Contents

1 Executive Summary

As human beings, we have a natural curiosity about our origins and our importance in the world. The discovery of more than forty extrasolar planets in the last five years has expanded the boundaries of our "world" in a very palpable way. These front-page discoveries have captured the attention of the public. They have made science education feel more relevant to students and they have fueled political support for science in general and space exploration in particular. At the heart of the continued public interest is the growing realization that planets may be commonplace. As the list of extrasolar planets grows, the question of whether there could be life parallel in some way to our own becomes more relevant and more highly charged.

The Doppler studies have discovered massive planets akin to Jupiter and more recently, Saturn. The true nature of these planets as gas giants was revealed by the measurable dimming of starlight during a planet-transit in November 1999. With forty-some planets, most discovered by members of this SIM team, we now know that within the mass range probed by radial velocities, the distribution of planet masses rises toward low masses. This is a common theme in nature: low mass stars are more common than high mass stars; grains of sand more common than boulders. The Doppler studies are also revealing an abundance of multiple-planet systems. Only one, Upsilon Andromedae, has been announced, but long term velocity modulation, often with curvature, is evident in at least one third of the stars we are observing with one known planet and a year-long baseline of radial velocity data.

The discovery of extrasolar planets has given birth to its own subdiscipline of astronomy. Data-starved theories of planet formation and evolution are now recharged with new boundary conditions such as the observation that all extrasolar planets orbiting beyond 0.2 AU have nonzero eccentricity. There is a strong suggestion from theoretical simulations that the inner 5 AU around Upsilon Andromedae is dynamically saturated. This observation has also been made regarding our own solar system. These new findings suggest that gravitational interactions in the protoplanetary disk may govern the ultimate architecture of solar systems.

The Doppler surveys will continue to detect more planets. The precision has already improved so that at small orbital separations, neptune-mass planets are detectable. With five more years of data, these surveys will begin to probe wider separations looking for evidence of true analogs of our own solar system, with a Jupiter at about 5 AU. Doppler surveys will also detect more multiple systems and more transit observations may occur. By increasing the number of detected planets, we will have a richer statistical understanding of the diversity and interdependencies of the physical characteristics of planetary systems.

However, SIM stands alone in it's ability to discover earth or neptune-mass planets at separations of a few AU. SIM is designed to chart the next era of big discoveries.

The Key Science teams will carry the responsibility of ensuring that SIM time is used efficiently and productively. Our team will deliver a target list that has been extensively scrutinized using adaptive optics, photometric monitoring and the highest precision Doppler observations available. From a database of more than 1000 stars, we will pick 50 stars ideally suited to ensure successful scientific results for SIM:

- From this large, well-studied database we will cull out ideal targets for finding terrestrial planets

- From a subset of stars showing very low amplitude periodicities, we will search for 5-20 M_{Earth} planets
- We will determine the absolute mass for known planets and search for additional planets
- We will determine the degree of coplanarity in known multiple systems.

Our goals are specific and our targets are well-understood. Engineering issues aside, perhaps the biggest challenge to achieving 1 μas precision will be astrometric jitter in the narrow angle reference stars from either astrophysical or dynamical sources. Since one criterion for target selection is the availability of reference stars, our team intends to meet this challenge head-on selecting targets and reference stars hand-in-hand. We will launch a vigorous Doppler campaign to eliminate stellar binaries and low mass companions among K giant reference stars, selected to be more than 2 kpc in distance. We will deliver 4–6 reference stars for every science target.

The Discovery of Planetary Systems

2 Introduction

We are witnessing the birth of a new observational science of planetary systems. In the past five years, 42 extrasolar planets have been discovered by precision Doppler surveys (Marcy, Cochran, Mayor 2000). The majority of these planets were discovered by members of this SIM team. We developed novel hardware and algorithms to attain the highest Doppler precision in stellar astrophysics. We propose to employ this same team, augmented with experts in interferometry, astrometry and data analysis, using SIM to:

1. detect terrestrial planets
2. detect 5–20 M_{Earth} planets
3. determine absolute masses of known planets and look for additional planets
4. determine the degree of co-planarity in known multiple systems.

The target list for this proposal will be drawn from the extensive Doppler database compiled by team members, and it will contain specific examples of systems with known attributes to address specific questions.

2.1 Properties of Known Extrasolar Planets

Extrasolar planets have been discovered around some 6% of FGKM main sequence stars with masses ranging from $M \sin i = 0.25 - 8$ M_{JUP} and semimajor axes from 0.04–2.1 AU. The largest orbits are set by the duration of Doppler searches. These planets have unexpected properties which bear on the design of the SIM Planet search:

- The distribution of planet masses is strongly peaked toward low masses (Figure 1), well fit with a power law: $dN/dM \propto M^{-1}$. The number of planets per unit mass rises steeply toward lower masses. Moreover, planet formation in protoplanetary disks is truncated at masses above $\sim$10 M_{JUP}.

- All 20 planets beyond 0.2 AU are in eccentric orbits, e >0.1 (Figure 2). A prospective explanation for the high eccentricities is that the planets formed in circular orbits in disks, but were scattered by gravitational perturbations with other planets, stars, or the host disk itself (cf. Lin et al. 1996, Artymowicz 1997, Levison et al. 1998).

- We discovered the first *system* of planets around a main sequence star, Upsilon Andromedae (Butler et al. 1999). Far from unique, we see secondary velocity trends in more than one third of the planet–bearing stars in our sample. *Thus, multiple planet systems appear to be common.*

- In November 1999, we co-discovered the first planet transit (Henry et al. 2000, Charbonneau et al. 2000) which yielded the first planet radius and hence density, and implied that the planets are gaseous rather than solid.

- In March 2000, we announced the first two sub–saturn mass candidates. (Marcy et al. 2000)

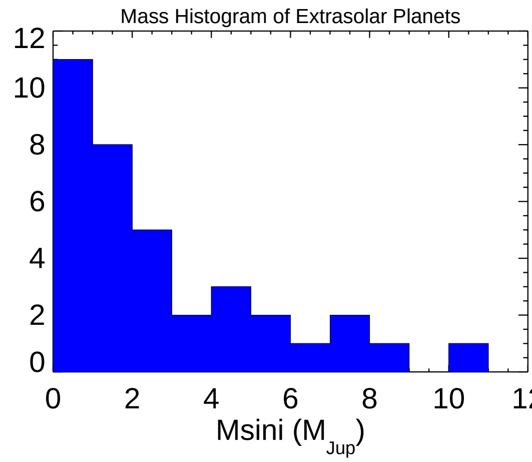

Figure 1: *The mass distribution of known extrasolar planets*

Our SIM planet search is designed to answer key questions about the cosmic properties of planets in general. What fraction of stars have planetary systems? How many planets are there in a typical system? What is their distribution of masses and semimajor axes? How common are circular orbits? How commonly do planetary systems have an architecture similar to that of our Solar System?

