Contents

1 The EPIc Survey: Executive Summary

The discovery of the nature of the solar system was a crowning achievement of Renaissance science. Similarly, future generations will view the elucidation of the properties of extrasolar planetary systems as a premier achievement of turn-of-the-millennium science. This quest is central to both the intellectual understanding of our origins and the cultural understanding of humanity's place in the Universe; thus it is appropriate that the goals and objectives of NASA's breakthrough *Origins* program emphasize the study of planetary systems, with a focus on the search for habitable planets.

We propose an ambitious research program that will use SIM—the first major mission of the *Origins* program—to explore planetary systems in our Galactic neighborhood. The centerpiece of our program is a novel two-tiered SIM survey of nearby stars that exploits the capabilities of SIM to achieve two scientific objectives: (i) to identify Earth-like planets in habitable regions around nearby Sun-like stars; and (ii) to explore the nature and evolution of planetary systems in their full variety. The first of these objectives was recently recommended by the Astronomy and Astrophysics Survey Committee (the McKee-Taylor Committee) as a prerequisite for the development of the Terrestrial Planet Finder mission later in the decade. Our program combines this two-part survey with preparatory and contemporaneous research designed to maximize the scientific return from the limited and thus precious observing resources of SIM.

Our first objective demands measurements with the highest possible astrometric accuracy ($\approx 1\ \mu$as) and thus requires long observing times for each target. Thus a survey addressing only this objective should focus on relatively few (~ 75) nearby stars. In contrast, our second, broader objective is best accomplished with reduced astrometric accuracy ($\approx 4\ \mu$as) and shorter integration times, allowing us to survey thousands of stars of many different types throughout a larger volume. We have juggled SIM's operational constraints to develop an optimized hierarchical observing strategy capable of achieving *both* objectives in a single, coordinated survey. The survey is designed to "hedge our bets" in the face of the current near-total uncertainty in the frequency and diversity of planetary systems. Our strategy virtually guarantees important and exciting scientific returns regardless of whether planetary systems like our own are typical features of most stars or rare and precious ornaments.

We request an allotment of 15% of SIM's observing time for a two-tiered *Extrasolar Planet Interferometric Survey* (EPIc survey, or EPIcS). The Tier 1 survey is designed primarily to address our first objective, the detection of Earth-like planets around nearby stars. The Tier 1 targets will consist of ≈ 75 main-sequence (MS) stars within 10 pc of the Sun. About a third of these will be G dwarfs resembling the Sun; this sample is large enough that even the absence of terrestrial planets would be an extremely significant—if discouraging—result. The remainder of the Tier 1 targets will be inactive MS stars of other spectral types: mostly K and M, but including ≈ 10 A and F stars to provide a preliminary survey of planets around young, massive stars. The Tier 2 targets will consist of ≈ 2100 stars from the following diverse classes: all MS spectral types, in particular early types; binary stars; stars with a broad range of age and metallicity; stars with dust disks; evolved stars; white dwarfs; and stars with planets discovered by radial-velocity surveys. Each class addresses specific features of the planet-formation process (are metals necessary for giant planet formation? does the number of planets decline slowly with time due to dynamical evolution? what is the relation between dust disks and planets?), and will contain > 100 targets to ensure that our findings are statistically robust.

The observing strategy is crafted for maximum efficiency and accuracy. We will observe each Tier 1 target ≈ 70 times over the course of the mission, with each observation comprised of ≈ 20 1-min integrations (10 each on a science target and a reference) that will be averaged to provide astrometry with ≈ 1 μas accuracy. Within the 15° radius Field of Regard (FOR) associated with each Tier 1 target, we will identify ≈ 28 Tier 2 targets that are bright ($R \lesssim 12$), and usually within 25 pc. We will observe Tier 2 targets with single 1-min integrations, aiming for ≈ 4 μas accuracy. This "piggybacking" of Tier 2 observations on Tier 1 pointings saves pointing overhead, provides some redundancy within each FOR, and decreases the systematic errors in Tier 1 observations.

We also propose a preparatory research program to maximize the scientific return from our survey, involving both target selection and the development of analysis pipelines. An important aspect of this program is the focus on identifying stable reference stars in each Tier 1 FOR, and developing analysis software that can handle the complications introduced by possible acceleration of the reference stars.

Our preparatory program includes radial velocity (RV) and adaptive optics (AO) imaging observations to help us select the best science targets and reference stars. For science targets, the main goal of these observations is to ensure that the targets do not have companion stars that would preclude the existence or detection of low-mass planets. For reference stars, the goal is to identify one or two reference stars within 1.5° of each Tier 1 target (Tier 2 targets can use more distant grid stars as references). We will study two classes of candidates: bright ($R \approx 10$ mag) MS stars in binary systems (chosen to have orbits that scour out any planets that could complicate the astrometry)and distant K giants at a distance of 1 Kpc. Because we can't rule out the possibility of planetary companions to K giants, two references are needed to unambiguously assign a planet to the target or one of the reference stars.

To maximize the return from SIM, we must analyze complex and scarce astrometric data with the highest possible reliability and efficiency. Traditional tools such as the Lomb-Scargle periodogram (LSP) and its variants must be sharpened. We have already created new methods that promise significant improvements over the LSP. A goal of our preparatory research is to have a tunable data analysis pipeline before mission start implementing a variety of methods for such tasks as delay calibration, planet detection, and estimation of orbital parameters.

Once the mission is underway, we anticipate that significant analytical and observational work will be needed to supplement the SIM observations. We will undertake important parts of this research ourselves, but also will adopt a policy of early data release to focus the attention and resources of the community on SIM and on extrasolar planets, to encourage independent analysis, to receive suggestions for revisions in our observing and sampling strategy, and to display our progress in time to justify an extended mission.

The EPIcS team brings together experts on ground- and space-based optical interferometry, low-mass stars and brown dwarfs, statistical techniques, theory of planetary formation and dynamics, stellar activity, and RV planet detection. In particular, among the co-investigators are the discoverers of the first brown dwarf, the first extrasolar planet system, and the first planet around a solar-type star.

2 Introduction

The discovery by Copernicus that the planets—including Earth—revolve around the sun dislodged humanity's home from the central position it occupied in medieval thought. This paradigm shift has had so profound an intellectual and cultural impact that it is known as the Copernican revolution.[1,2] In astronomy, the idea that we do not occupy a special place in the universe has affected greater and greater scales of exploration, with perhaps its ultimate expression being the so-called "Copernican principle" that is the foundation of much of modern cosmology.[3–5] Given that the Copernican revolution began with a study of the solar system, it is ironic that we are only now beginning to realize how provincial our understanding of astrophysics on the scale of planetary systems may be. This has been of necessity, for only in the last decade have we been able to identify extrasolar planetary systems. The great surprise is that those so far discovered—the millisecond pulsar sytem, and the main sequence systems with Jupiter-mass planets in close orbits—are very different from the solar system. Their discovery raises the question: is our home special after all?

We propose an ambitious key project that will use SIM to undertake a two-tiered survey designed to address this far-reaching question by achieving two focused scientific objectives: to search for Earth-like planets in habitable regions around nearby Sun-like stars; and to explore the nature and evolution of planetary systems in their full variety. Surveys separately addressing these objectives would have very different characteristics. But by carefully exploiting the capabilities and constraints of SIM, and by relying on significant observational to optimize target selection and preparatory research for analyzing data, we can design and execute a unified survey that economically uses SIM resources and virtually guarantees exciting scientific returns despite present uncertainties in the nature of planetary systems.

The EPIcS Team. The proposed effort is ambitious and its successful execution will require expertise across many disciplines. The EPIcS team has all the skills needed to undertake the proposed research and its size is appropriate for the work involved.

The PI Shao is the project scientist for SIM and is well known for his contributions to the field of optical interferometry. The deputy PI Kulkarni has long-standing interest in interferometry and direct detection of planets. He and his group are credited with the discovery of the first brown dwarf,[6] the cool companion of Gliese 229.

Wolszczan is the discoverer of the first extra-solar planetary system,[7] the four-planet system around PSR 1257+12. Queloz is the discoverer of the first planet around a normal star, 51 Pegasi B. Both have leading programs in the field of extrasolar planets and are expected to contribute to multi-planet analysis and the selection of targets and reference stars respectively.

Lin and Tremaine are leaders in the field of theoretical planetary sciences (planet formation and planetary dynamics). Their participation will ensure that the results obtained will receive the necessary theoretical support and interpretation. Baliunas is a well known stellar astronomer and a leader in the field of stellar activity. She will be intimately involved in the selection of targets.

Shaklan is known for his state-of-the-art picometer metrology program at JPL and has an innovative ground-based precision astrometric program (STEPS). Boden has played a key role in the development and use of the Palomar Testbed Interferometer and is responsible for data analysis for the soon-to-be completed Keck Interferometer. Loredo is well known for having solved many problems in astronomy with the Bayesian approach. His participation will ensure that our analysis of data will be optimal and rigorous.

The team has been tightly organized with each co-I directing activities in specific areas; see § 14. In addition, a number of our colleagues with much needed expertise will also contribute. Briefly, S. Unwin, Deputy Project Scientist for SIM, will contribute to optimizing our observing strategy. D. Kirkpatrick is an expert in nearby stars and L dwarfs and will contribute to selection of target stars and pre-launch observations. M. Mayor will assist D. Queloz in the considerable task of prelaunch RV studies. D. Stevenson is known for his theoretical work in planetary sciences and expects to interact with the team and also guide students at Caltech on joint theory-observational programs in this area. C. Beichman will contribute his expertise in zodiacal dust around stars and their relation to planetary systems.

