95 μm showed it was possible to obtain factors of 2-3 reduction in the astrometric dispersion by simple modeling.

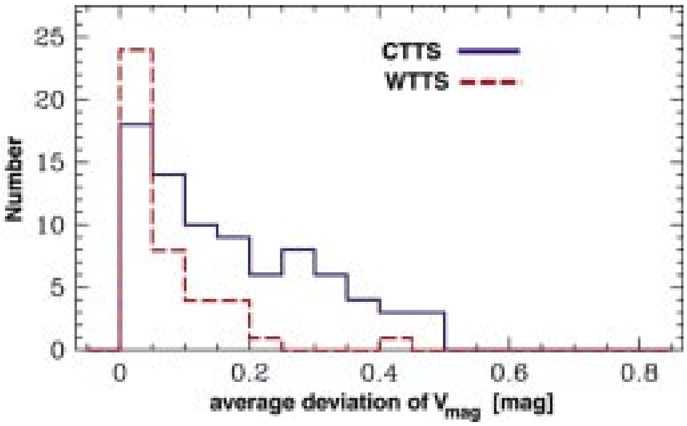

Figure 3. Histograms showing V-band variability of a sample of classical and weak-line T Tauri stars (Herbst et al. *1994; Herbst, private communication).*

b) Astrometric Shifts due to Disks. Time-variable scattering by a dust disk of light from a rotating star with hot or cool spots can also induce astrometric shifts. Calculations of the effects of the asymmetric scattered light pattern of the disk (using the model of D'Alessio *et al*. 1999) show that SIM's 10 m *baseline resolves out most of the perturbing emission*. Detailed simulations show that if a 30 AU disk is variably illuminated as a function of azimuth by $(1+0.5\times\cos\phi)$, then the peak-to-peak photocenter variation is 4 μas following the few-day rotational period of the star. The existence of significant diffuse structure will be immediately apparent in the SIM visibility data which can be used both as a flag for a potential problem and as a source of information for modeling to mitigate the effect.

Given these simulations, we believe that SIM can detect the presence of giant planets in still-accreting T Tauri stars provided care is taken in the selection of targets, specifically by rejecting stars with: (1) stars with large photometric variability; (2) stars with nebulosity as indicated by HST imaging or large ground-based telescopes at the 0.1 arcsec level; (3) spectral energy distribution (SED) evidence for particularly large, flared disks.

5. Sampling Strategy for Planets of Unknown Periods

One of the major challenges of finding planets is the fact that their periods are unknown and could range from days to years. We have adopted a solution to this problem developed for the Cepheid Key Project on Hubble Space Telescope (Freedman *et al*. 1994). Madore and Freedman (2000) developed a sampling strategy for characterizing Cepheid light curves in distant galaxies. In this scheme, $n=0,1,2\ldots N_{sample}$ observations are spread throughout a total observing period P_{obs}, according to a power-law distribution given by

$$D(n)=(P_{obs})^{a^n}.$$

An examination of range $0.9<a<0.995$ shows that the bias and dispersion in the amplitude of a model astrometric signature are minimized for $\alpha=0.98$.

The choice of N_{sample} is driven by the need to have enough independent (2-axis) measurements to detect and characterize multiple planets. A minimum of $5+7*N_{planet}$ observations is needed to characterize a multiple system in a least squares sense. The choice of $N_{sample}=40$ is consistent with an ability to characterize 3 planets with a factor of ~1.5 redundancy in the data. A critical part of our work in the years before the launch of SIM will be to carry out higher fidelity simulations of multiple planet systems to fine-tune the SIM observing strategy (§IV.A).

6. *Observing Time Requirements*

Since the majority of the YSOs are faint, V~14 mag, we must be as efficient as possible in observing them. We have used the scientific requirement of the reliable detection of 1 M_J planet at 1 AU to set a measurement accuracy that varies with the mass of the parent star and its distance from Earth. We will tailor our observations for maximum efficiency using the following modes:

a) Wide angle Observations. A Jupiter at 1 AU from a 0.8 M_o star at 50 pc has an astrometric amplitude of 25 μas. A 2σ detection requires only a single measurement accuracy of 12 μas which can be accomplished efficiently with multiple observations in wide angle mode.

b) Narrow angle Observations. The same planet at Taurus (140 pc) has an astrometric signal of 8 μas, requiring a narrow angle measurement of 4 μas, comfortably removed from SIM's ultimate performance limit.

To estimate the necessary duration of the narrow angle observations, we have derived an error budget from the information on the SIM web-pages that incorporates both brightness dependent and systematic errors.

Assuming that the narrow angle systematic error scales in a power-law fashion between 1° (1.7 μas) and 15° (7.7 μas), we can achieve a 4 μas accuracy relative to a reference star as far away as 4° from the target. The advantage of a reference star this far away is that we have an excellent chance of being able to use a SIM grid star as a reference. Grid stars are bright (V<10-12 mag) so they can be observed quickly and their astrometric properties will be determined by the project, at no cost to an individual program, to the <4 μas level. The time required to achieve this accuracy varies with the brightness of the target, but is approximately 1.2 hr for a V~14 mag star (one axis) including all grid stars, reference stars, and overheads.

c) Cluster Mode. There are natural groupings of young stars in star-forming regions that allow us to define groups of ~5-10 stars in regions <4° diameter (cf, Gomez *et al*. 1993). We intend to interleave narrow-angle observations of 5-10 stars into the one hour observing period described in the SIM web page. A typical observing sequence would consist of two 215 sec measurements each of the 5 target stars and the two bright reference stars (V~10-12 mag). This sequence would fit into the 3000 sec (50 minutes) available during a basic SIM integration block. The total time required to complete this observation, including all slew and settling overheads, would be 1.2 hours. The resultant astrometric sensitivity for five 13 mag stars is 3.8 μas which includes the uncertainty on two reference stars. This basic time needs to be doubled to make a 2-axis measurement, and then multiplied by $N_{sample}=40$ to obtain 96 hours to observe 5 stars over the course of the mission. Table 2 summarizes these observing modes and the times estimated to execute them for the clusters in question.

7. *Illustrative Sample of Objects*

Table 3 presents an illustrative group of stars drawn from the clusters listed in Table

2 that meet all our criteria of mass, distance, age, lack of strong disk emission or pronounced variability ($\Delta V<0.2$ mag). We also reject stars with stellar binary companions with periastrons less than ~100 AU (~1″) to avoid astrometric noise and the introduction of an additional astrophysical variable.