Properties of planets below 1 M_{SAT} may be estimated speculatively from known higher mass planets by extrapolation, the only estimate available. The rising mass function implies that a significant fraction, perhaps 30–50% of all single stars, will harbor planets of mass, M = 10 M_{Earth} − 1 M_{SAT}, detectable by SIM. Indeed, many (most?) will harbor multiple planets in that mass range. Our SIM planet search must be designed to anticipate the astrometric confusion stemming from multiple planets.

In addition, orbital eccentricities are ubiquitous within 2 AU for Jupiter-mass planets. It remains unknown whether terrestrial planets will also exhibit eccentric orbits. Clearly, therefore, a SIM planet search must obtain enough observations per star to adequately assess the often subtle eccentricity parameters.

We plan to obtain 10 years of precision Doppler measurements for each SIM target star. This Doppler reconnaissance of all SIM target stars establishes the saturns and jupiters within 3 AU, and provides Doppler suggestions of 10–30 M_{Earth} planets. We consider this Doppler reconnaissance of SIM targets to be a prerequisite of a SIM planet search. Many planets with Neptune-Saturn-Jupiter mass will be anticipated and included in SIM astrometric models.

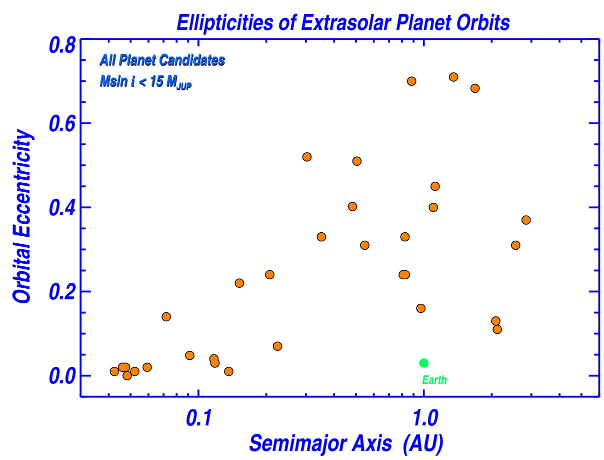

Figure 2: *The eccentricity distribution of known extrasolar planets*

Our Doppler reconnaissance has already begun for the SIM planet search. We are currently surveying the nearest 900 G,K, and M main sequence stars in the northern hemisphere with the Lick 3-m and the Keck 10-m telescopes. We are also surveying the nearest 200 GK southern hemisphere stars with the Anglo-Australian 3.9-m telescope. Moreover, with the 6.5-m Magellan telescope (on line in one year), we will extend our Doppler reconnaissance to another 600 GKM stars in the southern hemisphere. From the Doppler reconnaissance (both detections and nondetections), ideal SIM targets will be chosen, as described in section 4.

Indeed, by the time of the SIM launch post–2006, we project that 200 jupiter-saturn planets will be known, with hints of dozens of planets from 10-30 M_{Earth} within 1 AU.

In this SIM proposal, we plan to integrate precise Doppler measurements with SIM measurements, to optimize the integrity and precision of SIM orbital solutions. As described within, Doppler measurements will also be used to optimize SIM target selection, SIM reference star selection, SIM error analysis, and SIM orbital analyses.

Our SIM team consists of young, data-savvy scientists, all renowned practitioners in maximizing the precision of excruciatingly subtle and novel measurements. There is no administrative padding in our proposal, but rather it represents a cohesive team of active, hands–on researchers. We plan to work closely with the JPL SIM technical specialists and project manager, to improve SIM integrity and the SIM planet search.

3 Overview of the SIM Planet Search

A SIM planet search will require a cooperative approach, with the key-project science team working closely with the SIM technical teams. We are dubious that astrometric precision of 1 μas will emerge easily as a standard data product. Instead we expect that an intense collaboration between our team and others at JPL and ISDC will be required to identify systematic errors and to develop analyses to minimize errors.

Searching for planets with SIM will entail, first and foremost, detailed attention to the error budget, especially those errors that are not fully anticipated. Indeed, some of these errors are astrophysical in nature rather than technical. Therefore, this proposal will emphasize efforts to minimize SIM errors in narrow–angle astrometry, both prior to launch and after launch. Moreover, our planet search will emphasize the ground-based efforts that can be accomplished in the next 5 years to optimize the target selection, reference–star selection, and the interpretation of SIM astrometry.

We plan a SIM planet search with 50 target stars, chosen and partitioned in several categories as described in section 4. We will describe a strategy to achieve 1 μas precision, with special attention paid to establishing the integrity of the narrow–angle reference stars.

Indeed the "jitter" of reference stars due to orbiting companions portends a serious loss of SIM efficiency and precision. Worse, jitter in reference stars can introduce false periodicities in the astrometry of the target stars. Poorly chosen reference stars will have a binary frequency of ~67% causing significant havoc.

We deem the integrity of reference stars as crucial to achieving 1 μas precision. Therefore we discuss first in this proposal the establishment of the best possible narrow–angle reference stars, prior to describing the SIM planet search targets.

4 Narrow Angle Reference Stars

To maximize SIM's astrometric accuracy, we must have a local network of reference stars. These reference stars should be:

- astrometrically stable to 1 μas
- located within a 0.5 degree radius in order to achieve 1 μas precision
- brighter than V = 12 to minimize the exposure times.

The existence of a sufficient number of reference stars must be one of the selection criteria for science targets. Hence, the focus of pre-SIM-launch studies will be the identification of a reference grid around each of the targets selected from the Doppler program.