Over the course of preparing this proposal, our team has already achieved what is expected of an effective team: synergism and cross-disciplinary collaboration. The following papers—spanning theoretical, observational, and data-analytical topics—are all direct outcomes of discussions and interactions during the course of our team meetings and telecons:

1. `[EK2000]` Eisner, J. A. & Kulkarni, S. R. 2000, "Sensitivity of the Radial Velocity Technique in Detecting Outer Planets."
2. `[KM2000]` Konacki, M. & Maciejewski, A. 2000, "Multiple Planets: A Frequency Decomposition Approach."
3. `[L2000]` Loredo, T. 2000, "Bayesian Methodology for the Analysis of Reflex Motion Data From Planet Searches."
4. `[KM+2000]` Kulkarni, M., Boden, A. F., Eisner, J. A., Konacki, M., Shaklan, S., Shao, M., & Tremaine, S. 2000, "Binary Stars as Reference Stars for Astrometry."
5. `[WC+2000]` Wilkin, F., Catanzarite, J., van Buren, D., Shao, M. 2000, "Two Dimensional Lomb-Scargle Periodogram for Astrometric Data."
6. `[SL2000]` Stevenson, D. J. 2000, "Diversity in Extra-solar Planets."
7. `[CUS2000]` Catanzarite, J., Unwin, S. & Shao, M. 2000, "Measurement of SIM Baseline Attitude for Narrow Angle Astrometry."
8. `[BS2000]` Baliunas, S. & Soon, W. 2000, "Metallicity and Exoplanets."

These articles will be submitted to professional journals following the submission of our proposal.

We expect to actively involve young scientists in this project. Indeed, much of the tangible work to date, including preparation of many of the papers listed above, was accomplished in collaboration with students and postdoctoral fellows.

3 Background and Motivation

The circularity and the coplanarity of the orbits of the Sun's planets led Kant and Laplace to hypothesize that planet formation occurred in a circumstellar disk – an idea that survives to today. The more recent discovery of the ubiquity of dusty and gaseous disks around young stars led to the hypothesis of planet formation being part of the star formation process itself. In the now standard "bottom-up" or Safronov model of planet formation,[8–10] terrestrial planets and giant planet cores form by the coagulation of small solid bodies ("planetesimals") in a protoplanetary disk. Rapid accumulation of gas around the cores, quenched by formation of "gaps" swept out by the resulting protoplanet, produces the giant planets (Jupiter and Saturn). Cores that grow more slowly or that never reach critical mass for accretion become subgiant planets (Uranus and Neptune).

The dramatic discovery of terrestrial-mass planets orbiting the millisecond pulsar PSR 1257+12 by Wolszczan & Frail[7] suggested that planetary formation is more robust and diverse than had been imagined. Three years later, Mayor & Queloz found a Jupiter-mass planet around a nearby G star.[11] Marcy & Butler subsequently found many similar planets around a few percent of nearby G and K stars.[12,13] The observed stellar transit of one such planet[14,15] confirms that it is a gas giant; yet these planets are in close orbits, many smaller than 1 AU and with significant eccentricity ("hot Jupiters"). Not one of these systems resembles our solar system, or the planetary systems previously studied by theorists.

The majority of the extrasolar planets were discovered with the radial velocity (RV) technique, a technique not sensitive to planets with long orbital periods nor very low masses (see Figure 1). A significant region of the planetary system parameter space is so far unexplored and we should not presume that all exoplanetary systems are like the one discovered todate. Future studies must therefore be robust to uncertainty spanned by two extreme possibilities:

A: `Planetary Systems are Rare.` In this picture, the planets identified by RV are truly representative of extrasolar planets. If so, the solar system is the exception rather than the rule.

B: `Planetary Systems are Ubiquitous.` In this picture, one expects that the bulk of the stars ($\sim$97%) for which RV studies have not reported any candidates host a variety of planetary systems that are not easily accessible to RV studies. The possibilities range from segregated planetary systems like our solar system to systems without any massive gaseous planets or systems comprised of lunar-mass "planetary embryos."

It is challenging to plan future observations in the face of such great uncertainty. If extrasolar planetary systems are rare (case `A`), then it is essential to survey a large number (1000s) of targets; otherwise, we could face an outcome similar to that of the pioneering planet search survey of Campbell and Walker[16] which could have detected the extra-solar planets now known to exist, but examined too few stars. However, if planetary systems are common and rich (case `B`), each candidate system must be observed at many epochs (to characterize orbits of multiple planets) and at the highest precision possible (to detect low-mass planets). This seriously limits the sample size, because SIM is a slow machine: the total integration time needed to obtain astrometry accurate to 1 μas is $\lesssim$ 1 hour. Thus we can obtain a mere 4500 measurements over 5 years, assuming that 15% of SIM time is allocated to this project.[1] Considering that we would need measurements at $\gtrsim$ 50 epochs to characterize a planetary system with, say, three planets, in this scenario we should survey $\approx$ 90 stars rather than 1000s.

The EPIc survey strategy is designed to efficiently use SIM's resources to address a wide range of scientific questions reflecting these broad present observational and theoretical uncertainties. Specific questions motivating our strategy include the following:

1. What is the mass function of planets? Planets in our own solar system can be divided into three broad classes (excluding Pluto): *Giant planets*, *sub-giant planets* and *terrestrial planets.* All the extrasolar planets detected with RV belong to the giant planet branch. SIM will allow us to detect

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[1] According to the AO, there will be at least 5000 hr per year for science observations. An upper limit of 6100 hr is reached by limiting grid observations and other housekeeping tasks to 30% of SIM time.

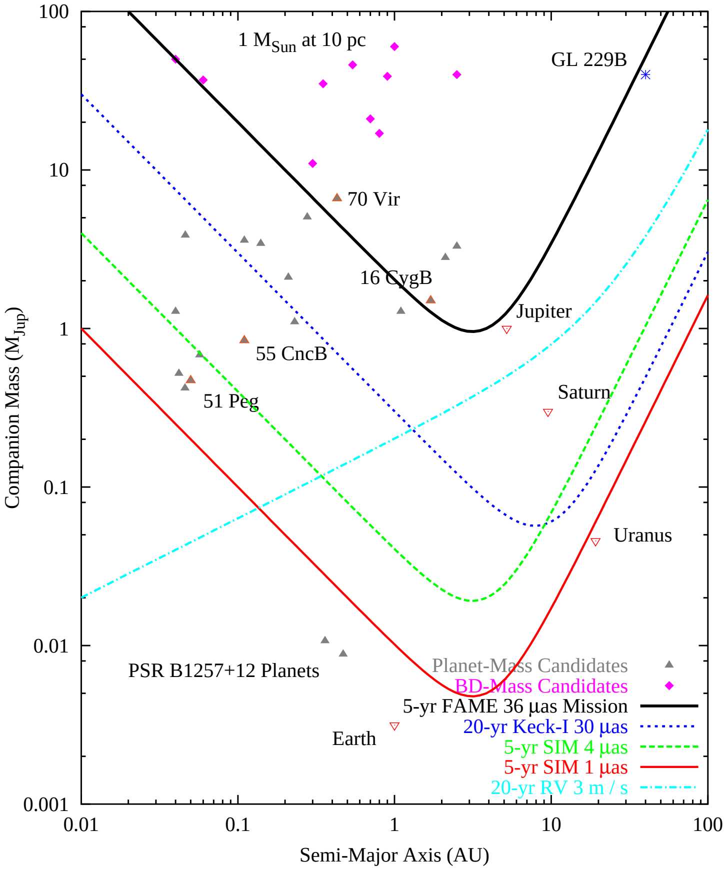

Figure 1: *Masses and orbital radii of planetary and brown dwarf companions to nearby stars identified through the radial velocity technique. Also shown are planets in our system and the planets in the PSR 1257+12 system. Curves show sensitivities of RV surveys and astrometric surveys for 1* $M_\odot$ *targets at 10 pc.*

subgiant and terrestrial planets. A bimodal or even trimodal distribution of masses would provide support for this classification and for the bottom-up model and would constrain the structure of gaseous and planetesimal protoplanetary disks. Failure to find multimodality will force us to consider a wider range of possible planetary types than those represented in our solar system.

A related issue is planet composition, which appears to be related to planet mass. Figure 2 graphically displays the compositions of planets in the solar system. One can imagine planets[2] of a kind unlike those presently known. Examples include "SubJupiters" (bodies that are mostly gas but much less massive than Jupiter) and SuperGanymedes (bodies containing several Earth masses of ice and rock) [SL2000].

2. How common are terrestrial planets?

Although related to question 1, the frequency of terrestrial planets is of particular interest, not only for its relevance to planetary diversity, but for its relevance to our understanding of the origin and prevalence of life. There is

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[2] Throughout this proposal we define a "planet" to be a body smaller than ten Jupiter masses, and "terrestrial planets" to be planets composed mainly of condensable materials (rock and ice). We define brown dwarfs as objects with masses in the range 10–80 M_J.

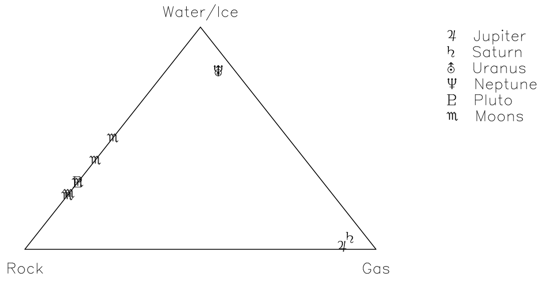

Figure 2: *Composition Triangle for planets. SuperGanymede and SuperJupiter are shown by* * *and x, respectively.*

thus a dual motivation for tailoring a survey to detect terrestrial planets. If we find a significant number of terrestrial planets, we can determine the extent to which configurations resembling the inner solar system are rare or common. In addition, such a discovery will provide the foundation for followup *Origins* missions such as the Terrestrial Planet Finder (TPF) that will more directly address issues related to the origin of life.