We have in hand lists of stars that would be suitable for observation even if SIM were to be launched tomorrow. There are a few hundred stars in the field and in over a dozen nearby clusters from which to draw an optimized SIM target list. However, it is well worth the investment in precursor observations to fine-tune and augment the list over the next few years to maximize the scientific return from this program. Thus, over the next 3-5 years we will carry out a substantial program of ground- and space-based observations to select stars in appropriate mass and age bins that are free from characteristics that would degrade SIM's astrometric measurements (§II.A.4, II.D). We will continue to add the closest, youngest low mass stars (<100 Myr, < 50 pc) to our program as they are identified by X-ray, spectroscopic, and proper motion studies. For example, previously unknown pre-main sequence K dwarfs with ages from 10-100 Myr will be identified within 25-50 pc using 2MASS/ TYCHO2 data to select candidates and new high resolution spectroscopy to measure lithium and other age sensitive indices (Fischer 1998).

Table 3. Illustrative Target List for Planet Searches

Star	Avg. V (mag)	σV (mag)	IR binary	HST Nebl	Mass (M)	Age Log(yr)	IR Excess Δ(H-K) mag
BP Tau	12.13	0.12	No	No	0.47	5.78	0.19
CI Tau	13.11	0.15	No	No	0.48	5.84	0.56
DN Tau	12.36	0.07	No	No	0.37	5.66	0.31
DH Tau	13.64	0.13	No	No	0.34	5.75	0.29
V1121 Oph	11.42	0.09	No	No	0.54	<5.0	---
Haro1-16 Oph	12.5	0.06	No	No	1.1	6.00	---
SR4 Oph	12.83	0.06	No	No	0.36	5.00	---
ROX3 Oph	13.18	0.03	No	---	0.27	5.77	---
V819 Tau	13.18	0.05	No	No	0.49	5.88	0.04
V836 Tau	13.12	0.09	No	No	0.6	6.33	0.12
SU Aur	9.2	0.1	No	---	2.32	6.41	0.43
DoAr21 Oph	13.94	0.07	No	---	2.4	5.50	---
TAP35 Tau	10.24	0.01	No	---	1.37	6.72	0.01
TW Hya	11.03	0.1	No	Yes	0.73	6.9	0.11
TWA-7	10.7	---	No	---	0.36	6.9	0.02
TWA-8A	11.5	---	Wide	---	0.30	6.9	0.03
TWA-10	12.3	---	No	---	0.28	6.9	0.11
TWA-13	11.5	---	Wide	---	0.35	6.9	---

8. *Numbers of Planets Expected in the Survey*

It is impossible to predict with confidence the number of planets SIM will find around young stars, but we can use the results of ongoing radial velocity studies of mature stars in conjunction with various theoretical models to bound the problem. We adopt three different, mutually-exclusive, assumptions, which range from most pessimistic to most optimistic, to define the following cases:

A. The incidence of giant planets around stars of any age is ~5%, e.g. equal to the radial velocity discovery rate for close-in giant planets.

B. From the fact that the RV results cover only a small part of the SIM discovery space around any given star, and using the results of Trilling *et al*. (2000) as a rough guide, one might assume the incidence of giant planets around stars of any age is about 10%.

C. Use the Trilling *et al*. (2000) migration calculations as a guide to the loss of planets early in the history of sun-like stars. Since migration timescales, including gas and post-gas dust, would plausibly be 1-10 Myr, we estimate that >30% of stars younger than 10 million years have giant planets, but only 10% of stars older than that maintain giant planet systems (i.e., at least one giant planet). Nor, of course, can we exclude the possibility that all young stars have planets.

Under these three different assumptions, we expect to find roughly 7 planets (Case A), 15 planets (Case B) or >35 planets (Case C) around star stars younger than 100 Myr and a few (2-5) planets around the older Pleaides sample. Thus the total number of planets we expect to detect ranges from 7 to >35, and possibly up to as many as >100 planets.

What do the above results imply for deriving information on giant planet formation? In Case A, the paucity of objects found would be a significant scientific result implying that giant planet formation may be rarer than presently thought. It is also clear that Cases B and C are distinguishable from each other; i.e., if indeed giant planet formation is a not-uncommon process, we should be able to see the effects of migratory loss in our discovery statistics around younger versus older stars.

B. Fundamental Properties of Young Stellar Objects

Understanding the formation and evolution of stars is a second major objective of the Origins Program. Since planet formation is a part of the phenomenon of star formation and evolution to the main sequence, understanding the properties of YSOs is essential to understanding the environment of planet formation. SIM offers unique capabilities to improve our understanding of how stars like our Sun and smaller evolve toward the main sequence.

Mass is the most fundamental property of a star and determines its early evolution and ultimate destiny. Yet we don’t know the masses of most young stars, particularly those of a solar mass and less, to within a factor of 2. Accurate knowledge of masses will help calibrate early YSO evolution; the identification of large numbers of accurate masses and mass ratios will enable theorists to determine definitively the formation mechanisms of binary star (Clarke 2000).

Because the masses of only a few, young, low mass stars are well known, the pre-main-sequence (PMS) evolutionary tracks used for estimating YSO masses and ages are not accurately calibrated. Current models for the tracks give masses and ages for a $1L_o$ K7 PMS star which vary by a factor of ~2 (Table 4). The discrepancy is even greater for later type stars. As a result, parameters essential to theories of star formation, such as stellar ages, star forming region history, initial mass function and the distribution of masses in binaries are poorly known. The SIM program proposed here will, by calibrating the calculations of PMS evolution over a decade in stellar mass, improve our knowledge of these astronomical parameters and, equally importantly, resolve our uncertainties of the physical inputs to the calculations, e.g. atmospheric

Table 4. Theoretical Mass and Age Estimates for a K7, L=1.0 L PMS Star

Calculation	*M/M_o*	*Age (Myr)*
Cohen and Kuhi (1979)	0.85	2.0
Swenson *et al.* (1994)	0.65	1.0
D'Antona and Mazzitelli (1997)	0.45	0.8
Baraffe *et al.* (1998)	0.80	1.0
Palla and Stahler (1999)	0.80	2.0

opacities, convection mechanism, and the equations of state (cf. White *et al*. 1999).