The optimal stars to serve as local reference stars are K giants. Because of their bright intrinsic luminosity, K giants can be found at greater distances than almost any other star of the same apparent magnitude. Hence, they offer the smallest astrometric jitter from dynamical effects (e.g., planets and stellar companions) compared to other stars of the same apparent magnitude. With a typical brightness of V = 11.5 at 2 kpc, K giants are plentiful enough to provide several candidate reference stars for most science targets. Indeed, we consider K giants to be the only objects suitable to serve as narrow angle reference stars.

4.1 The Contaminant: Stellar and Jovian Companions

A serious problem looms for a SIM planet search. The frequency of binary stars is ~67%, implying that stellar companions will contaminate the reference stars in various ways. Wide binaries, with separations of 100-1000 AU (0.1–1 arcsec), will pollute the SIM fringes. Close binaries (0.1–100 AU) cause astrometric "jitter" in the form of curvature of >1 μas during the 5 year SIM lifetime. Thus binary stars must be eliminated from the K giant reservoir, including companions spanning 4 orders of magnitude of separation, 100 μas - 10^6 μas.

Moreover, Jupiter–mass companions and brown dwarfs within 5 AU will also ruin the reference stars. For example, a companion of 3 M_{JUP} orbiting 5 AU from a K giant at a distance of 1 kpc will cause an astrometric jitter of 15 μas. Clearly Jovian planets and brown dwarfs cause jitter 15× the desired astrometric stability tolerance of 1 μas. The occurrence rate of such companions is at least ~15%. This jovian occurrence rate represents a simple extrapolation of our Doppler survey results, for which 6% of stars have a Jupiter within just 2 AU, and an additional 1% of stars have a brown dwarf companion.

Therefore, both stellar and jovian companions to >75% of the K giant reference stars will add noise well above the 1 μas level. The detection of planets is severely compromised by this contamination of reference stars, unless treated properly, as we propose to do.

4.2 The Details of Contamination

The precision of SIM narrow angle astrometry depends directly on the astrometric stability of the reference stars. The target star selection is mutually dependent on the available reference stars, as each target star must be accompanied by 4–6 reference stars with astrometric jitter less than a few microarcseconds. Finding the best targets and reference stars will be an iterative process that requires years of dedicated effort.

Binary companions to these reference stars will be detrimental to SIM in two ways:

- identification of astrometric wobble due to a companion will require extra effort in modeling the reference stars and will demand wasteful SIM observations.
- if the companion is bright enough and within 1" (≈ 1000AU) of the reference star, it will pollute the fringe pattern. Even if ISDC identifies such binaries after one or two observations, it would be wasteful of SIM time to cull reference stars by using SIM itself.

One may assess the magnitude of the problem caused by binary systems. The progenitors of the Pop I K giants that would make up most of the narrow angle reference stars are late-F or early-G dwarfs. Studies of the binary frequency of F7 - G9 dwarfs (Duquennoy and Mayor 1991) indicate that ~67% of these stars reside in multiple systems. Separations less than 100 AU will create the greatest jitter. For such binaries, the reflex astrometric motion is $\sim 10^5$ μas (!) due to a stellar companion.

While much of the orbital motion for binaries with orbital periods between 10–100 AU will be absorbed as proper motion, there will be some curvature that will contaminate 5 years of astrometric SIM data above the level of 1 μas. Since about half of the binary systems have separations less than 100 AU, we expect that unless these stars are studied from the ground, there will be a significant failure rate for the K giant reference stars, just from binary stars alone. This can be avoided with a focused campaign from the ground.

Astrometric jitter in the reference stars can also originate from the nonuniformities in the photosphere, i.e. spots, rather than from a dynamical source. These same photospheric sources contribute to scatter in the radial velocities. Thus, precision Doppler measurements provide a good way to eliminate photospheric variable stars as well as binaries among reference stars.

The existence of a sufficient number of reference stars must be one of the selection criteria for target stars. Our delivery of an extensively scrutinized list of target stars depends on an intense campaign to cull astrometrically stable reference stars for the target stars.

4.3 Culling Suitable Reference Stars

The Hipparcos catalog is incomplete for magnitudes fainter than V = 9. The Tycho catalog is fairly complete down to V = 12, but only provides positions, proper motions and the Tycho magnitudes B_T and V_T. To check the density of possible reference stars, we searched the Tycho catalog for objects within a 1 degree radius of stars with known extrasolar planets. To further select for giants, we transformed the Tycho $B_T - V_T$ to the Johnson photometry scale and sieved for stars redder than Johnson $B - V = 0.9$.

Target stars in the galactic plane typically had 20 – 30 candidate reference stars within a 0.5° radius, while stars out of the galactic plane (such as 47 UMa) had sparser fields, generally 5 – 10 candidate reference stars. We estimate that about half of the initially selected candidate reference stars will turn out to be nearby faint dwarf stars. Of the distant K giants, perhaps 67% will binaries. *Thus, we expect that only about one fourth of the initial candidate reference stars selected from Tycho will graduate to true reference star status.*

We will need to supplement the candidate reference stars from Tycho, particularly for those targets that promise to contribute unique and important results. For example the three closest single stars, GJ699, GJ411, GJ406 would be excellent narrow angle astrometry targets to search for terrestrial planets. The Tycho catalog lists 26 stars redder than $B - V = 0.9$ within a 0.5° radius of GJ699, but only 9 stars for GJ411 and 7 stars for GJ406. Assuming that many of these reference star candidates will not have sufficient astrometric stability, we would need to identify additional candidate reference stars. There are several ways to address this problem.

- We will select stars on the basis of color and magnitude from the USNO-A2.0 catalog and use the 2MASS catalog to discriminate dwarfs from giants.

- The magnitude limit on the reference stars may be softened to V=12.5 or 13, incurring only a modest increase in exposure times

- We could select candidates at a slightly wider radius, at the cost of a slight degradation in astrometric precision, if tolerable scientifically. The error budget for narrow angle astrometry grows linearly with radius. Drawing reference stars from a 1° field radius, rather than 0.5° radius, provides us with four times the number of candidate reference stars but should render the astrometric errors no worse than 2 μas.

- We could use narrow band filters that select for distant K giants (Patterson et al. 1999) to identify uncataloged stars in the 1 degree field.

4.4 Eliminating Reference Stars with Astrometric Jitter

Some members of our team are already involved in a campaign to identify stable grid stars. The P.I.'s data pipeline for the planet search project has already been expanded and is now being used by Frink and Quirrenbach to assess intrinsic velocity variations of K giant stars. Thus, we are uniquely positioned to provide a clean set of reference stars and associated target stars with this data pipeline.