3. What is the relation between hot Jupiters and the giant planets in our own solar system? The standard bottom-up model while successful in explaining the solar system is unable to predict the numbers, orbits, or masses of the planets that are expected to form from a given protoplanetary disk. Clearly this model has difficulty in explaining the hot Jupiters because Jupiters are expected form in the outer colder regions of planetary systems.[17,18] If the standard model is universal, the hot Jupiters found by RV surveys must have migrated inwards, probably through gravitational interactions with the gaseous protoplanetary disk[19–21] or the planetesimal disk.[22]

If giant planets form at a few AU around a fraction f_1 of solar-type stars, and a fraction f_2 of these migrate inwards, then from RV obsevations, $f_1 f_2 \sim 0.03$ but we are unable to estimte f_1 and f_2. Perhaps $f_1 \sim 1$ and only a small fraction of Jupiters migrate (perhaps those formed in the most massive disks[22]), or perhaps $f_2 \sim 1$ and almost all giant planets migrate, in which case our own solar system is an unusual exception.

Alternatively, hot Jupiters could form by gravitational instability in a gaseous disk.[23] Interestingly, this would remove the distinction between protoplanet formation and protostar formation. A related issue is whether there is such a distinction between brown dwarfs and planets. However, as can be seen from Figure 3 and the rarity of brown dwarf companions, there does appear to be some distinction between brown dwarfs and planets; however, this is not a robust conclusion.[24] A third possibility is that hot Jupiters form like stars–a model which naturally explains the similarity of the eccentricity distribution of hot Jupiters to that of binary stars.

Accurate measurements of orbital parameters, particularly eccentricity and inclination, may provide the critical information we need to test these models and other basic assumptions of current theories. For example, SIM measurements will tell us whether or not multiple-planet systems have coplanar orbits: near-coplanarity is expected in any disk-formation scenario, although planet migration can excite orbital inclinations and even lead to counter-rotating planets.[27]

4. How does the presence of one planet affect others? A fundamental issue is whether the properties of planetary systems are determined by nature or nurture. In its present configuration, the solar system is almost certainly stable on timescales of a few Gyr, but unstable on longer timescales.[28,29] The instability timescale shortens dramatically if the planet masses are even a factor of two larger.[30,31] Moreover the outer solar system is "full" in the sense that there is no room for additional test particles on stable orbits.[32,33] These considerations strongly suggest that the solar system once had more plan-

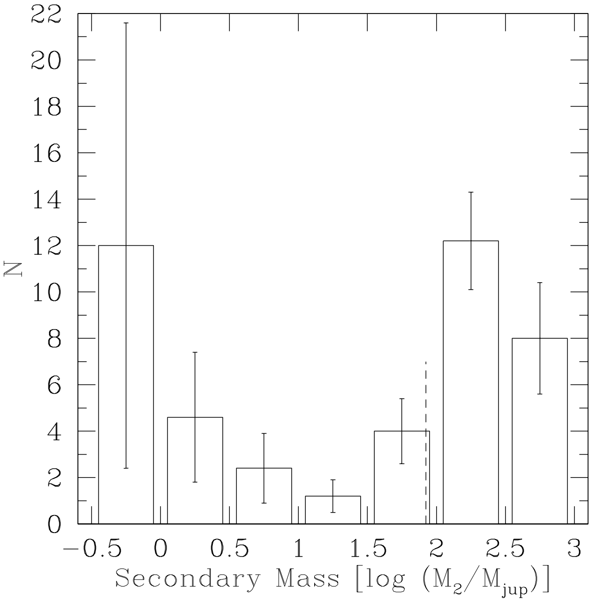

Figure 3: *Histogram of masses of sub-stellar companions. Objects with mass above about* $10 < 80 < M_J$ *appear to be rare and have a different* dN/dM *distribution*[25,26]

ets, which have been ejected over its lifetime through weak dynamical instabilities.

A broad survey, capable of detecting many multiple-planet systems, would allow us to compare the separations and masses with the minimum values required for stability, thereby indicating the role of stability considerations in determining the configurations of planetary systems. By searching for more distant planets in systems already containing hot Jupiters, we could determine whether the eccentricities of the hot Jupiters have been excited by tidal perturbations.[34]

5. How do the properties of planetary systems depend on the nature of their host stars? The pulsar planets, the ubiquity of dusty disks around young stars, and the presence of Mercury-size satellites around Jupiter and Saturn show that planet-mass bodies can form in diverse environments. We must explore a diverse range of targets to see how environment affects planet formation.

Full Range of Main Sequence Stars. Of necessity, RV searches have been restricted to solar-type stars with little activity. SIM must survey the full range of main sequence stars.

Metallicity. It has been claimed[35] that the host stars of hot Jupiters are metal rich; we believe that this result is not firmly established [BS2000]. Regardless of this controversy, it is worth noting that RV searches are focused on solar-type stars with shallow convection zones, which can be easily contaminated by migrating planets or infalling planetesimals.[36] We must survey stars with a wide range of convection zone sizes to allow us to distinguish pollution from intrinsic metallicity differences. We should also examine low-metallicity stars, which are important probes because planetary cores cannot form in the absence of metals; planets around such stars must have formed by gravitational collapse.

Binary Stars. RV studies have avoided close binaries (separations less than a few arcseconds). A binary companion is likely to affect planet formation (by affecting the protoplanetary disk) and certainly will affect orbital evolution (by creating a zone of unstable orbits).[37] With SIM, we can study systems with very little restriction on binary separations.

Stars of Different Ages. We have discussed how planetary systems may evolve significantly as a function of time. If so, it is crucial to study planetary systems around stars of various ages, particularly the range 10^6 yr to 10^9 yr.

Stars with Dusty Disks. Approximately 15% of main sequence stars are surrounded by circumstellar rings of orbiting solid material.[38,39] Gaps and asymmetries in such dusty disks might be due to the presence of planets. We have no data as to the presence of planets around these stars. A study of stars with dusty disks, intrinsically interesting from a planetary perspective, is also relevant to planning future NASA missions (e.g., zodiacal dust is considered to be a primary factor in designing TPF).

4 Overview of EPIcS

Consideration of these diverse questions has led us to identify two scientific objectives for a SIM key project focused on planet studies: to search for Earth-like planets in habitable regions around nearby Sun-like stars; and to explore the nature and evolution of planetary systems in their full variety.

The first objective requires a survey providing "extreme" precision astrometry ($\approx 1\ \mu$as), requiring long integration times and thus limiting the number of targets. It is most strongly motivated by issues related to the origin of life. Such a survey would also address important issues in planet diversity by providing information about the low-mass end of the planet mass spectrum. In contrast, the second objective is best addressed with a less demanding "high" precision ($\approx 4\,\mu$as) survey that sacrifices sensitivity to low mass planets in order to permit observation of a very large number of diverse targets. See Figure 1 for the magnficent sensitivity afforded by SIM.

Given the great extent of our uncertainty about the frequency and diversity of planetary systems (cf. cases `A` and `B`, above), it would be unwise to undertake only one of these two surveys. Indeed, only by achieving both objectives can we determine whether our solar system is special or typical. Yet to perform both types of survey independently would consume an excessive amount of SIM's observing time. Therein lies the dilemma.

Fortunately, we have devised a "Two–Tiered" program that can achieve both objectives in a unified, highly efficient manner. The centerpiece of our program is a carefully constructed two-tiered SIM survey that in essence "piggybacks" a high precision survey of thousands of targets on an extreme precision survey of $\lesssim 75$ targets.[3] This combined survey achieve a higher target throughput than would be possible with two independent surveys. We now provide an overview of the survey and the preparatory research program; subsequent sections provide details about various technical issues.

Two-Tiered Survey. `Tier 1` targets will be observed at extreme precision, with a single Tier 1 target per pointing; our survey will observe ≈ 75 such targets, each at ≈ 50 epochs. Within the 15° FOR associated with each Tier 1 pointing, we will observe ≈ 28 `Tier 2` targets at high precision, for a total of ≈ 2100 Tier 2 targets.

The Tier 1 targets will be chosen primarily to address our first objective of finding Earth-like planets in habitable zones. The targets are chosen for proximity (to maximize the astrometric signature) and brightness (to minimize Poisson noise). We will select the nearest main sequence stars with R magnitude brighter than 10 and with the following proportion of spectral types: 5% A, 5% F, 30% G, 30% K, 30% M. Stars in close binary systems will be excluded from this group (but included in the Tier 2 group). The detection of Earth-like planets around any of these targets, especially in the habitable zone, will have a profound scientific and cultural impact. The sample size is large enough that an absence of a detection, though disappointing, would still have a profound impact, both intellectually, and programmatically for TPF.

The Tier 2 targets will include stars from the following diverse classes: stars with known RV planets, a large sample covering the entire range of main sequence, in particular the early type (F, A, B) stars; binary stars; stars with a range of metallicity, a range of ages and a range of magnetic fields; stars with dusty

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[3] The exact number will depend on the observing efficiency of SIM and can vary, for the requested 15% of the mission time, from 75 to 90 stars.

disks, evolved stars and white dwarfs. We will ensure that each class has at least a hundred stars (and many will have more) so that an absence at the level of 3% (frequency of RV planets) will be a significant result. Technical details of our two-tiered approach can be found in §5.

Achieving the highest possible astrometric accuracy requires careful choice of another category of targets: `Reference Stars`. An ideal reference star has no planet at a level that SIM can detect. This is necessary in order to obtain secure orbital information and not merely be content with detections that leave important orbital parameters (or even host identification) undetermined. However, finding such reference stars requires a mission more sensitive than SIM. We believe that we have met this critical issue head-on and have devised two possible classes of reference stars: distant K giants and bright ($R \approx 10$) MS stars in eccentric binary systems [KM+2000]. Further details can be found §6.

Preparatory Research. To maximize the scientific return from our survey, we must carefully select the targets in both tiers, and we must also ensure that our data analysis algorithms make full use of SIM's capabilities. Our preparatory research will include a substantial data analysis component that will develop new tools for optimized statistical analysis of planet survey data. Further details can be found in §8 and §9. Our extensive observational work to identify Tier 1 and Tier 2 and their reference stars is summarized in §7.

The global astrometry data provided by Interferometer Science Center (ISC) will not be accurate at the 1 μas level we need. We will develop an analysis pipeline that will work with calibrated delays; see §10. A goal of our preparatory research is to have the entire analysis pipeline in place before mission start in order to facilitate quick analysis and facilitate an early release of data and results; see §11.