While FAME will make major improvements in reducing uncertainties in mass, that mission cannot provide data of precision sufficient to calibrate evolutionary tracks so that they can become predictive over the full range of ages and masses — from ages when accretion ceases (1-10 Myr) to the ZAMS (10-30 Myr later). With only a small investment in observing time (5% of our total), we can take advantage of the power of SIM for ultra-high precision distance and mass estimates for faint objects to produce a unique database that theoreticians can use to calibrate PMS tracks to 1% precision.

Observations of visual and spectroscopic binaries (Mathieu 1994; Ghez *et al*. 1995; Thiebaut *et al*. 1995; Simon *et al*. 1996; Casey *et al*. 1998; Prato 1998) and the mapping of circumstellar (CS) disk rotation (Dutrey *et al*. 1994, 1998; Koerner 1997; Mannings & Sargent 1997; Guilloteau & Dutrey 1998) provide the only reliable determinations of stellar masses. We propose to use SIM to measure distances and inclination angles of a sample of ~100 stars for which sufficient dynamical data exist to enable us to measure the stellar masses to high precision. Figure 4 compares the masses measured by CS disk rotation (Table 5) with PMS tracks calculated by Baraffe *et al*. (1998, BCAH98) and D'Antona and Mazzitelli (1997, DM97). Since these masses scale with distance, the distance-independent parameter L/M^2 is plotted versus effective temperature. In this format, if a star does not lie on the track corresponding to its nominal mass, either its distance is not the reference value (140 pc), or the theoretical track is wrong. The distances to these stars are not well enough known now to distinguish between these two possibilities. The figure indicates that a meaningful test of the tracks requires absolute uncertainty of the measured masses of less than about 5%. Since the internal precision of the dynamical mass measurements is better than a few percent (Table 5), we require that the distance and inclination measurements not compromise the overall uncertainty.

Table 5. Dynamic Masses Derived from Disk Rotation (∝D/140 pc)

Star	M_*/M_o
Singles:	
MWC 480	1.65 ± 0.07
LkCa15	0.97 ± 0.03
DL Tau	0.72 ± 0.11
GM Aur	0.84 ± 0.05
DM Tau	0.55 ± 0.03
CY Tau	0.55 ± 0.33
BP Tau	1.24±0.32
Binaries:	
GG TauA	1.28 ± 0.07
UZ Tau E	1.31 ± 0.08

In the following sections, we describe three approaches to obtaining dynamical masses: 1) visual binaries (VBs), 2) spectroscopic binaries (SBs), and 3) mapping of circumstellar disks with CO interferometric millimeter observations. Approaches 1) and 3) require precise SIM distances to determine the masses; approach 2) requires SIM measurements of the binary orbit parameters (particularly inclination angle). Table 6 gives the dependence of mass estimates on distance and shows that 1% distance measurements are well within SIM's design limits. This value is chosen so that the distance of a star will not compromise the overall value of its mass and therefore will allow the best possible comparison with the theoretical PMS tracks. Through Associate Investigator Baraffe and her collaborators, our team has dedicated access to some of the best numerical codes available for the future development of evolutionary tracks calibrated using SIM.

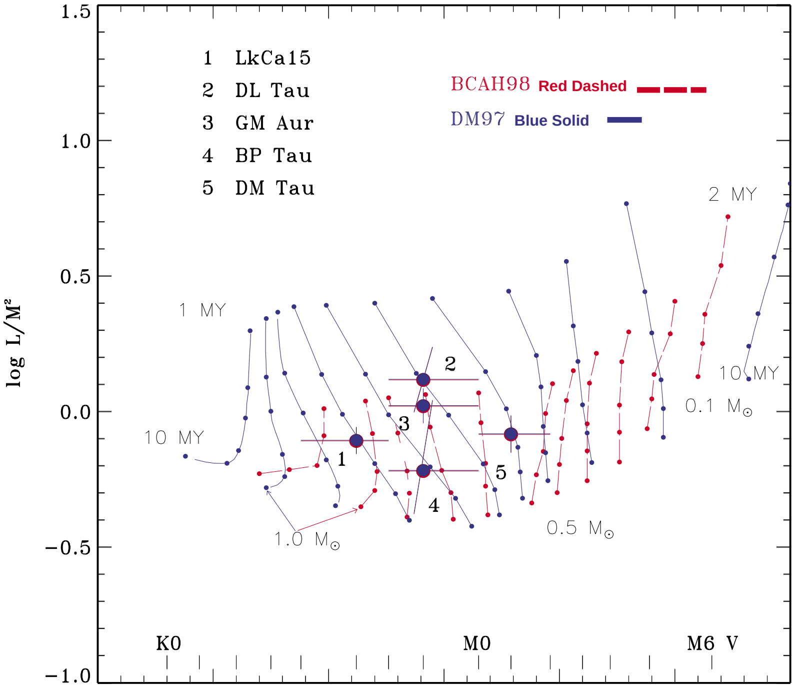

Figure 4. PMS tracks for stars of mass 0.1 to 1.2 M_o calculated by DM97 and BCAH98 and masses of single cTTs measured by disk rotation. The uncertainties displayed are ±1 spectral type sub-class and the propagated internal uncertainties of the mass measurement and an assumed ±10% uncertainty in luminosity. The small filled circles mark ages 1, 2, 3, 5, 7, and 10 Myr for DM97, and 2, 3, 5, 7, and 10 Myr for BCAH98.

1. *Visual Binaries*

Table 7 lists some of the visual binaries (VBs) for which orbital motions are now being mapped from the ground and with HST (Ghez *et al.* 1995, Thiébaut *et al.* 1995, Simon *et al.* 1996). These have $a > 20$ milliarcsec so their primaries and secondaries are resolvable by SIM. SIM observations will measure not only the parallax but also, for systems with detectable orbital motion of the primary and secondary, the ratio of the semi-major axes of the primary and secondary, a_1/a_2, and hence M_1/M_2 permitting solution for both M_1 and M_2. Detection of any wobble in the motion of the primary or secondary would reveal additional companions.

Table 7 shows that the precision needed for accurate mass determinations falls well within SIM’s wide angle capabilities and can be obtained with a modest investment in observing time. The table also estimates the precision that FAME will obtain for a given brightness. For stars fainter than V=12.5 mag, a FAME parallactic uncertainty of ~250 µas will yield an overall uncertainty in the absolute mass of 10%, which is insufficient for a meaningful test of the evolutionary tracks.