At Lick Observatory, a proxy sample of nearby K giants has been surveyed for the past year (Frink, Quirrenbach 2000 SPIE). While these stars are too close to serve as reference stars, they offer the first real assessment of the dynamical and photospheric stability of K giants. Figure 3 shows a histogram of the velocity scatter for 42 K giants.

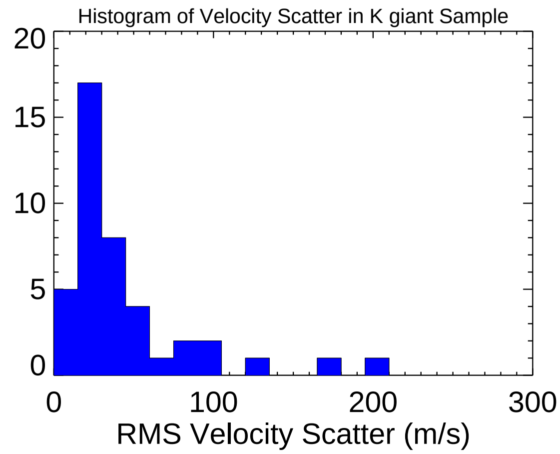

Figure 3: *Velocity scatter in a proxy sample of 42 K giants with more than 3 observations per star spanning a minimum time baseline of 3 months. Half of these K-giants (preselected to be single) have radial velocities that are constant at or below 20 m* s^{-1} .

All of these proxy K giants have more than 3 velocity measurements obtained over time baselines greater than 3 months. This sample of stars was preselected to consist of single stars, based on published ground-based work. The Frink and Quirrenbach results can be summarized:

- virtually all stellar companions can be identified with only two observations with 20 m s^{-1} precision

- half of the observed K giants (preselected to be single) are photospherically stable at or below 20 m s^{-1}

- the proxy sample sets the target velocity precision to identify astrometrically stable reference stars.

4.5 Reference Star Summary

Finding acceptable astrometric reference stars for narrow angle astrometry must be done iteratively with the selection of science targets. Our procedure for identifying these stars is the following:

1. Select K giant candidates within 1° of potential target stars.

2. If the target star is deemed extremely high priority, and not enough reference stars are available, supplement the list as described in Section 3.3.

3. Carry out narrow–band photometry (Patterson et al. 1999) or use existing catalogs (USNO and 2MASS) as a first filter to distinguish between late type dwarfs and K giants.

4. Adaptive optics imaging will be carried out for all candidate reference stars to detect stellar companions within 2 arcsec with brightness ratios of 100:1.

5. Obtain a single, high S/N optical spectrum of each reference star to eliminate double–line spectroscopic binaries (SB2). The spectrum further distinguishes dwarfs from giants, based on gravity-sensitive lines. This spectrum will further serve as a template for Doppler monitoring of surviving candidate reference stars.

6. Five years of Doppler monitoring to identify SB1 stars will be carried out. Doppler work will effectively reveal stellar companions within to 10 AU. For those stars requiring the highest precision astrometry, the Doppler work for target stars and reference stars will be done as part of the Keck planet search project. Jovian companions within a few AU will also be detected, allowing rejection of those reference stars.

We will scrutinize 8 K giants for every science target. We will start with reference stars that appear to be at the greatest distances and smallest angular separations from the program stars. Despite culling reference stars that are apparently free of stellar and jovian companions we expect that some 10% of the reference stars will have undetected low amplitude variations, resulting in jitter at the few μas level. To minimize the low amplitude jitter, we will aim to identify K giants at distances greater than 2 kpc. We will approach SIM launch year (2006) with redundancy in the number of available reference stars. At a minimum, we will provide 4 reference stars for each science target. However, for those target stars of highest scientific priority, which place the greatest demands on astrometric precision, we will provide 6 reference stars.

5 A Surgical Planet Search with SIM

5.1 Terrestrial Planets

We propose to search for 2–5 $M_{\rm Earth}$ planets around a subset of stars that have been intensely surveyed with the highest precision Doppler measurements. The targets for this work would be those stars closer than 5 pc with no discernible companions detected by Doppler techniques in the inner few AU. In the next five years, the high precision Keck Doppler survey will have a time baseline of nearly a decade. This survey will be sensitive to planets of 0.5 $M_{\rm JUP}$ and orbital periods as long as 10 years. Such planets represent true analogs of our own solar system and if detected, these would be good targets for follow up observations by SIM to detect terrestrial planets with orbits of 2 - 4 years.

Every known star closer than 5 pc of F,G,K,M spectral type is already being observed in our surveys. Since these stars constitute targets for which the highest astrometric precision is desired, we will increase our ground-based monitoring (both sampling frequency and S/N) in order to obtain the highest precision Doppler reconnaissance for planetary companions. The candidate reference stars to the 5 pc sample should also be observed at the higher Doppler precision.

A detection of a terrestrial planet will be extremely challenging because the amplitude of the signal is so low. Figure 4 shows simulations of astrometric data for a 1 M_{Earth} planet at 3 pc, a 2 M_{Earth} planet at 4 pc, and a 3 M_{Earth} at 5 pc. In these simulations, as in all other simulations shown in this proposal, the data are plotted as if the parallax and proper motion were known and cleanly removed. In fact, absolute parallaxes may not be known for these stars unless the reference stars are modeled as grid stars, so the astrometric perturbations due to orbital motion will actually be tiny wobbles on top of enormous signals.

5.1.1 Extracting Low-Amplitude, Complex Signals

A problem fundamental to analysis of radial velocity or astrometric observations is the detection and characterization of unknown periodic signals in noisy time series data. Even the highly relevant case of unevenly spaced observation times is an old problem with many proposed solutions. A rigorous Bayesian analysis (Bretthorst 1998, Bretthorst 2000) has largely unified this topic, by showing how the question "What is the most probable frequency present?" can be answered using the approximate Schuster periodogram or the more accurate and statistically well-behaved Lomb-Scargle Periodogram (Scargle 1982, Scargle 1989). In collaboration with Larry Bretthorst, Scargle has already found that this approach can significantly improve orbital determinations.