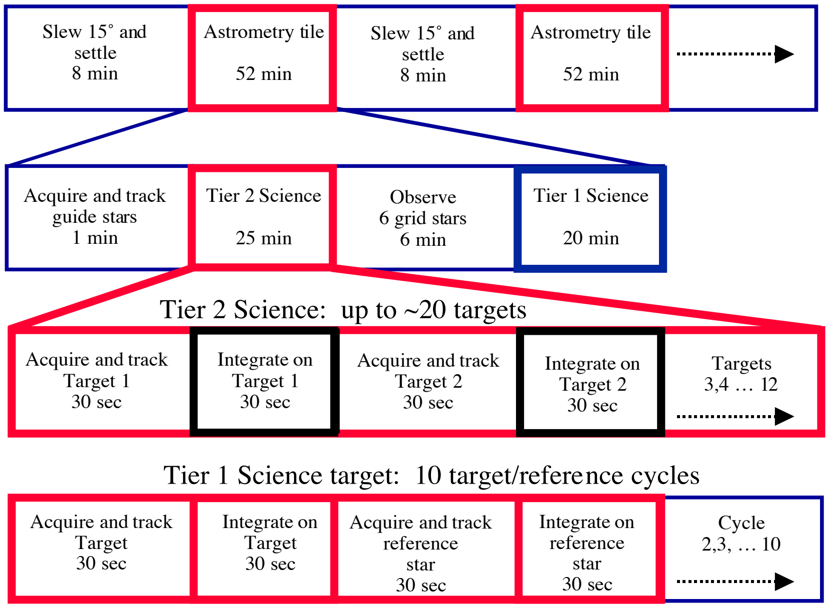
5 An Optimized Observing Strategy

Traditional narrow angle astrometry (such as with HST, ground-based telescopes and interferometers) measures the position of the target star with respect to a number (4–12) of nearby reference stars. We have re-examined how SIM can make narrow angle astrometric measurements and have developed a novel strategy providing high target throughput. This strategy combines Tier 1 and Tier 2 observing in a way that takes little time beyond what would be used by an independent Tier 1 survey, thus giving us all the Tier 2 science—about 2100 stars at 4 μas—almost for free. Understanding this strategy requires a proper appreciation of the error sources for narrow angle measurements.

SIM's limiting accuracy is determined by a combination of hundreds of systematic and random errors. The resulting expected variance in the angular position of the target (in one axis) is given by

$$\begin{aligned}\sigma^2 &= (0.494)^2 + (0.122\theta_R)^2 + (0.025t_C)^2 \\ &\quad + (n_C/10)^{-1}(0.507 \times 10^{(R-10)/5})^2. \quad (1)\end{aligned}$$

Here σ is in units of μas. The first term arises from imperfect calibration of the metrology beam with respect to the stellar beam; this issue is discussed in §10. The second term is caused by "beam walk" as the delay line is slewed and the siderostat is rotated (§10). This error grows linearly with the angle to the reference star, θ_R (in degrees). Thermal drifts in the spacecraft structure lead to optical misalignments, optical deformations, and result in metrology errors. Based on a thermal model for SIM (§10), for observations on timescales of minutes, the variance is proportional to t_C^2 as shown in the third term; here t_C is the cycle or "chop" cycle time (in minutes) for observing the target and reference stars. The last term is the uncertainty due to counting statistics; n_C is the number of cycles



#Tier 1 Targets	75
#Tier 1 Visits	70
#Tier 2 Targets	2100
#Tier 2 Visits	50
Tier 1+Tier 2 Visit Time	0.92 hrs
Total Hours	4813 hrs
Fraction of 5yr	11%

Figure 4: *Timeline for tier1-tier2 observations and Observing Time Summary.*

each of duration 120 s of which 30 s is spent integrating on the source (see Figure 4). R is used as a representative magnitude; recall that the SIM bandpass is from 0.4 to 0.9 μm.

Inspecting equation 1 suggests the following strategies to improve the efficiency of observations:

1. Use bright reference stars ($R < 10$ magnitude) to minimize photon noise.
2. Use reference stars that are close to the target.
3. Chop rapidly between target and reference.
4. Use the minimum number of reference stars.

In Figure 4 we present a sequence of observations optimized to yield the highest precision astrometry with SIM. The sequence begins by slewing the spacecraft to center the field of regard on a Tier 1 target. After locking on to the guide stars, we will carry out observations of typically 25 Tier 2 stars interspersed with half a dozen grid stars. By this time, the instrument will be thermally settled and we will then commence 10 target-reference star cycles, each of 2 minute duration.

For an interferometer, the instrumental parameters are the baseline vector (B), and the delay offset (C).

$$\text{delay} = \vec{s}\cdot\vec{B} + C \qquad (2)$$

where $\vec{s}$ is unit vector to the star. In order to derive $\vec{B}$, we will use grid stars at the edge of the FOR (7.5° from the target) instead of the traditional approach of using nearby ($\sim 1°$) reference stars. The "lever arm" of the grid stars means that we can obtain the needed 1 μas accuracy with 5 μas measurement precision whereas in the traditional approach reference stars would have to be measured to a precision of 1 μas with a concomitant increase in integration time by a factor of ten; [CUS2000] provides further details.

C can be calibrated by observations of nearby reference star(s)measured to 1 μas precision. Ideally we would need only one narrow angle reference star. Hence if we can find just one "clean" (at the 1 μas level) narrow angle reference star we can reduce the observational cost of a Tier 1 target by 60%. More conservatively, we should allow for the possibility that the reference star itself has planets; then we would need 2 reference stars (see §6) and the resulting savings would would be 40%. Our Tier 2 science program of ≈2100 stars is the result of those savings.

Our observing strategy (Figure 4) also results in superior precision for Tier 2 targets. A standard wide angle measurement of a Tier 2 target against grid stars in a 15° field in 1 hr would yield an accuracy of 9 μas. However, by using reference stars no farther than 5° from the targets and a 20 min thermal chopping cycle we would achieve a precision of 4 μas—a factor of two improvement over the standard approach.

Figure 4 also summarizes the observing time estimate for our two-tiered EPIcS program. We will have 75 stars in our Tier 1 sample, each with approximately 28 Tier 2 targets within a 7.5° proximity. On a given visit we will observe the Tier 1 target, reference stars, and 20 of the 28 associated Tier 2 targets in a per-visit time of just under one hour. Over the course of the 5-yr SIM mission each Tier 1 target will be observed 70 times, and each Tier 2 target will observed on average 50 times by rotating the Tier 2 targets serviced in each visit. The total time requirement for the program is 4813 hr, or approximately 11% of the SIM mission time.

6 Reference Stars

We have repeatedly emphasized the importance of identifying "clean" reference stars for narrow angle extreme precision astrometry. These stars have to be bright ($R < 10$ magnitude), preferrably within a degree of the target star and astrometrically stable (or modelable) to 1 μas. It is the last requirement that is a major challenge.

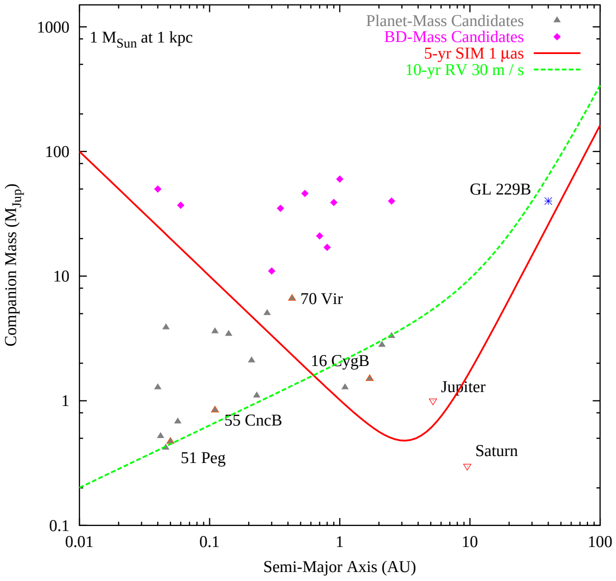


Figure 5: *Limiting astrometric perturbation sensitivity for a reference star at 1 kpc. The rms velocity of the metal-poor giant and clump stars is unlikely to better than 30 m/s. Brighter giants have considerably worse RV noise.*[40]

The SIM grid stars are obvious candidates for references stars.[4] However, the density of grid stars with $R < 10$ is too low (S. Majewski, pers. comm.) and we are thus left with the problem of selecting and studying our own set of reference objects. We will consider two classes of candidate reference stars: clump giants and binaries.

Distant giants. As can be seen from Figure 5, a Jupiter-mass companion in a 4 AU orbit would result in an astrometric signature of $4/d_1$ μas where d_1 is the distance in kpc. We need $d_1 > 4$ to keep astrometric noise below 1 μas, but our $R < 10$ restriction then corresponds to absolute magnitudes $M_R < -3$, corresponding to stars at the tip of the giant branch which are much too rare (and likely astometrically unstable) to serve

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[4] Metal-poor K giants ($M_V = -1$ magnitude), were favored in the last SIM Grid Worskhop (January 20-21, 2000; Pasadena). The grid requirement is $V < 12$.

as potential Tier 1 reference stars. On the other hand, clump giants[41] (metal-rich horizontal branch stars) are prevalent (1.5 $\deg^{-2}$ with $R < 10$ at the galactic pole), bright ($M_V = +1$, V−I$\sim$ 1.25) and stable. (Including F and G class III giants raises the density by a factor of 1.7.)

Our $R < 10$ requirement places the clump giants at about 1 kpc. Thus, as noted above, we must confront the possibility of contaminating giant planets. Unfortunately, as shown in Figure 5, RV studies are of little use in the orbital separation range 1–10 AU where SIM is most sensitive; they can only detect planets in orbits too small to corrupt the reference star for SIM.