2. *Spectroscopic Binaries*

An active effort is in progress to identify spectroscopic binaries (SBs) among the young stars and, since their periods tend to be typically less than a year, to derive their orbital parameters (Mathieu 1994; Neuhäuser 1999). Also underway is a project to identify additional double-lined SBs by complementing visible light spectroscopy of SB1s with high spectral resolution observations in the near-IR where the secondary star is brighter than it is in optical light (Prato 1998; Mazeh *et al*. 2000;

Steffen *et al*. 2000).

Table 6. Required Parallax Accuracy		
Technique	$\frac{\Delta M}{M}$	Taurus (140 pc)
CS Disks	$\propto \Delta D/D$	71 μas
Visual Binaries	$\propto 3\Delta D/D$	24 μas

The SIM observations will convert SBs to VBs by measuring the inclination angle, *i*. For double-lined SBs, this will yield each of the component masses. We will include the few known (Corino *et al*. 2000), eclipsing double-lined SBs in our program as they are identified to provide an independent determination of their masses.

3. *Mass Measurements of Stars with Resolved CO Disks*

Maps of disk rotation measured by mm-wave interferometry provide a unique means to measure masses of single stars, and a number of precision values are already available (Table 5). The derived mass scales linearly with distance to the star because it depends on the physical radius at which a given velocity is measured. Table 5 lists the mass derived from recent ^{12}CO J=2-1 observations of cTTs in Taurus (Simon *et al*. 2000). The precision of the masses in Table 5 is limited by uncertainties in the disk inclination and in the distance. SIM will improve the precision of the mass measurements for the brighter stars relative to FAME, and enable a precise measurement of the fainter stars (V>14 mag).

4. *The Total Program*

The total masses program will consist of observations of the visual and spectroscopic binary stars and the stars with CO disks (Tables 5 and 7). Over the next 3-5 years, we will identify new targets, with a particular emphasis on late K-M spectral type stars, $M<0.4\ M_o$, through a combination of imaging, spectroscopy and CO mm observations, for a total of ~100 stars. By scaling the observing times listed for the stars in Table 7, we anticipate that approximately 100 hours will be required for these observations.

As calculations of PMS tracks become more sophisticated, particularly by including realistic stellar atmospheres, it will become possible to compare them directly with the observed quantities. Using judiciously chosen observed colors and magnitudes, corrected for veiling and extinction, we will mitigate the uncertainties of spectral type estimates and conversion of spectral type to effective temperature. *These improvements, along with precise masses determined for the first*

TABLE 7. Exposure Time Estimates for Representative Sample

Star	*V (mag)*	*Precision Reqd. for 1% mass (μas)*	*Est. FAME Sens. (μas)*	*SIM mission total (hr)*
Single Stars				
DM Tau	14.0	71	>350	0.6
DL Tau	13.1	71	270	0.6
GM Aur	12.9	71	250	0.6
LkCa15	12.1	71	180	0.6
Visual Binaries				
FW Tau	16.4	24	>500	1.0
F0 Tau	15.4	24	>500	0.6
HV Tau	14.0	24	>350	0.6
DI Tau	12.9	24	250	0.6
Spectroscopic binaries				
Haro 1-14c (P=591d)	12.3	21	180	1.2
0425+3016 (P=2530d)	11.6	24	250	1.2
1559-2233 (P=2.4d)	11.2	21	120	1.2
GW Ori (P=242d)	9.8	7	70	1.2

time by SIM, will enable a breakthrough in our understanding of the early evolution of solar type and lower mass stars. Further, the greatly improved evolutionary tracks will give us a chronometer with which to order the sequence of events that leads to the formation of planetary systems.

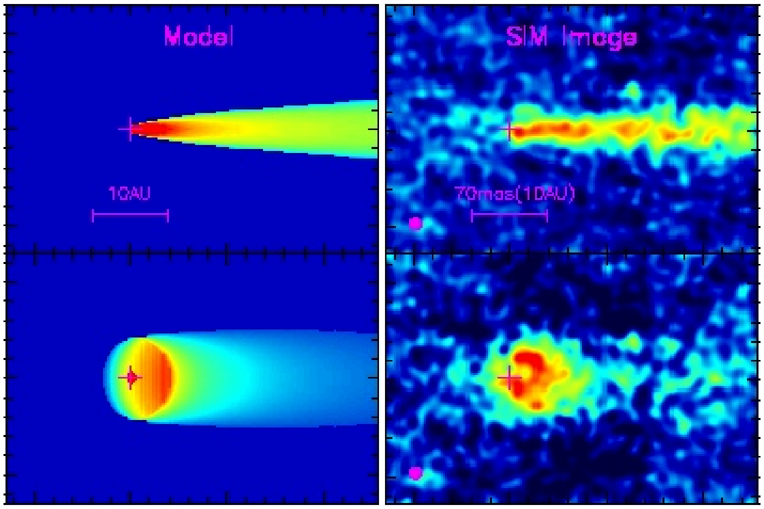

Figure 5. Left panel: Models of the central region of DG Tau (0.28''x0.14'') assuming (top) the jet is launched from a compact region (r ~10 R_o) at a narrow opening angle, or (bottom) it is launched from the disk within a region ~5 AU. Right panel: The corresponding simulated Hα images for SIM. The star's emission has been subtracted in both the model and SIM images (using data from adjacent wavelength channels).

C. The Structure and Origin of YSO Disks and Jets

Jets and outflows play a key role in the evolution of accretion disks and thus may be an important factor in the formation of and survivability of giant planets close to central stars.

We propose a small program to image Herbig-Haro jets driven by YSOs in Taurus. Little is known about the size scale on which jet acceleration and collimation occur which would allow us to distinguish between a "disk" wind (Konigl 1989) or a "stellar" wind (Shu *et al*. 1995). Extrapolating the widths of jets from HST images inwards suggests widths of ~15 AU, easily resolvable by SIM, that favor a disk wind interpretation (Burrows *et al.* 1996; Reipurth *et al.* 2000). However, stellar wind models cannot be ruled out and would predict much narrower jets that would be unresolvable by SIM.