This work will be extended in several directions:

1. By considering the possible presence of more than one periodic signal, we can compute the posterior probability as a function of the number of planets in the model. The maximum of this gives the most likely number of periodic signals – *i.e.* a completely objective estimate of the number of planets supported by the data. This procedure also yields the most probable values of all the orbital parameters, plus a full description of their uncertainties.

2. We are developing a scheme for computing probabilities of signal frequencies that explicitly takes into account the true elliptical shape of the orbit. We call this a "Keplerogram," to contrast it to the periodogram, which assumes a sinusoidal signal. Combining these two procedures should significantly increase the accuracy of the orbit parameters, and possibly allow detection of weaker signals – *i.e.*, smaller planets.

3. We plan to improve procedures for selecting observation times. It is well known that the semi-random sampling, often forced on astronomers by the practicalities of observing, greatly diminishes aliasing – the leakage of power to frequencies different from the true frequency. Nevertheless, we have detected aliasing in radial velocity data –

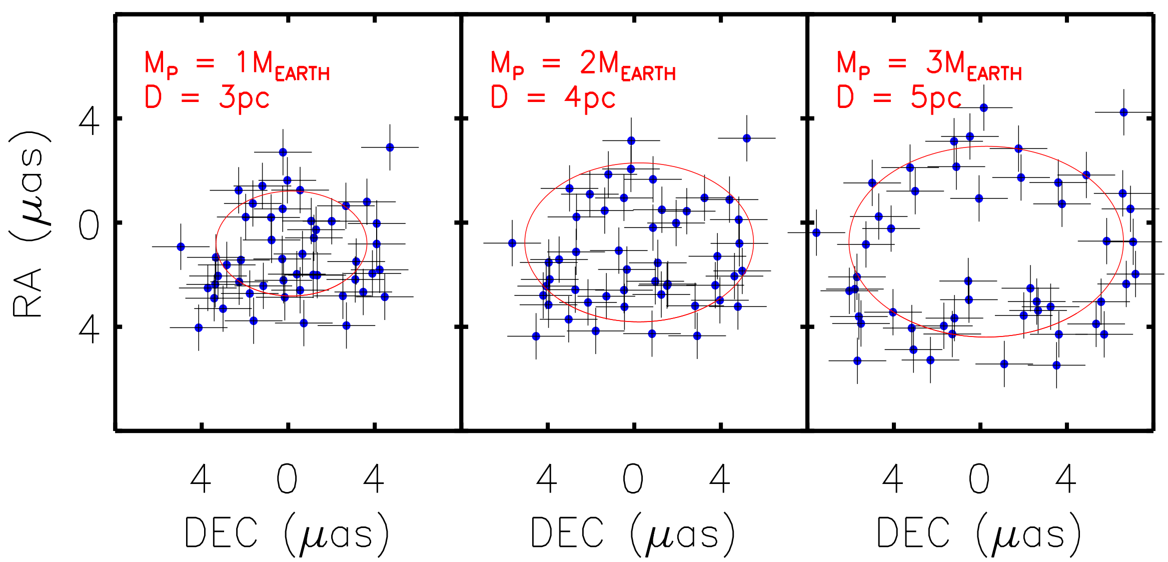

Figure 4: **(left)** *Simulation of astrometric displacement for a star with a 1* $M_{\rm Earth}$ *planet at a distance of 3 pc. All simulations in this figure assume inclination,* $i = 45°$. **(middle)** *Astrometric displacement for a star with a 2* $M_{\rm Earth}$ *planet at a distance of 4 pc .* **(right)** *Astrometric displacement for a star with a 3* $M_{\rm Earth}$ *planet at a distance of 5 pc.*

due to the one-day interval characteristic of earth-based observations. We will develop a procedure to select observation times during the night, as well as during the month and year, to minimize spectral leakage.

All of these analysis innovations hold great promise to improve the reliability and sensitivity of our planetary detection program.

5.2 5–20 $M_{\rm Earth}$ Planets

A subset of our SIM target stars may be identified from weak Doppler periodicities we have detected. Many stars exhibit Doppler periodicities of low amplitude, indicative of planets having masses of ∼10-30 $M_{\rm Earth}$. Some show multiple periods of low amplitude. Most of these low amplitude Doppler periodicities are publishable only as footnotes but not as definitive planets (Cumming et al. 1999). What is the cause of these low amplitude Doppler periodicities? One likely answer is that some represent the tail of Doppler detectability at the lowest planet masses.

We plan to investigate stars that exhibit weak periodicities in Doppler measurements with SIM astrometry. Such Doppler periodicities, with amplitudes of typically 2–5 m s^{-1} , identify stars with a higher probability of harboring 10–30 $M_{\rm Earth}$ planets. Indeed our Doppler detection of two sub–saturn candidates shows the potential to detect sub–Neptune mass planets, albeit marginally. Fourier power analysis of velocities acquired continually at Keck will reveal any periodicities with amplitudes of ∼2 m s^{-1} , corresponding to ∼10 $M_{\rm Earth}$ at 0.5 AU. (A planet of 10 $M_{\rm Earth}$ at 0.5 AU produces a wobble of 1.2 m s^{-1} , just at threshold in power spectra of multiple velocity

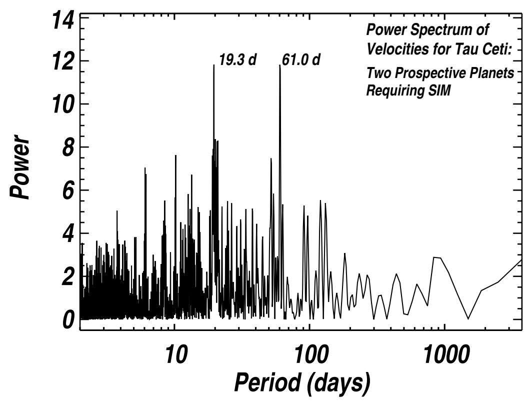

Figure 5: *Power spectrum of the Doppler measurements of Tau Ceti. The two peaks imply orbital periods of 19.3 and 61 d, both of low amplitude (~4 m s^{-1} , corresponding to ~20 $M_{\rm Earth}$.*