However, contaminating companions can be identified provided we observe another reference star (in a round-robin manner) and carry out a three-way analysis (target−reference$_1$, reference$_1$−reference$_2$, target−reference$_2$). The penalty is an increase in observing time by 1.5 and potentially a $\sim$ 17% loss in sensitivity (due to the target being common to both reference stars; we will investigate this issue in the near future).

Binary Reference Stars. Binary reference stars are attractive because the stellar orbits destabilize companions over a range of orbital separations.[37] For a binary with $e \approx 0.3$ and $q \equiv m_2/m_1 = 1/2$, stable circumstellar orbits exist only for $a < 0.21a_b$ (primary) and $a < 0.14a_b$ (secondary), and stable circumbinary orbits exist only for $a > 3.5a_b$. Binary reference stars with $a_b \sim 1$ AU thus can provide truly clean references over the orbital range 0.3–3 AU.

The 10 mas fringe spacing of SIM will resolve such binaries, but modelling the binary fringe pattern utilizing SIM visibility measurements is straightforward,[42,43] particularly when supplemented with moderate precision (0.1 km s^{-1}) RV data. We have considered a potential concern—the astrometric signal from the binary ($a \sim 0.1$ as) overwhelming the expected μas planetary signature of the target—and conclude that this does not affect the sensitivity except around a small range of periods near the binary period.

The density of FGK main-sequence binaries with R <10 is about 2 degree^{-2} of which we expect 3–5% to be in the period range 0.5 – 3 yr.[44] Such binaries exhibit a wide range of eccentricities, with $e \sim 0.3$ being typical.[45] Thus we can expect to find a suitable binary reference reference star within a few degrees of our target, and such reference stars at a typical distance of 100 pc are particularly attractive alternatives for astrometric references in the Galactic plane.

7 Pre-Launch Preparatory Activities

Our proposed SIM key project is ambitious: nearly a hundred nearby stars observed at the highest precision possible with SIM and well over two thousand stars representing seven major categories of nearby stars observed at 4 μas. Nonetheless, for any key project to succeed the input list of targets must be constructed with great care. Here we describe our two-step “preparatory” program. Briefly, we will form a list of potential targets from existing databases (largely) and then undertake an extensive observational and analysis program to cull from this list to form the final target list.

Tier 1 Targets. The primary criterion for Tier 1 targets is proximity since the astrometric signature is $\propto$ distance^{-1}. The targets need to be bright, R<10 magnitude, so that the measurements are not limited by photon noise (Equation 1). Inspecting the latest version of the Catalogue of Nearby Stars (CNS; Jahreiss, pers. comm.) we find over 250 suitable Tier 1 candidates within 10 pc of the Sun. 70% of these have spectral type M, 25% are types G and K, and the remaining 5% are A stars, F stars, and white dwarfs. Baliunas will lead the effort to eliminate very active stars.

We will exclude all binaries with separations less than 3 arcseconds based on literature search and on-going AO surveys. The list will be further reduced to the desired number of about 75 by keeping only the closest stars while preserving a mixture of different spectral types, roughly in the proportions: 5% A, 5% F, 30% G, 30% K, 30% M.

Leaving aside the A and early F stars, most of the potential Tier 1 candidates are already included in the ongoing precision RV studies. With the considerable RV resources at our disposal (Table 1) we will ensure that the remaining candidates will get observed. Nearly 10% of the Lick RV sample[46] exhibit long term acceleration, 5 m s^{-1} yr^{-1} or greater. This acceleration is due to a companion with orbital period exceeding that of the survey, $P_b >> 10$ yr, and mass $M \sim 3M_J(a/10\text{AU})^2$ where a is the orbital radius. It is crucial that we identify especially these "acceleration" companions otherwise the acceleration due to such companions can potentially dwarf the astrometric signature of long-period planets.

Fortunately, high dynamic range imaging has been a principal thrust of Kulkarni for almost a decade now and he has an extensive program at Palomar, Keck and Mt. Wilson and as a part of the NSF Center for AO, Kulkarni and associates (Brown, Dekany, Shelton) are developing coronagraphy and dark speckle techniques. We will observe all Tier 1 candidates in these AO program; the southern sources will be observed at ESO by Mayor and Queloz. The goal of these observations is to identify stellar companions (and perhaps even warm brown dwarfs). We also have ambitious plans for observing the more interesting targets with HST (+NICMOS, +ACS). In addition, such images are also useful to identify field stars (18 magnitude or brighter) that may bias astrometric measurements (over the duration of the SIM mission).

Telescope	Instrument	Nights	co-I
OHP 1.9-m	ELODIE	35	DQ
1.0-m	CORAVEL	77	DQ
Euler 1.2-m	CORALIE	200	DQ
ESO 3.6-m	HARPS	45	DQ
HET 9-m	HRS,NIRDI	30	AW
P200 5-m	AO/PHARO	20	SRK
P60 1.5-m	Ech/CCD	30	SRK
Keck 10-m	NIRC2,NSPEC	20	SRK
MWI 2.5-m	AO+c'graph	40	SRK
MWI 2.5-m	HK Phot	180	SLB

Table 1: *Telescope Resources Available to the Team. The allocation shown above is typical of past annual usage or institutionally assured annual time (OHP, MWI, Euler, HET). Time to JPL investigators at Keck, P200 is included. In addition, team members expect to request additional time on national or international telescopes for specific projects.*

Spots on stars will result in displacing the photocenter and thus cause astrometric shifts. We will pay particular attention to Tier 1 M dwarfs. For example, a spot covering 0.4% of the area on HD 95735 (V=7.6, M2.5V, 2.6 pc) will induce a 0.8 μas displacement. Activity in earlier type stars is less of an issue. Fortunately, Baliunas is leading a large program tracking the activity of stars at Mt. Wilson (Table 1) and together with the Coralie survey we will monitor the activity of all of our Tier 1 candidates (and if need be supplement with Baliunas' share of time at the Automated Photometer Telescope).

Reference Stars for Tier-1 targets. In §6 we discussed the importance of identifying reference stars and proposed two approaches: a pair of clump giants or a dwarf (G) binary. The former is a perfectly good solution but incurs observing time penalty. The latter is a novel idea and needs to be investigated. Our present plan is to proceed along both directions since, in any case, the proposed RV work (see below) is needed for Tier 2 targets.

`Clump Giants.` We will identify potential clump giant candidates in the vicinity (1.5° radius) of Tier 1 targets (using Palomar Quick V and the 2MASS surveys). We will observe with the echelle on the Palomar 60-inch and ESO facilities (DFOSC or FEROS) to separate the giants from the dwarfs (as well as identify the rare metal-poor giant) using the MgH+Mgb feature.[47] Great preference will be given to clump giants closest to the target (0.5°).

`Binary Stars.` The selection of suitable binaries (FGK binaries with moderate eccentricity) is a significant observational program. Based on the known binary statistics[44] (8 out of 164 stars with $250 < P_b < 3000$ d) we expect to perform a RV search on about 20 (quickV+2MASS photometrically-selected) candidates to yield one suitable eccentric binary star within 1.5° of the target. Detection of binarity would require 3 RV measurements (54 nights on ELODIE and 42 nights on CORALIE; see Table 1). Candidate binaries would be further observed (10 epochs) to select the five best candidates and a further 10 measurements for the final two candidates (to characterize the orbits). We estimate to obtain preliminary orbits at a cost of 200 total nights on the above instruments. Even though the yield is low (we expect one in five detected binaries to be a desirable reference star) we will, in most cases, obtain a suitable reference star.

Tier 2 Targets. As noted earlier (§4 the Tier 2 targets will cover the following seven groups: stars with planets identified by RV, a large sample covering the full main sequence range, binary stars, stars with a range of metallacity, young stars, stars with dusty disk and white dwarfs. The main requirement is that the Tier 2 stars must lie within 7.5° of a Tier 1 star. With the help of SIMBAD and CNS we have carried out an exercise of identifying potential Tier 2 targets around a number of Tier 1 targets. We find an average of 20 Tier 2 targets with $V < 12$ magnitude including a star earlier than F, a known or suspected binary, a star younger than 1 Gyr and at least two will be typically included in one of the RV surveys. While the Tier 2 list is substantial it is important to note of the tremendous observational progress in this area thanks to HIPPARCOS, the ongoing NSTARS program etc.

Baliunas and Queloz will undertake culling the metallicity sample (supplementing with observations if so needed and going out to 50 or even 100 pc to include relatively metal poor stars). The main sequence sample will include stars out to 50 pc so as to include equitable representation from the earlier type stars. Ongoing and our own RV observations (see above), speckle surveys and finally our ongoing AO survey of bright stars at Mt. Wilson (Kulkarni, PI; see Table 1) will be used to form the binary star sample. Beichman will be responsible to form the dusty disk sample based on IRAS and SIRTF Legacy databases. A youngish (10^8 to 10^9 yr) star sample will be formed using statistical age indicators (e.g. ROSAT X-ray emission) by Baliunas and for this sample we will tolerate larger distances 50 pc (or even larger). For some of these samples (e.g. youngish stars, dusty disks and metal poor stars) Kulkarni will undertake AO observations at Mt. Wilson (followed by detailed studies if so warranted at Palomar/Keck). Given the great power of RV, we will ensure that each Tier 2 target has at least 3 RV measurements (with new observations if so necessary).

We end by noting synergism of the proposed program with the following proposed efforts: Beichman's key project (stars with age $< 10^8$ yr), Kulkarni's interdisciplinary scientist position project (one component of which is planets around white dwarfs; we will include field white dwarfs not covered by Kulkarni's program here) and Boden's data scientist position proposal (planets around binary stars with $P_b < 150$ d). We have already discussed possible overlaps and will ensure that the final target list[s] will be truly synergistic.

8 Analysis: Planet Detection and Inference of Orbital Parameters

By mission start, we will develop a tunable, documented data analysis pipeline for use by all SIM investigators. It will implement a variety of analyses to accomplish the following three main tasks:

`Delay Calibration.` We view calibration as an integral part of analysis since the accuracy needed for planet searches is an order of magnitude better than that provided by global astrometry (1 μas per epoch instead of 9 μas per epoch). We thus cannot use the global positions provided by the Interferometer Science Center (ISC). Instead, we will directly work with calibrated delays.