Jets radiate strongly in optical wavelength emission lines such as [S II] 671.7/673.1 nm and the 656.3 nm Hα line. SIM will resolve structures down to 0.01" (1.5 AU) in nearby YSO jets that could constrain certain jet models in a way impossible even with major advances in ground-based adaptive optics. The result will be a scientifically important and visually compelling demonstration of space interferometer imaging, a critical precursor for the observations planned with the Terrestrial Planet Finder.

We propose SIM visibility measurements to map the brightness distribution of five YSO jets in Taurus (Table 8). In the single SIM spectral channel that includes the Hα line, a significant fraction (~20%) of the total flux is expected to come from the extended jet so that a lack of contrast will not be an issue in the data reduction.

We have simulated aperture synthesis images for the DG Tau (V=12 mag) system, assuming 7 sidereostats providing 13 independent baselines from 0.8 m to 10 m sampled at 0.8 m intervals and by rotating the baseline in steps of 10^o. The simulations include appropriate levels of phase, amplitude, and photon noise and show that SIM should be able to resolve a jet driven by a

Table 8. Potential Sources In Taurus For Jet Imaging

Star	V (mag)	Hα (EW)	[SII] (EW)
DG Tau	12.0	113	9
CW Tau	12.4	135	2
DM Tau	14.0	139	---
DP Tau	14.2	85	-
DO Tau	14	100	1

disk wind with just a few hours of integration time (Figure 5). We anticipate spending 40 hours (8 hours ×5 objects) to observe 5 stars plus an additional 10 hours to measure 1 or 2 bright unresolved point sources for calibration purposes.

Without invoking full synthesis imaging we will carry out a second imaging experiment in direct support of the astrometric observations. As discussed in §II.A.4, time variable illumination of disk structures may induce shifts in the photocenter measured by SIM. We will use the visibilities obtained in multi-wavelength single-baseline u-v sampling at several orientations to characterize the disk photocenter and any asymmetries. These data will allow us to develop techniques to assess and mitigate, if necessary, the influence of disk structures on the astrometry of the entire sample. We allocate 25 hours to carry out these experiments toward 5 stars with a variety of disk characteristics.

D. Precursor and Supporting Observations

A variety of precursor observations are essential for defining the best possible lists of target and reference stars (Table 9). The highest priority use for SIM funds (§IV.B) will be to pay for the travel and postdoctoral assistance needed to identify and characterize the stars for planet search part of program. Co-I Ghez (UCLA) will coordinate this program which will take advantage of national observatories as well as facilities to which relevant team members have access (Table 12).

1. Variability

We will use a combination of FAME and ground-based photometry using small telescopes to reject highly variable stars or to identify variable stars that might be simply modeled. Associate-Investigator Herbst has considerable experience in making these observations. Beichman and Shao are members of the FAME team and will have access to FAME photometry prior to its release for this purpose.

2. Binarity

We will use AO imaging from large ground based telescopes and HST snapshots to search for close binary companions to target stars, rejecting stars with companions closer than ~100 AU. We will also use spectroscopy to identify spectroscopic binaries using 2-3 spectra to look for radial velocity variability. Objects removed from the planet search sample could be added to the fundamental properties sample. FAME data will be useful in weeding out target and reference stars with stellar or brown dwarf companions.

3. Reference Stars

In addition to using SIM grid stars whenever possible, we will use 1-2 bright reference stars (V~10-12 mag) within 4^o for planet searches in clusters. We recognize the difficulty of finding reference stars in star forming regions where extinction can block the distant giants we would like to use. However, since we have selected relatively nearby, high latitude, star-forming regions, it is possible to see through these regions to distant stars over a 4^o scale. We will select reference stars by using 2MASS and visual photometry to identify candidate

K0-M0 giants brighter than V~10-12 mag (Bessell and Brett 1988). We would then use spectroscopy to verify that the stars are truly giants free of perturbing companions. The clustering of YSO targets reduces the number of reference stars we will have to identify and characterize.

4. Observations Of Disks

We will use the following techniques to determine whether disks or other nebulosity will be a problem for stars in our sample: use of 2MASS and other near-IR data to reject stars with massive accretion disks (Lada and Adams 1992; Meyer *et al*. 1998); expansion of the HST snapshot imaging sample (Stapelfeldt *et al*. 1998) to investigate nebulosity or disk structures at the 0.1″ scale; continued observing programs at Keck and Palomar to assess the presence of disks and binary companions using adaptive optics imaging.

5. Other Observations

We will augment and refine the target list for the stellar masses part of the program with precursor observations using SIM funds plus other research support. These observations will include identification and characterization of visual (Ghez, Simon, Mathieu) and spectroscopic binaries (SB1s, Mathieu; SB2s, Prato) as well as continued millimeter mapping of disks around single stars (Simon).

E. Data Analysis and Data Products

1. Companion Searches

We assume that the Interferometry Science Center (ISC) will provide time-tagged delay line values, observed visibilities and photometric amplitudes, instantaneous baseline

Table 9. Precursor Observations In Support Of Planet Search

Program	*Facility*	*# of Sources/ Nights*	*Participants*
Variability	FAME; 0.6 m Weslyan Telescope and Yale 0.6 m telescope (CTIO)	200 stars; 10-20 nights/yr for 3 yr	*Hillenbrand* Herbst
Search for unseen companions: Radial velocity variability or shift relative to molecular cloud	Lick: Echelle spectrograph WIYN: Hydra/MOS spectrograph, MMT Gemini South: Phoenix IR spectrograph SIM Grid star program	2-3 spectra/obj for 100-200 stars (targets plus references) 5 nights/yr for 5 yr	*Mathieu* Stauffer Ghez Hartmann
Search for unseen companions (imaging)	HST: WFPC2 and NICMOS snapshots	100 stars; 50 orbits	*Stapelfeldt*
	Keck/Palomar: AO with near-IR imaging	100 stars; 2-4 nights/yr for 5 yr	Ghez Beichman
Identifying new YSOs within 50 pc and with 5<ages<100 Myr	2MASS/Tycho-2 photometric selection plus Echelle spectroscopy for lithium and Hα dating. Lick, NOAO, CTIO , MMT	200 stars in 6 runs over 3 years	*Stauffer* Hartmann Strom
Identifying and characterizing circumstellar disks	Near-, mid- IR Photometry with 2MASS, SIRTF HST: WFPC2 and NICMOS snapshots	MIPS/IRAC observations of ~100-200 stars	*Hillenbrand* Carpenter Stauffer Stapelfeldt

vectors, corrected for differential stellar aberration and gravitational deflections by solar system bodies. We will then use the photometric data to look for variability and the visibility data to look for resolved structures or luminous companions that might produce spurious astrometric signatures. We will then correct the data for relative parallax and proper motion to produce a time series of relative two-dimensional astrometric measurements between the target and the reference star(s). *The corrected, relative two-dimensional astrometric measurements for each star constitute a fundamental deliverable of our project.*