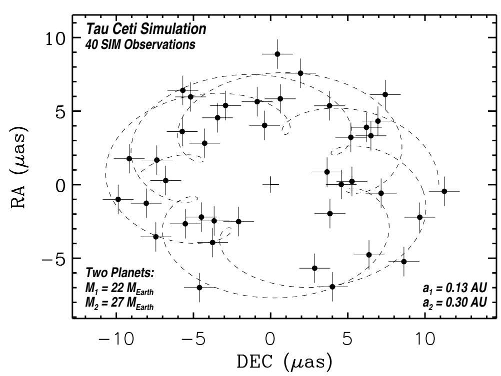

Figure 6: *Simulated SIM observations of Tau Ceti, based on the two prospective low–amplitude Doppler periodicities. With an assumed inclination of 45°, the two planets have absolute masses of 22 and 27 $M_{\rm Earth}$ at 0.13 and 0.30 AU. SIM will detect a confusing astrometric signal due to errors (1 μas errors bars shown). Doppler measurements render this star high priority as a SIM target and resolve the confusion between multiple planets and noise, as periods are known a priori. The Doppler periods set the SIM sampling frequency.*

measurements.) Such 1–σ detections of ~10 $\rm M_{Earth}$ planets from Doppler work are not secure by themselves, but require SIM to verify. **Thus, Doppler periodicities of low amplitude serve to identify stars having a high probability of harboring planetary systems with low–mass planets.**

We are currently monitoring 1,100 nearby FGKM dwarfs with Doppler measurements at precision of 3 m s^{-1} . Several dozen of these stars already reveal Doppler periodicities with amplitudes of 1–5 m s^{-1} , indicating low mass planets that cannot be verified by Doppler measurements alone. One such system is Tau Ceti.

Figure 5 shows the periodogram of the velocities for Tau Ceti, which exhibits two peaks at periods of 19.3 d and 61 d. A two-planet fit suggests velocity amplitudes of 4.0 m s^{-1} and 3.2 m s^{-1} , corresponding to $M \sin i$ of 15 and 19 $\rm M_{Earth}$ respectively. Adopting an inclination of 45° increases the absolute planet masses to 22 and 27 $\rm M_{Earth}$. Neither planet can be verified at such low amplitudes, but SIM would be able to detect them.

Figure 6 shows the expected astrometric results from SIM for Tau Ceti for the two prospective planets implied by the Doppler measurements. Both planets would be detected, assuming SIM errors of 1 μas. However, we note that the Doppler measurements play crucial roles in discovering such planets:

- Doppler measurements serve to identify Tau Ceti as a high–priority SIM target star, with its prospective planetary system.

- The two periods imply the required sampling frequency of SIM measurements.

- Astrometric noise plus a *single* planet could be the Occam's razor explanation for data in Figure 6, were it not for the multiple periods in the Doppler measurements.

- Combining Doppler measurements with SIM tightly constrains the final orbits.

Within the next 3 years, our Doppler measurements of 1,100 stars will have identified 30–50 stars with low–amplitude periodicities, suggestive of 10–30 M_{Earth} planets. We propose that ∼20% of our SIM target stars be drawn from among these Doppler–based prospective planetary systems. This Doppler–selected target sample will constitute a rich mine for planetary systems, and ultimately yielding SIM-based orbital properties and masses.

In addition, SIM target stars that are systematically rich in low–mass planets help ensure success for SIM. Low–mass planets are more likely to be detected around stars that show 1–2σ hints in the Doppler data. Obviously, the Doppler selection mechanism biases the type of planetary systems that will be found, and thus must be post–analyzed for statistical uses. However, Doppler selection enables orbits and masses to be acquired both quickly and securely for planets of ∼10 M_{Earth} , with less time wasted on empty nests.

5.3 True Masses of Known Exoplanets

We propose to use SIM in narrow angle astrometry mode to establish the orbital inclination and to obtain true masses for some carefully chosen stars that have Doppler-detected planets. There are two classes of Doppler–based targets that will be particularly important to investigate:

- Single planets with moderate periods (20–600 d) and which have no evidence for additional planets.

- Multiple planet systems.

The combination of precision radial velocity data with astrometric data is much more powerful than the sum of results from the two techniques independently. Black and Scargle (1982) have shown that when less than 2 orbital periods have been observed, a linear component of the orbital displacement will be absorbed in the proper motion solution. The effect is a spurious reduction in both the amplitude and period of the derived astrometric orbit. In cases where the Doppler observations provide the orbital period, the accuracy of the SIM orbital solution is dramatically improved.

5.3.1 Moderate-Period Planets

Exoplanets with orbital periods less than about a week induce such a small displacement of the stellar photocenter that they are rendered undetectable by SIM. However, there are several stars with Keplerian periods between 40 - 100 d that would have astrometric amplitudes of order 10 μas. With a minimum number of observations, these stars serve as a test of the start-to-finish astrometry data analysis.

A representative target for this initial effort is the star ρCrB. At a distance of 17.4 pc, this star has a planet with $M \sin i$ = 1.0 M_{JUP} in a 0.22 AU orbit (P=39.8 d). The radial velocities for ρCrB are shown in Figure 7. The corresponding astrometric displacements have been modeled with 1 μas Gaussian errors and are plotted in Figure 8. The simulated astrometric data arbitrarily assumes an orbital inclination of 45 degrees. With SIM's 1 μas goal precision, this 10 μas amplitude represents a straightforward detection, obtained in six weeks with sixteen observations. An astrometric orbit for this planet, consistent with the radial velocity data, would provide a quick and powerful confirmation of the end-to-end SIM data product.

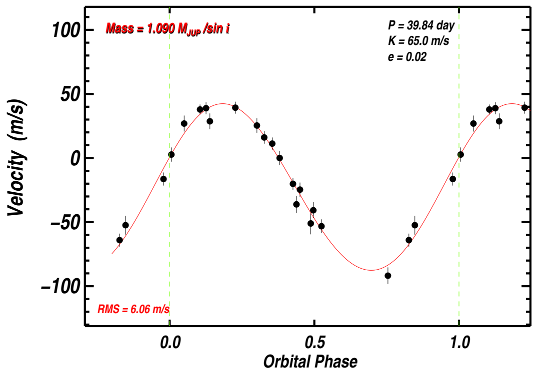

Figure 7: *Phased radial velocity observations for* ρCrB *give the orbital period and eccentricity.*

In addition to demonstrating that SIM is working as advertised, these observations would produce a scientific result of merit. First, by determining the orbital inclination, SIM provides the absolute mass for these planets. Second, with continued, but infrequent sampling over a longer time baseline, SIM would also provide evidence regarding the existence of additional companions at wider separations. Indeed, the origin of the ubiquitous orbital eccentricities found to date may stem from more distant companions, which SIM could detect.