`Detection and Discovery of Planets.` The Lomb-Scargle periodogram[48] (LSP) is the traditional tool for planet detection with astrometric data.[49,50] The model underlying the LSP is a sine wave buried in zero-mean noise. However, as pointed out by Black & Scargle,[51] astrometric data have nonzero position offsets and proper motion; these corrupt LSP results, particularly in the long period limit. A similar problem arises in RV studies and has motivated[46] LSP variants ("floating means" and "floating slopes"). For the RV case, this problem can be avoided by using a least-squares model that includes the systemic velocity [EK2000].

Along these lines we have developed a two dimensional least squares approach for astrometric data. Our simulations show that for most orientations of the orbit our approach results in the expected $\sqrt{2}$ improvement in the signal-to-noise ratio (SNR), relative to the standard (1-D) LSP. The next level of generalization is to consider a full Keplerian orbit. We call the resulting statistic the Kepler periodogram or K-gram [L2000]; it can include complications unique to SIM such as non-simultaneous measurement of the two projections and varying baseline orientations.

`Estimation of Orbital Parameters.` Estimating the orbital parameters of a single planet has been well studied.[52] But with SIM's sensitivity we must be prepared to analyze signals with signatures from multiple planets. This is a difficult problem but we have made substantial progress with two approaches.

First, we have developed a frequency decomposition (FD) method [KM2000] that iteratively fits sinusoidal components to the data. Application of FD to eight years of PSR 1257+12 data[53] led to the identification of a fourth planet. We have recently applied FD to 16 Cyg B data.[54] The method resembles the well-known CLEAN method,[55] but FD fits the model to the original data at every iteration, whereas CLEAN works only with the latest residual. The dynamic range and convergence properties of FD are superior to those of CLEAN. The next step is to combine FD with the 2-D LSP and tailor it to SIM.

Co-I Boden has taken the approach of working directly with Keplerian orbits rather than using harmonic analysis. This requires sophisticated minimization routines given the large number of parameters that are involved. From simulations he finds that this direct approach works quite well when multiple planets are well separated in parameter space. A hybrid model is to apply FD first (since its simplicity is so attractive) and use the parameters thus derived as inputs to the direct Keplerian approach. In the coming years we intend to continue development of these techniques and understand their limitations.

Bayesian Approach. It is now generally accepted that Bayesian methods can outperform more convential methods (e.g., least squares) in nonlinear parametric problems. Models of eccentric orbits are nonlinear and are thus particularly well suited for Bayesian analysis. We are developing Bayesian methods for detection and estimation, building on the Bretthorst algorithm[56–59] that has been used with great success to detect and characterize complicated and possibly weak periodic signals in NMR time series. This approach overcomes difficulties with non-linear parameters (e.g., ambiguity accounting for the number of periods searched to find the maximum) encountered in other approaches.[60] Co-I Loredo has developed the necessary methodology for the single-planet case; this work identified the K-gram ([L2000]). We will extend this work to handle multiple planets. It is worth noting that the LIGO community has now converged on a similar Bayesian matched filter approach for detecting neutron star coalescence events.[61–63]

An important and unique aspect of the Bayesian approach is that it unites detection and estimation with rigorous *population analysis*—inference of properties of the population of planetary systems. Such inferences are crucial for addressing many of the questions identified in §3. Our near-term research program will apply this unified Bayesian analysis to existing RV data, and then implement it for SIM data.

9 Sampling Strategy and Long Period Planets

Given the anticipated small number (~ 50) of measurements per target (see §4) over the 5-year mission, the sampling strategy assumes vital importance. Uniform sampling will result in aliasing for periods $P < 72$ d. We have identified power-law and geometric-progression sampling schemes that yield near-uniform sensitivity, free of aliasing, over a wide range of periods. Figure 6 provides a demonstration of this capability. A major advantage of these sampling schemes is the virtual absence of a limiting Nyquist frequency, so that our search can be extended to planets with periods down to a few days. We note that the HST Cepheid Key Project team uses a similar (power-law) scheme.

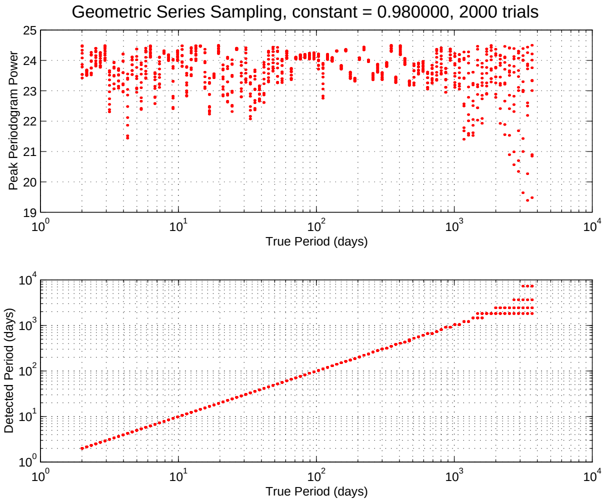

Figure 6: *Periodogram peak power response to a sinusoid for geometric sampling. The 50 samples are spaced as* $\Delta t(i) \propto A^i$ *with* $A = 0.98$. ***Top:*** *Periodogram power at the detected period vs. true period. The maximum possible power is 25.* ***Bottom:*** *Period of the peak-power bin vs. true period.*

Combining SIM and Other Planet Search Data. The short lifetime of SIM ($T = 5$ yrs) results in a diminished astrometric signature for planets with $P \gtrsim T$ (see Figure 1). This naturally raises the question whether other data sets with longer baselines can be advantageously combined with SIM.

Combining with Radial Velocity Data. RV studies are sensitive to inner planets whereas SIM reigns supreme with increasing orbital period (Figure 1). The cross-over orbital period is

$$P_* = 109 d_{10} \sin(i) \frac{\theta_{cr}}{v_{cr}} \text{ d}; \qquad (3)$$

note that this is independent of the mass of the star. Here, v_{cr} is the velocity amplitude (in m s^{-1}) that is reliably detected from RV observations, and θ_{cr} (in μas) is the corresponding quantity for SIM observations; d_{10} is the distance in units of 10 kpc. If RV studies are limited by stellar activity with $v_{cr} \sim 3$ m s^{-1} then the transition for Tier 1 is at $P_* = 25$ d (assuming $\langle \sin(i) \rangle = 0.7$). For our Tier 2 sample, θ_{cr} is worse by a factor of 4 and thus P_* may range from 25 d (active stars; $v_{cr} \sim 12$ m s^{-1}) to 100 d (inactive stars).

Given the differing slopes of the sensitivity of RV and astrometry, combining SIM with RV will be advantageous only in a restricted range around P_*. Co-I Boden has developed a package to analyze astrometric, interferometric and RV data and applied it to ground-based data with considerable success.[42] Simulations suggest that in the range $0.5P_* < P < 2.0P_*$ the orbital elements improve by as much as the expected $\sqrt{2}$. There is little leverage offered by RV studies for planets beyond this period range.

`Combining with other astrometric data.` If a planet has an orbital period much longer than the duration of a survey, then the survey can only measure the acceleration caused by a companion. The resulting astrometric signal grows as T^2, with T the mission duration. Thus T^2/σ, where σ is the precision of the survey, is a fair metric for comparing astrometric surveys. Of the planned or existing astrometric surveys (Keck, MAP, Hipparcos, and FAME), only the Keck survey with its planned 30 μas accuracy and > 10 year time baseline could make a modest improvement to SIM results.

10 Challenges to Precision Astrometry: Instrumental Errors & Calibration

The detection of Earth-mass planets is the most ambitious goal of SIM and this goal requires that SIM perform at 1 μas precision which is 10^{-4} of the fringe spacing. The metrology (which measures the fringe delay) must be understood at the few picometer level. Separately, global astrometry values supplied by ISC are insufficient to reach 1 μas precision. One must work with the calibrated delays. Team members Shao and Shaklan are familiar with the key issues of picometer metrology, calibration of field-dependent errors and global astrometry. Below we summarize the important technical issues.

`Laser Diffraction Error.` When a laser beam of finite diameter propagates, it diffracts. The "edges" of the wavefront become curved giving rise to a small difference between the geometric distance and the phase of the wavefront. For a 2° field, the difference is about 400 pm. Modeling the difference to the required 5 pm precision is stymied by beam obscuration due to gaps in the corner cubes.

`Beam Walk Error.` Beam walk arises when the starlight and metrology beams "walk" across the surface due to imperfect articulation. One source of imperfection is small irregularities in the delay line rails. Beam walk combines with optical imperfections at the $\lambda/100$ level to produce astrometric errors.

`Polarization Error.` Reflection off a metallic coating, with a finite real and imaginary index of refraction, will result in phase shifts that are polarization dependent. The phase shifts change when the optics articulate to observe different stars in the FOR; the effect is <100 pm over a 1 degree field-of-regard

`Thermal and Structural Warp Error.` On SIM, the metrology measures the optical path at the center of the starlight beam. If the optics warp so as to produce a "focus" error the metrology beam will no longer represent the true starlight optical path. Modeling predicts that the structure will bend up to $10\,\mu\mathrm{m\ hr}^{-1}$ as SIM moves from source to source. The resulting misalignments of the optics cause further beam walk errors.

The use of a nearby reference star and rapid target-reference switching will diminish the above errors (see §5). Nonetheless, it is possible that we may have to modify our procedure once SIM is in orbit, depending on the severity of the systematic effects. We will use our intimate knowledge of the various calibration errors to develop the needed modifications. For example, one way to mitigate systematic optical pathlength errors due to diffraction is to observe a given target at different delays (different baseline orientations) spaced so as to cancel the quasi-periodic error. Rather than continuously observing a tile for one hour, it may prove useful to cant the spacecraft a few degrees after a half-hour of narrow-angle chopping, then continue the chopping with the new delay. This modification could change the selection and the order in which the grid, reference stars, and Tier 1 and Tier 2 targets are observed.