Table 10. Analysis of A Three Planet Simulation

	Planet 1	Planet 2	Planet 3
Input Parameters			
Semi-major axis (μas)	32	16	8
Period (day)	869	548	345
Mass (M_J)	2.2	1.5	1
Inclination(deg)	75	75	75
Derived Parameters			
Semi-major axis (μas)	35.4±0.5	15.1± 0.3	8.1± 0.3
Period (day)	881±3	562±2	349±1
Mass (M_J)	2.4±0.1	1.4±0.1	1.0±0.04
Inclination (deg)	78.6±0.7	70.4±1.3	83.0± 1.8

We will use the standard method of Lomb-Scargle (LS) periodograms (see Black and Scargle 1982) which should be reliable and robust for periods up to the duration of the SIM mission (although Cumming *et al.* (1999) suggest alternatives to simple LS periodogram analysis that may be relevant to our SIM analysis). Because the astrometric measurements are relative, there is a formal degeneracy as to which object has the periodicity; this degeneracy can easily be broken by identifying common periodicities among pairwise periodograms between multiple target and reference stars. This degeneracy can also be broken if an independent observation method (e.g. radial velocity or photometry) indicates common periods among the target or reference stars.

Simulations of multiple signal extraction suggest that detection of multiple companions should proceed iteratively by systematically and successively identifying, estimating, and removing statistically significant periodicities from the data set. In particular, this means the identification of periodicities from LS periodograms, and then the fit of a Keplerian orbit model to the astrometry data. From the inclination and semi-major axis of the model the companion mass (formally the companion/star mass ratio) is directly inferred.

Provisional detections of some of the larger and higher-frequency periodicities are likely to be available at the halfway point of the mission. However as the extraction of smaller-amplitude signals are dependent on the correct removal of larger signals these companions will largely go undetected until near the end of the mission. As a final step, the optimal signal extraction will utilize a simultaneous estimation of companion orbit models initialized with the results of the serial extractions. We will use an extensive program of Monte Carlo simulations based on our exact SIM observing strategy to assess the completeness and reliability of our survey so that we understand quantitatively the significance of the absence of planets around a particular star.

We have developed planet detection algorithms based on astrometric work carried out using the Palomar Interferometer Testbed (co-Investigator Boden; e.g. Boden *et al.* 1999; Boden and Lane 2000). We have used these algorithms on simulated data for systems of up to three planets orbiting a 0.8 M_o star at the distance of Taurus. Consider a co-planar system of three planets inclined by 75°. We simulated our proposed 2-dimensional observational sequences with 40 measurements, each with a precision of 4 μas with samples distributed through a 5-yr period with a power law α=0.98 (§II.A.5). Successive examinations of the LS periodogram revealed the three planets with high significance and led to the parameters given in Table 10. Even in the 3-planet system, we were able to derive the mass of a 1 M_J planet at 1 AU with 4% accuracy.

We will build on our existing planet search algorithms to develop a working, prototype pipeline as early as possible during the program. This prototype will be used to improve the algorithms, understand interfaces with the ISC, and optimize our observation strategy.

2. Luminous Companions

The above analysis will be carried out to help characterize the fundamental properties of binaries in the T Tauri star sample. One modification will be to examine the visibility data for direct evidence of light from the companion itself. We estimate that we will able to measure the brightness and separation of a companion as faint as ΔV=5 mag at 10 mas separation and ΔV=4 mag at 5 mas. In these cases, we will be able to characterize the properties of a coeval pair of stars with well determined mass, temperature and luminosity differences.

3. Imaging Analysis

The basic data for this mode are the calibrated visibilities at all wavelengths on the various baselines and rotation angles. We will make images with these data using standard Fourier-based image processing techniques (AIPS). Modifications to this technique might include using adjacent continuum channel images to improve the phase accuracy in the line channels and using images from HST or other facilities to fill in short spacings not well covered by SIM itself (<0.8 m). Team members Velusamy and Stapelfeldt have extensive experience with the advanced imaging processing techniques (direct and Fourier) needed for this analysis.

4. Data Products

This program will generate a number of primary and derived datasets that will form the basis of our scientific investigations. Table 11 lists some of these products. We will work with the ISC to develop a release schedule that is consistent with NASA policy and with our desire to release reliable, well-calibrated data to the community in a timely manner.

Table 11. Program Data Products
Primary Products released to ISC
Astrometric properties of T Tauri Star sample (distances and proper motions)
Calibrated, relative astrometry between planet search targets and reference stars
Calibrated visibilities for disk images
Secondary Products Published in Journals and Released to ISC
Derived Properties of T Tauri Stars and their companions (masses and orbital information)
Derived properties of planet search companions
Channel maps of disk/jet images

III. Education & Outreach

We will use the wealth of scientific concepts and innovative SIM technology to expand the understanding of science, math and technology among the general public. For example, the concepts of angular resolution, interferometry, and spacecraft design demonstrate the interaction of science, math and technology. The derivation of the properties of planetary systems via Kepler's Laws demonstrates the connection between theory and observation to advances in our understanding of the Universe. Explanation of these connections is fundamental to enhancing the public's understanding of the benefits of scientific research and is in keeping with the goals of national education reform efforts such as those outlined in the 'Benchmarks' publication of *Project 2061*.

Members of this scientific team have experience partnering with the formal and informal educational community. Team members Yorke, Stapelfeldt, Hillenbrand, and Norman, have past and present partnerships between elementary and secondary schools through participation in programs such as Project ASTRO. In addition, Stapelfeldt and Ghez have experience in presenting at the National Science Teachers convention, developing courses for college professors to help bring research into the classroom setting, and developing exhibits and material for museums. A few members (D. Norman, L. Hillenbrand) have participated in programs designed to encourage groups historically underrepresented in science, e.g. science workshops for girls through programs like the Girl Scouts, Rural Girls in Science Camp and Expanding Your Horizons.