5.3.2 Multiple Planet Systems

In 1999, a triple planet system was detected around the star Upsilon Andromedae (Butler et al. 1999). Figure 9 shows residual radial velocities after subtracting the velocity variations expected for the inner planet, UpsAnd(b). The red line in this plot shows the

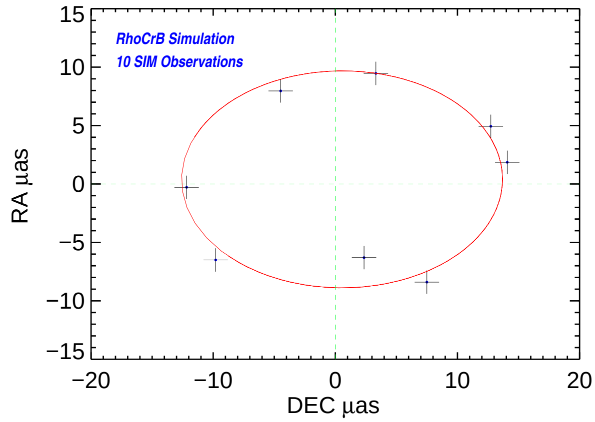

Figure 8: *Modeled astrometric observations of* ρCrB. *The astrometric orbit uses the radial velocity orbital solution and the Hipparcos distance for this star of 17.4 pc. The simulated astrometric data include 1* μas *Gaussian noise and assume the following additional orbital parameters:* $i = 45°$, $\Omega = 180°$, $\omega = 45°$. *The red curve shows the theoretical astrometric orbit for this system. SIM will determine the relative orbital inclinations of the outer two planets, indicating their dynamical history.*

two-Keplerian fit that provided the orbital parameters for the outer planets. Figure 10 shows a simulation of astrometric data. With an angular displacement amplitude of about 2 μas, the innermost planet is invisible in the astrometry data, but the outer two planets have enormous astrometric signatures and would be easily detected. In this mock data set, P, e and ω are taken from the radial velocity parameters, but an arbitrary orbital inclination of 45° is assumed in order to set the absolute masses for UpsAnd(c) and UpsAnd(d) in the astrometric simulation.

The orbital dynamics for this 3-planet system have been intensely investigated with theoretical simulations (Bodenheimer et al. 2000, Rivera & Lissauer 2000, Laughlin & Adams 1999). These simulations demon-

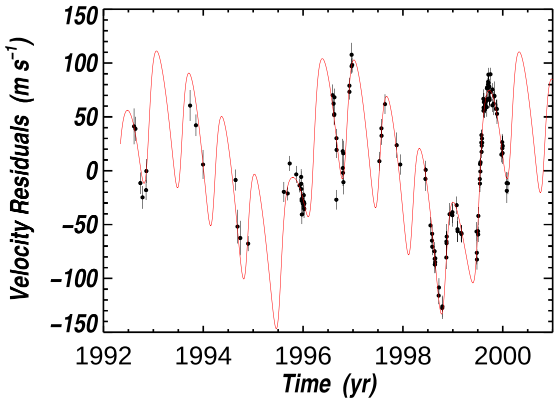

Figure 9: *Radial velocity for Upsilon Andromedae. High frequency velocity variations arising from the inner planet have been subtracted from the data to make it easier to see the remaining two long-period trends. The red line shows the 2-planet Keplerian fit to these residual velocities.*

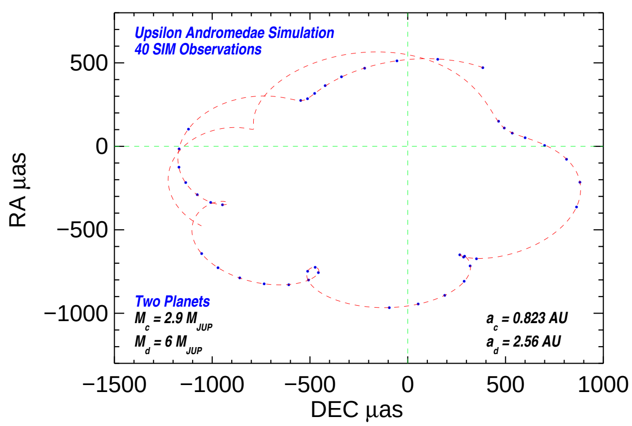

Figure 10: *Simulated astrometric observations using parameters from the Doppler observations and the Hipparcos distance of 13.5 pc. The simulated astrometric data include 1 μas Gaussian noise and assume the following additional orbital parameters: $i = 45°$, $\Omega = 180°$, $\omega = 45°$. The red curve shows the theoretical astrometric orbit for this system.*

strate islands of orbital stability that set upper limits to the mass, and therefore the inclination of the planets. However, non-coplanarity is allowed by these simulations and may even be likely if gravitational scattering caused the eccentric orbits of the two outer planets. **SIM can easily determine the orbital inclinations for each of the two outer planets, and their degree of coplanarity establishes the role of past gravitational scattering in this enigmatic planetary system.**

One of the most profound results to emerge from Upsilon Andromedae is its *dynamical saturation.* An earth-mass test particle within 5 AU is unstable and quickly dynamically ejected. This phenomenon of dynamical saturation also applies to our own solar system. The importance is that we are virtually guaranteed that Upsilon Andromedae contains only the three known planets within 5 AU, thus constituting an exquisite test of SIM. The SIM results must reproduce the known orbits, with no additional parameters.

How common are multiple systems? *In our velocity sample, more than one third of the stars with known planets and a sufficient time baseline of data, show secondary velocity trends.* In many cases, these secondary trends show curvature and we are waiting until a full orbit is completed to derive the orbital elements and announce the additional multiple systems.

Multiple planet systems are architecturally fascinating. But if (as evidenced from the Doppler data) they predominate in nature, multiple systems will present a tremendous challenge to modeling astrometric orbits. Some hard questions will arise if most of the astrometric orbital solutions show significant jitter above and beyond the assessed astrometric errors. It will then be critical to assess the source of this jitter.