11 Post-launch Activities

A key goal of our preparatory research is implementation of a fully functional analysis pipeline by the time SIM is launched, including a tunable calibration/analysis pipeline. Team members at JPL hope to work intensively with the ISC especially in the area of instrument modeling and calibration (see §10). We anticipate a working calibration/analysis pipeline by the end of the first year.

This pipeline will enable us to analyze the data as it arrives to the greatest extent possible. We believe that monitoring the observations is essential especially if the results by year 3 are a complete surprise (rich astrometric signals or rare detections). We may then elect to revise our observing and sampling strategy. This is a difficult issue and we intend to explore and study a variety of contingency plans during the preparatory phase.

At the end of mission year 3, we intend to have a major result *and data* release based on the first 2.5 years of data. We hope that such a release will renew excitement in the field, highlight SIM, and perhaps even justify an extended phase. Members of our team are prepared to work along with ISC staff so that the continuously evolving nature of the SIM grid solution will not be limiting the data release.

We also intend to rapidly disseminate interesting results to encourage follow-up observations, e.g. occulations based on orbital parameters. We expect ~ 2 and ~ 20 occultations of Tier 1 and Tier 2 targets, respectively; these estimates are based on the 1% combined Venus-Earth occultation probability. Anticipated astroseismology missions will be in a position to undertake the needed 10^{-4} precision photometry. Jovian planet occultations are easily studied[14,15] from the ground. Direct-detection techniques such as coronagraphy,[64,65] dark speckle[65,66] and dark hole[67] benefit enormously (by arranging deeper nulls at specific positions or radii) from knowledge of the orbital parameters. Such follow-up observations will help make the EPIc survey a substantial and enduring legacy of SIM to the astronomical community as a whole.

12 Possible Degradation in SIM performance.

Our program has been designed presuming that SIM reaches the goals of $1\,\mu$as narrow angle astrometry, and $4\,\mu$as wide angle astrometry. Performance may instead be limited to the "floor" accuracies of $3\,\mu$as and $30\,\mu$as, respectively. Our strategy is robust to such a degradation in performance.

The parameters of our Tier 1 program are heavily influenced by photon noise because at 1 μas, almost half the error variance is from photon statistics. If instead instrumental errors are 3 times larger than expected, the situation is quite different. In our two-tier program, Tier 1 would lose roughly a factor of three in sensitivity, from 3 $M_\oplus$ planets in a 1 AU orbit at 10 pc, to about 9 $M_\oplus$. Tier 1 would thus still provide important information about low-mass planets.

Tier 2 would suffer less. Members of this key project team have developed the 400+ term SIM astrometric error budget and have determined that if SIM were only able to reach the 3 μas floor over a 1° field, Tier 2 accuracy would be degraded by only about a factor of 2. The Tier 2 program at 8 μas on 2100 objects would still be a major advance.

13 Education and Public Outreach

The discovery of planets around other stars in recent years has kindled, or at least much enhanced, a widespread interest in the general public about our place in the universe. Speculations about whether our solar system home is unique and whether there is life elsewhere in the universe date back to ancient times. But even for people who don't normally think about the universe beyond the Earth's surface, the fact that other planets do exist is hard to ignore.

This renewed public interest will be the focus of our Public Outreach program. Of all the science which SIM will do, searching for planets probably has the most immediate interest and appeal. But SIM will not produce images, so the outreach effort must convey the excitement we as astronomers feel, when we use 'indirect' techniques for making discoveries. The challenge is to present non-image material in a way that is understandable and interesting. Explaining interferometry to the public is a major challenge, and in most contexts would not be not practical. But conveying the concept of a stellar 'wobble' due to unseen planetary companions can be as simple as building a mobile with very different-sized weights. Construction and explanation of how a mobile worked was recently done by one of our team as a 5-th grade class exercise in a Los Angeles school. It was a tremendous success. In a classroom setting, simple demos, combined with the instructor's enthusiasm, can make a real impact.

One existing educational project that we can work with is the Caltech Precollege Science Initiative (CAPSI), a collaboration between Caltech and the Pasadena Unified School District, which has developed a number of interrelated activities, beginning at the elementary-school level, in a hands-on inquiry-centered approach. Originally dubbed Project SEED, and supported in part by the NSF, this program has been successful in reforming science education locally, by bringing together scientists and teachers who share a commitment to improved science education.

Our proposal team has a lot of combined experience in giving public lectures on a variety of astronomical topics. We are very keen to work with the Outreach Scientist, and the SIM Project's Education and Public outreach (E/PO) program, in developing and implementing a long-term E/PO strategy for SIM. We are not proposing a detailed program at this time, but have used the example of CAPSI as one of several possible approaches to educational outreach. The SIM Outreach Scientist's role will be vital to an E/PO program that avoids duplication, and which makes an impact not by starting over, but by leveraging off effective programs wherever possible. We look forward to sharing our enthusiasm with students and with the public.

14 Appendices

Project Structure and Role Statements

The investigators of the EPIcS key project are responsible for a range of activities that we have grouped into the major tasks enumerated below.

1. *Theory and Interpretation*: This activity defines the goals of the EPIcS program and will interpret results in an astrophysical context. The members of this group will identify target categories, including specification of observational goals for each category (e.g., detection of complex planetary systems in nearby targets, detection of subgiant planets for more distant targets, etc.). They will also work with the data analysis team to interpret EPIcS findings, drawing astrophysical conclusions about system formation and evolution from survey results.

   Team: Tremaine (lead), Lin, Baliunas, Kulkarni, Kirpatrick, and Queloz.

2. *Target and Reference Star Selection*: This activity is aimed at supplying a list of candidate targets and reference stars for SIM observations. The team will be responsible for creating the candidate target list for Tier 1 and Tier 2 programs, and the final target selection based on our preparatory observation program.

   Team: Kulkarni (lead), Baliunas, Wolszczan, Kirpatrick, Queloz, Shao, and Boden.

3. *Pre-Launch Observations*: Our pre-launch program is geared at assisting the selection of targets and reference stars to maximize SIM sensitivity and performance in the EPIcS program (§ 7). We will obtain as much information as possible from existing databases on our selected targets and references, but particularly with regard to reference star selection a significant pre-launch observational campaign is necessary.

   Team: Queloz (lead), Wolszczan, Baliunas, Kulkarni, and Kirpatrick.

4. *Instrument Modeling*: This task is aimed at optimizing SIM narrow-angle astrometric measurements. This team will interact with the project and ISC to advise on inclusion of flight hardware (for on-orbit calibration), on appropriate software for ground data processing, and to design appropriate operational sequences for on-orbit calibration sequences. This activity would include the development of the "low" level data analysis software specific to planet detection, to produce precise relative astrometry.

   Team: Shaklan (lead), Shao, Boden, Unwin, and Loredo.

5. *Data Analysis*: The data analysis segment encompasses the high level reduction tasks; going from accurate positions to the detection of planets, their orbits, and ultimately, statistical summaries of the prevalence of planetary systems in the solar neighborhood. This task deals with the development of the analysis software. The whole key project team will be involved in using this software as well as the "low level" instrument calibration software in the preceding item, to make scientific investigations.

   Team: Loredo (lead), Boden, Tremaine, Lin, Kulkarni, Wolszczan, Baliunas, Shaklan, Shao.

6. *SIM Observation Planning*: A SIM observing schedule must be synthesized from our Tier 1 and Tier 2 target lists, and that schedule must be provided to the ISC for integration into the overall SIM schedule. Our specification must include appropriate calibration sequences, integration times for each object, and schedules for observing target set over the 5 year mission. This task has two phases; the first is a preliminary observing plan for the early part of the SIM mission, and second is the possible reallocation of observing resources depending on analysis of early SIM data.

   Team: Boden (lead), Unwin, Shao, and Skaklan.

Individual Role Statements

PI Shao will coordinate the overall EPIcS project activities. As the project proceeds, there will likely be minor adjustments to the planned work, from target selection to analysis to observation planning. There are several key decision points in the next few years, and Shao will work with the team to arrive at consensus decisions. These decision points include specifying our strategy for selecting Tier 1 reference stars, and selecting the approach/algorithm for planet detection/orbit characterization. In addition to his coordination activities, Shao will work extensively with the instrument calibration-modeling and the SIM observation planning teams.

Deputy PI Kulkarni will serve as co-PI within the group for overall coordination of science and target selection, the first 3 items in the list above. In addition, Kulkarni will be responsible for the detailed selection of targets (item 2). He will also support the pre-launch observational program for imaging observations of targets, (item 3: AO and conventional imaging and perhaps imaging with HST; he will be assisted in this matter by D. Kirkpatrick). Kulkarni will be the main coordinator for team publications and ensure that results, both in the preparatory and post-launch phase, are promptly written up and disseminated.

Co-I Baliunas will work prior to launch on selecting Tier 1 Tier 2 and reference stars for Tier 1 objects in close collaboration with other co-investigators. Baliunas will work on sample selection from existing and newly-developing sets of measurements of candidate target properties including *inter alia* surface magnetic activity, e.g., x-ray fluxes (ROSAT and CHANDRA) or Ca II H and K emission and photometric fluxes (Mount Wilson data sets), HIPPARCOS, metallicity, rotation, angular momentum, mass, age and evolutionary state. Information for target stars will be linked with a data base program. The Mount Wilson data base of surface magnetic activity measurements of 2200 late-type stars will first be re-reduced with a newly developed procedure to enhance the precision of the data, then be analyzed for metallicity (determined from the reference passband fluxes), rotation, average activity and activity variance. The average activity and rotation will be transformed into an indicator of age for lower main sequence stars, based on ages of established objects already observed in the Mount Wilson catalog. Results will then be analyzed jointly with information from other co-I's, e.g., the radial velocity measurements made by D. Queloz. Indices from spectra will be transformed to the Mount Wilson index. Baliunas will also assist with the planned AO observations. After launch Baliunas will assist with scientific analysis and preparation for dissemination and publication of results.