One team member (Mathieu) is involved with the National Institute for Science Education in Madison, Wisconsin developing curriculum modules that use leading-edge research as a tool for introducing science concepts into introductory college classes. The EPO team can use the search for planetary systems to infuse K-14 curriculum modules with new ways to present elementary concepts in math, astronomy, physics, chemistry and biology.

As shown in the organizational chart (Figure 6) for the YSO science team, Educational and Public Outreach (EPO) efforts will be supervised and coordinated by the Deputy PI, ensuring that EPO will be a high priority of our team. The budget presented below shows that ~4% of the project funds will be used for EPO activities with the majority of the funds to be expended after launch to provide partial support for a post-doc with interests in education.

The EPO team has established contacts with OSS Forums and Broker/Facilitators at JPL and DePaul University and will work closely with the Office of Space Sciences (OSS) to be sure that the programs and materials developed reflect the national goals and standards for science, mathematics and technology education. The EPO team will also establish additional new contacts with other minority institutions and teaching centers through NASA's Educational Division, Minority University Research and Education Division and the Regional Teacher Resource Centers. The EPO team recognizes the need to evaluate the impact of our efforts. Therefore, we will ask external, professional evaluators to review our program periodically.

IV. Cost and Budget

A. Science Team Structure

The overall SIM-YSO program is led by the Principal Investigator, C. Beichman (JPL), who has overall responsibility for the success of project and for the execution of the tasks listed in the Work Breakdown Structure (WBS) described below. The science team is organized both by scientific interests (Table 12) and into six working groups that reflect the major tasks that must be accomplished for a successful program (Figure 6). This WBS was used to develop the cost estimate for this proposal. It should be noted that funds are allocated purely on the basis of the WBS and are not sent to team members just by virtue of their being on the science team.

The Theory Group is led by J. Lunine (LPL) for planet formation issues and by Lee Hartmann (CfA) for YSO phenomena. During the pre-launch phases, the group will ensure that the proposed measurements are appropriate to developing the best understanding of the physical processes of planet formation and stellar evolution. This will be done through participation in target star selection (ensuring an appropriate spread of ages, metallicity, etc.,) development of software tools for prompt analysis of detected planets, and interface with the Hartmann-led group on YSO phenomena to optimize selection of disk observations for information on planetary formation processes. The theory and data analysis groups will conduct simulations of planet-detection with the SIM-YSO target list to quantify the uncertainties in derived parameters such as planetary initial mass function, and optimize the list to minimize these uncertainties where possible.

Table 12. Science Team Affiliations and Interests

Name	Institution (Observatory)	Primary Scientific Interest
Co-Investigators (Core Team)		
Beichman, C	JPL (Palomar)	Planet Searches
Boden, A.	JPL/IPAC (Palomar, Mt. Wilson)	Planet Searches
Ghez, A.	UCLA (Keck, Lick)	YSO Binaries
Hartmann, L.	CfA	YSO Properties
Hillenbrand, L.	CIT (Palomar, Keck)	YSO Properties, Planet Searches
Lunine, J.	LPL	Planet Formation And Migration, Disk Structure
Simon, M.	SUNY	YSO Properties
Stauffer, J.	CfA (MMT, Magellan, Mt. Hopkins 48", 60")	YSO Properties Planet Searches
Velusamy, T.	JPL	Disk/Jet Imaging
Associate Investigators		
Baraffe, I.	U. Nancy	YSO Evolution
Carpenter, J.	CIT (Palomar, Keck)	YSO Properties Planet Searches
Herbst, W.	Weslyan (Van Vleck 0.6m telescope)	T Tauri Star Variability
Kulkarni, S.	CIT (Palomar, Keck)	Planet Searches
Lin, D.	UCSC (Lick, Keck)	Planet Formation And Migration
Mathieu, R.	U. Wisc. (WIYN)	YSO Properties
Norman, D.	SUNY	EPO
Prato, L.	UCLA (Lick, Keck)	YSO Properties
Shao, M.	JPL	Planet Searches
Strom, S.	NOAO	YSO Properties
Stapelfeldt, K.	JPL (Palomar)	Disk/Jet Imaging
Yorke, H.	JPL	Jet Theory

Precursor Observations. This group is led by A. Ghez of UCLA and has the critical role during the years before launch of gathering the data needed to enable final target selection. Team members and postdocs will make and reduce observations from Northern and Southern Observatories as well as with HST to assess photometric and spectroscopic variability, and identify the presence of disks, companions, and nebulosity (Table 9).