Does it arise from absorbed motion of the astrometric reference stars? From systematic errors in the astrometry? From low amplitude signals originating from multiple planets in the astrometric detectability zone? We propose to observe stars like Upsilon Andromedae, which on dynamical grounds, are likely to be free of additional perturbing planets in the astrometric detectability zone. *These stars will serve as a control sample to help us to evaluate sources of astrometric jitter that are bound to creep into the data.*

6 Technical issues

SIM observing time will be limited and the mission lifetime finite. It is imperative that we extract the most science out of the fewest number of observations. Likewise, the proposed science investigations should be uniquely suited for SIM, rather than tractable projects for ground-based astrometry. We propose to divide our allocation of SIM observing time among 4 science projects:

- search for terrestrial planets around ten stars closer than 5 pc
- search for 5–30 $M_{\rm Earth}$ planets around an enriched sample of ten stars provided by periodogram analysis of Doppler data
- search for additional planets around twenty stars that only have one detected planet, despite intense scrutiny with Doppler observations
- determine orbital inclination for individual components of about ten multiple systems to determine coplanarity of the orbits and provide empirical evidence for theories of planet formation.

6.1 Ground-Based Preparatory Work

6.1.1 Science Targets

The 50 proposed science targets will require extensive ground-based work to ensure the most efficient use of SIM time. We will:

- carry out 10 years of the highest precision Doppler observations for potential science target stars. These stars will have the best information regarding the presence of companions. We will monitor Ca H&K lines for chromospheric activity and carry out abundance analysis. To meet these goals, we will observe these stars more often and with higher than normal S/N. This process of target identification can be absorbed into our ongoing program with no additional cost to SIM.
- carry out photometric monitoring of all potential science targets to reject variable stars
- observe all target stars with AO to look for faint companions

6.1.2 Reference Stars

The 50 science targets will require ground based identification of 4–6 stable narrow angle reference stars. The process for identifying these reference stars is outlined in Section 3.5. We expect to begin with ≈ 10 candidate reference stars for each science star. We will quickly filter this sample of about 500 stars using narrow band photometry and available parallax's to identify the K giants. Next, we will use spectroscopy and AO to eliminate binary stars.

Most stellar binaries can be eliminated with just two observations. The proxy study of K giants sets the astrophysically attainable Doppler precision to 20 m s^{-1} . However, this is much higher precision than is needed to identify stellar companions. We will use an initial Doppler precision of 50 m s^{-1} to speed up identification of stellar binaries. This first filter can be done at Lick and other 3m class telescopes like the AAT.

The total number of spectra that we will need are estimated in Table 1. We can obtain velocity precision of 50 m s^{-1} in 5-10 minutes with the Lick 3m telescope and can obtain about 60 observations per night. We would request 5 nights per semester, or 10 nights per year at Lick. Expecting 7 clear nights, we could obtain 420 spectra per year or 2100 spectra over 5 years. At Keck, the observations would be one minute long and about 200 observations could be made in one night. Thus, the first phase of identifying single reference stars could be carried out largely at Lick, supplemented with a few nights per year at another 3m class telescope like the AAT in the southern hemisphere. For the final two years, 2–3 Keck nights per year would be sufficient to continue monitoring the best reference stars at higher velocity precision.

6.2 SIM Observing Time Requirements

We have outlined a Key Science project that is ambitious in its scientific goals but technically within our reach. The research projects we have described are designed to take advantage of the 1 μas precision that SIM will offer. If SIM performs at less than 1 μas precision, we have inherent flexibility to use these targets or select new targets that will accommodate the ultimate operating precision of SIM.

We will deliver a set of astrometrically stable reference stars to accompany the best 50 targets in our high precision Doppler project. We are proposing to use SIM time to observe a set of extremely well-studied targets to insure low-risk, solid scientific results for SIM. Our estimate for the amount of SIM time required totals 2900 hours, somewhat in excess of the 2500 hours a Key Project can expect to receive. We will use a very surgical approach that provides an adequate, but not excessive number of data points to extract the expected low amplitude signals and find low mass planets.

6.2.1 Terrestrial Planets

During each pointing of SIM, 10 sets of target and reference star observations will be obtained in one hour. Each observation has a single measurement error of 3 μas; 10 observations per pointing reduces the error to 1 μas. The search for terrestrial planets around ten of the closest stars will be extremely demanding. We expect this effort will require a minimum of 10 observations per year. Because orthogonal positions must be obtained in two pointings, this translates to 20 pointings per year or a total of about 1000 hours of SIM time.

6.2.2 5–10 M_{Earth} Planets

The Doppler sample will also provide a set of 30–50 stars with extremely low amplitude signals evident in the periodogram. The expected astrometric amplitude depends on the period. We will select the 10 best candidates to observe with SIM. The number of observations depends on the expected amplitude, but we expect that generally, about 6 observations per year will be needed, so this project will require about 600 hours of SIM time.

Table 1: Estimated Total Number of Spectra Required

Year 1	500 stars × 1 obs	(drop sb2's, some M dwarfs)
	450 stars × 1 obs	(eliminate most stellar companions)
Year 2	300 stars × 2 obs	(reject stars with high rms scatter)
Year 3	250 stars × 2 obs	(drop low amplitude SB's, high rms stars)
Year 4	220 stars × 2 obs	(maintain monitoring)
Year 5	220 stars × 2 obs	
5-year total:	2,930 observations	

6.2.3 Absolute masses

Those stars with one known planet will be observed to resolve the orbital inclination. The Doppler observations provide orbital period and eccentricity, reducing the number of free parameters and therefore the number of SIM observations. These systems are expected to show large astrometric amplitudes, so in principle fewer observations per year are required. The orbital period of the known planet will set the frequency and duration of the initial observations, but we expect 4 astrometric positions will be required for each of these 20 targets per year. This project would require about 800 hours of SIM time.

6.2.4 Multiple Planet Systems

We would like to choose the 10 best multiple systems from our sample and use SIM to resolve orbital inclination and establish coplanarity of the orbits. Stars with more than one planet obviously have many more free parameters and require a significant amount of data to model robustly. The constraints on the number and characteristics of possible planets will come from Doppler observations and dynamical arguments. We estimate that about 5 data points will be needed each year for a total of 500 hours of SIM time.

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Appendices