Co-I Boden will have primary responsibility for the required binary star reductions in the

EPIcS program: the integrated astrometric & radial velocity binary model reductions for binary targets and binary reference stars. Boden will assist in the overall Tier 2 target selection, coordinate the selection of the binary system component of the Tier 2 target sample, and lead the analysis of this sample for sub-stellar companions. Additionally, Boden will participate in the EPIcS data analysis team, contributing to the development of data analysis strategies before launch, and to the execution of these strategies in signal detection and extraction post-launch. Finally, Boden will lead the observation planning task, and coordinate the interaction of the investigation team with the Interferometry Science Center; submission of observing lists and schedules to the SIM scheduling team at the ISC, and delivery of SIM science data products from the ISC to the EPIcS data analysis team.

Co-I Lin will serve on the theory task, investigating theoretical models of the formation, evolution and dynamics of the planetary systems accessible to SIM. In the pre-launch phase he will analyze the overall strategy for Tier 1 and Tier 2 campaigns based on theoretical models of planetary formation and evolution. He will identified the central issues we must address and design tests which may provide quantitative constraints on theoretical models. He will construct dynamical models for potential target planetary system and help to optimize the observational schedule. As results come in he will interpret the results and their implications for understanding planet formation and dynamical evolution.

Co-I Loredo will lead the EPIcS data analysis team, and oversee the development, implementation, and application of statistical methodology for EPIcS. The primary emphasis of his work, particularly in the first years of EPIcS, will be on development of new Bayesian algorithms for detecting planets and estimating planetary system parameters, both with RV data and with SIM data, including such complications as planet multiplicity and non-inertial reference star motion. He will also develop methods for combining individual system inferences in order to make inferences about the population. These algorithms will be applied on RV data throughout our preparatory observing program, as well as on SIM data during the actual mission. Loredo will lead the design and construction of data analysis pipelines that will implement a variety of methods for analysis of stellar motion data from RV and SIM observations.

Co-I Queloz will lead the pre-launch observation team. Our pre-launch observation program will include a range of techniques, (conventional and AO imaging, spectroscopy) but will be dominated by radial velocity observations of Tier 1 candidate targets and reference stars. Queloz will be responsible for coordinating the required RV support work described in § 7. The required high precision RV observations will utilize the infrastructure of the ongoing Geneva Extrasolar Planet Search Program[5], of which Queloz is a member. This investigation will require approximately 400 observing nights, roughly 150 in the Northern hemisphere using CORAVEL, ELODIE, and HET (in collaboration with Co-I Wolszczan, see below), and 250 in the Southern hemisphere using the CORALIE and HARPS instruments depending on the final target distribution. Queloz will be responsible for obtaining observing time at these facilities, integrating the targets into relevant observing lists, processing the spectra to extract RV and component rotation data through the established processing pipelines, and forwarding the RV data to Pasadena to be archived.

Co-I Shaklan will lead the instrument modeling team providing optimized SIM narrow-

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[5] http://obswww.unige.ch/∼udry/planet/planet.html

angle observing and calibration techniques. In the pre-launch phase he will study observing strategies that will reduce the effects of systematic errors and he will develop on-orbit calibration techniques that are specifically designed to reduce systematic errors in narrow-angle observations. Shaklan will also continue to work closely with the technology development and flight integration teams to maintain a thorough understanding of the important error sources. During the mission, he will aid in the interpretation of calibration data. As described in the proposal text, the observing strategy is optimized to yield the best astrometric measurement for both Tier 1 and Tier 2 targets. Shaklan will continue to refine the observing strategy along these lines as our pre- and post-launch knowledge of SIM performance grows.

Co-I Tremaine will lead the theory team and investigate theoretical models of the formation, evolution and dynamics of the planetary systems accessible to SIM. In the pre-launch phase he will apply models of planet formation and evolution to help design the Tier 2 target selection. In particular he will set up simple ad hoc scenarios for planet formation and test how well these can be discriminated using proposed target lists. These tests will determine what classes of target we observe, how many stars in each class should be observed, what orbits and masses we can hope to detect, etc. He will also investigate how to optimize the Tier 1 and Tier 2 sampling strategy (number and spacing of observations to detect long-period planets and multiple planet systems, and to eliminate aliasing from short-period planets). As results come in he will lead the interpretation of the results and their implications for understanding planet formation.

Co-I Wolszczan will participate on the pre-launch and data analysis teams, contributing to work on adapting algorithms developed for the detection and characterization of multiple planets around neutron stars to analyze astrometric data from SIM and the RV data from ground-based telescopes. This involvement will include further development of the already working frequency decomposition (FD) method, analysis of planetary perturbations, and research toward creating hybrid methods that would combine FD with a 2D Lomb-Scargle Periodogram (LSP) approach, and with a direct harmonic analysis of Keplerian orbits. Wolszczan will also lead a RV measurement program with the Hobby-Eberly Telescope (HET) over the duration of the EPIcS project. Both pre-launch and post-launch activities may benefit from using the HET. At Penn State, a project has been initiated to design and construct a near-IR (0.8-1.6 um) dispersive interferometer to search for planets around K and M dwarfs with a 1 m/s precision (Ge, Ramsey, Wolszczan, Rushford). This instrument is planned to become available on the HET in 2001 and it may become a source of important SIM-complementary science.

Statement of Work

The EPIcS Key Project requires a significant amount of preparatory research. This work falls under the following categories:

- Tier 1 target selection (∼75 targets)
- Tier 1 reference star selection
  - identify candidates
  - observations of candidates
- Tier 2 target selection (∼2100 targets)
  - Define categories of targets designed to resolve astrophysical questions on planetary system formation and evolution
  - Identify specific targets within 7.5 deg of Tier 1 targets
  - Observations of candidate targets
- Instrument modeling and low level data reduction
- Data Analysis for planet detection and orbit characterization
- SIM observation planning

The first task to be initiated is the Tier 1 target selection. This is divided into two subtasks; first the identification of candidates, and using existing data, eliminate candidates that are stellar binaries with orbits that would preclude the existence of planets we wish to find. Second, for the few stars where this data is not available we will conduct a rapid imaging and RV observational program. Because subsequent phases of the program development rely on the results of the the Tier 1 selection, the Tier 1 list should be 90% complete after six months (mid FY 01), and 100% complete 12 to 18 months after the proposal is funded (mid FY 02).

Because of the two-tier structure, work on reference star selection and Tier 2 target selection must wait until the Tier 1 list is compiled. Six months into the program when the Tier 1 selection is primarily completed, reference star and Tier 2 target selection will commence (mid FY 01) and proceed in parallel with the final completion of the Tier 1 list.

Tier 1 reference star selection is a lengthy process. The goal is to have the Tier 1 reference star candidates selected within three to six months of the selection of the Tier 1 targets (early FY 02). The reference candidate list will be 10 20 times larger than the Tier 1 list. After compilation of the reference star candidate list, an observational program will be conducted to select the final reference list. We estimate this observation program will take approximately three years, ending in FY 05.

Tier 2 target selection starts with the Theory group's identification of the different categories of stars we will study for the presence of planets. This category identification will be completed in six to nine months (completed mid to late FY 01). By this time the tentative Tier 1 list will be nearly complete, and work using existing data identifying specific Tier 2 target candidates within 7.5 deg of Tier 1 target can commence. Since Tier 2 targets are R<12, the preliminary identification can be done using existing data. An observing program will be initiated to narrow the Tier 2 list, primarily designed to eliminate unintended stellar binarity, and to assure the target is actually a member of the intended catagory. This activity will be a low level observing program that will end roughly a year before launch. Roughly two years before SIM launch we will revisit the theoretical landscape and possibly modify our list of what categories of stars to include in our Tier 2 program. Because of the large size of the Tier 2 sample, searching existing databases will be laborious, and even our limited observing program for Tier 2 candidates screening will be time and labor intensive.

Instrument modeling, calibration, and low level data reduction is another required task. Several members of the Key Project team will follow the progress of the SIM picometer technology program, especially the major system level testbeds. Studying the results from these testbeds, the key project team will report to the project before the start of phase C/D (nominally FY 04) advising the project on the hardware, calibration procedures, and on orbit data reduction software specific to narrow angle astrometry. In addition, this key project will work with the ISC to define in detail what data products will be delivered to the EPIcS team (to be completed in FY 05). Under this task is the development of software for making use of calibration data specific to this Key Project. This task will be relatively low level until the start of phase C/D. At that time, this activity will increase as the data products from the ISC are defined in detail.

SIM plans to conduct a six month period of on orbit checkout after launch prior to the start of regular science observations. Part of this six month period will be spent verifying narrow angle astrometry and the on orbit calibration manuevers needed for 1 uas narrow angle astrometry. The key project team will work with the project, helping define the set of initial on orbit tests for narrow angle astrometry, along with the corresponding data reduction algorithms and observational procedures.

Data analysis is defined as the processing needed to “discover” planets and characterize their orbits. The team will develop the necessary software using a variety of approaches both for the discovery process and for orbital solutions. This development will continue from FY 01 through FY 05, at which time any necessary input the target scheduling below must be in place. The final software for instrument calibration and modeling may be integrated with the planet discovery and characterization software. The schedule of activities in this task mirrors the instrument modeling task. We will analyze data from SIM on-orbit checkout in FY 06 and advise the project of instrument performance, making any necessary modifications to our observing, calibration, or analysis strategies.

Observation planning is the last task in our work breakdown. This activity will be very low level until the information necessary to do this work is available. Detailed observation planning requires that we know what our Tier 1 and Tier 2 targets are as well as any specialized calibration sequences SIM needs to perform before making narrow angle observations. We will try to maximize use of automated scheduling tools being developed by the ISC. Starting 18 months before launch (start FY 05), work will commence on developing a tentative detailed observing schedule to be delivered to the ISC six months before launch (mid FY 06). Then as a result of initial analysis of SIM checkout data in FY 06 or identification of interesting signals in continuing analysis of program data, modified observing plans may be developed during the SIM mission.

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