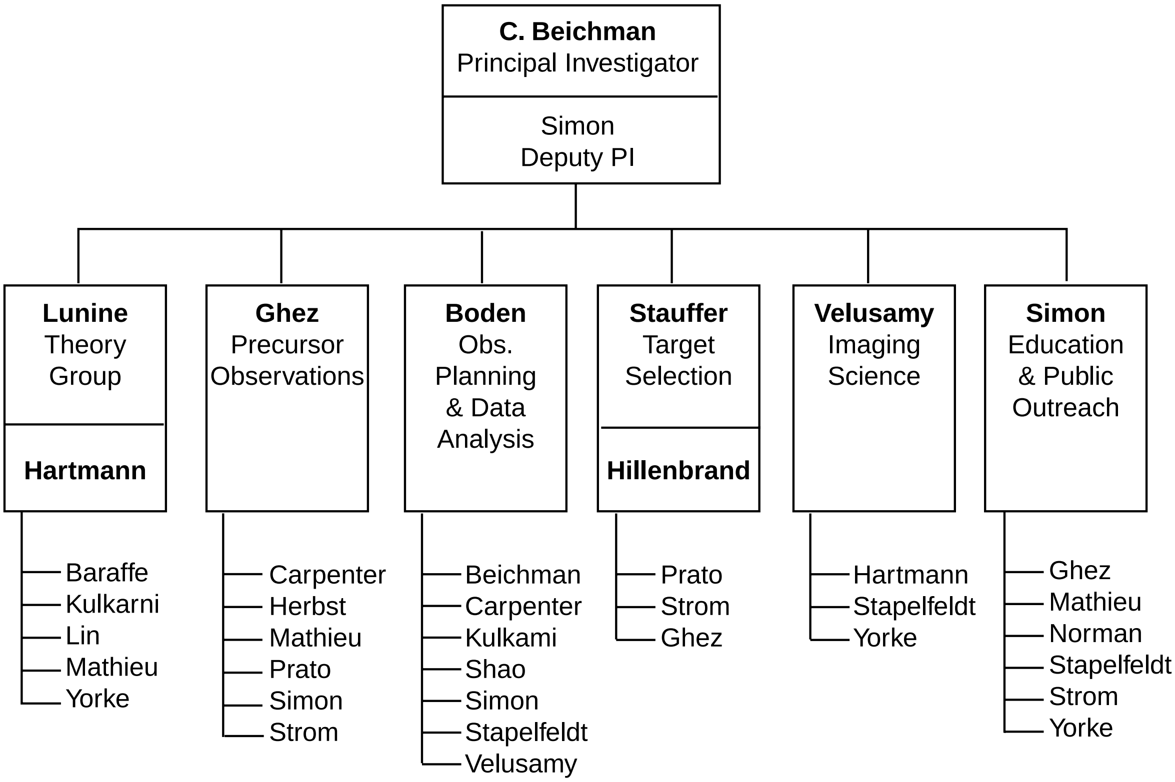

Figure 6. A simplified Organization Chart and Work Breakdown Strucutre for the SIM YSO project shows the basic tasks that must be accomplished prior to launch and during the mission.

Observation Planning. This group is led by Andy Boden (JPL and ISC) and will address the key issues of sampling unknown periods and the choice of most efficient data acquisition modes. This group will help to develop an integrated simulation capability to minimize the number of observations needed for planet detection, as well as to optimize their scheduling.

Target Selection. This team is led by John Stauffer (CfA) and takes input from the teams responsible for Theory, precursor observations, and observation planning to come up with an integrated list of targets. This team works intensively during the year or so before launch to define and refine the observing list.

SIM Data Analysis. The largest part of our budget goes to the team members, postdocs, and programmers working to reduce the SIM data. The available budget limits the scope of this activity, so we must rely heavily on receiving reliable, useful products from the ISC in a timely manner. The Data Analysis team (led by A. Boden, JPL and ISC) will interface with the ISC to define appropriate products and to understand key ISC algorithms. The group will also develop algorithms for planet searching and characterization. In conjunction with the entire science team, the data analysis group will reduce and analyze the data to derive relevant astrophysical quantities suitable for archiving by the ISC and publication in professional articles. We show a modest software development from the onset of the project to support the planet search prototyping.

Table 13. SIM Science Team Workforce (FTE)

	2001	*2002*	*2003*	*2004*	*2005*	***2006***	*2007*	*2008*	*2009*	*2010*	*2011*
Theory	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**	**1**	**1**	**1.1**	**1.1**	**1.1**	**1.1**
Postdoc	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6
University	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	0.3	0.3
JPL	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
Precursor Obs	**2.45**	**2.45**	**2.45**	**2.45**	**0.85**	**0**	**0**	**0**	**0**	**0**	**0**
Postdoc	2	2	2	2	0.5	0	0	0	0	0	0
University	0.25	0.25	0.25	0.25	0.25	0	0	0	0	0	0
JPL	0.2	0.2	0.2	0.2	0.1	0	0	0	0	0	0
Obs Planning	**0.2**	**0.2**	**0.2**	**0.3**	**0.6**	**0.4**	**0.2**	**0**	**0**	**0**	**0**
Postdoc	0	0	0	0.1	0.5	0.2	0.1	0	0	0	0
University	0	0	0	0	0	0	0	0	0	0	0
JPL	0.2	0.2	0.2	0.2	0.1	0.2	0.1	0	0	0	0
SIM Data Analysis	**0.35**	**0.35**	**0.35**	**0.85**	**1.2**	**1.7**	**1.7**	**1.7**	**2.5**	**2.5**	**2.5**
Postdoc	0	0	0	0.5	0.5	1	1	1	1.5	1.5	1.5
University	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.25	0.25	0.25
JPL	0.25	0.25	0.25	0.25	0.5	0.5	0.5	0.5	0.75	0.75	0.75
Target Selection	**0.3**	**0.3**	**0.3**	**0.4**	**0.8**	**0.6**	**0**	**0**	**0**	**0**	**0**
Postdoc	0	0	0	0.1	0.5	0.5	0	0	0	0	0
University	0.1	0.1	0.1	0.1	0.2	0	0	0	0	0	0
JPL	0.2	0.2	0.2	0.2	0.1	0.1	0	0	0	0	0
Imaging Science	**0**	**0**	**0**	**0**	**0.1**	**0.1**	**0.75**	**0.75**	**0**	**0**	**0**
Postdoc	0	0	0	0	0	0	0.5	0.5	0	0	0
University	0	0	0	0	0	0	0	0	0	0	0
JPL	0	0	0	0	0.1	0.1	0.25	0.25	0	0	0
EPO	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.3**	**0.3**	**0.3**	**0.3**
Postdoc	0	0	0	0	0	0	0	0.2	0.2	0.2	0.2
University	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
JPL	0	0	0	0	0	0	0	0	0	0	0
Management	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
Postdoc	0	0	0	0	0	0	0	0	0	0	0
University	0	0	0	0	0	0	0	0	0	0	0
JPL	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Totals	**4.2**	**4.2**	**4.2**	**4.9**	**4.5**	**4.0**	**3.9**	**4.0**	**4.0**	**4.0**	**4.0**
Postdoc	2.5	2.5	2.5	3.2	2.5	2.3	2.2	2.3	2.3	2.3	2.3
University	0.7	0.7	0.7	0.7	0.9	0.6	0.6	0.6	0.7	0.7	0.7
JPL	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1

Imaging Science. A small group of scientists led by T. Velusamy (JPL) will carry out the jet imaging experiment and support the analysis of the disk imaging relevant to the astrometric observations.

Education and Public Outreach. We have allocated approximately 4% of the team budget to enable team members to carry out the efforts described in §III and to support the SIM project's EPO team as requested. To ensure high visibility for this task, the effort will be led by Deputy-PI M. Simon (SUNY) who has worked on a variety of AAS-led activities in education.

Management. There will be a small administrative effort at JPL to coordinate funding, meetings, reports to the project and to NASA, etc. This activity will include a part-time contract monitor/financial analyst (~0.1 FTE) to track funding and milestones on specific work areas.

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