SIM PlanetQuest:

A Mission for Astrophysics and Planet-Finding

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ABSTRACT

SIM PlanetQuest will exploit the classical measuring tool of astrometry with unprecedented precision to make dramatic advances in many areas of astronomy and astrophysics. Of particular importance to NASA's goal of searching for habitable planets will be SIM's surveys of the closest ~100 stars for planets of a few earth-masses to identify potential Earth analogs and determine their mass and orbital properties. SIM will also survey a few thousand stars of a much wider variety of ages, spectral types, and other properties than is possible with radial velocity studies to build up a complete understanding of the formation, evolution, and architecture of planetary systems generally. But the scientific return from SIM is far broader than searching for planets and will include improving our understanding of the physical properties of stars, determining the mass, including the dark matter component, and its distribution in our Galaxy, observing the motions of the Milky Way’s companions in the Local Group, and probing the behavior of supermassive black holes in other galaxies. More than half of the assigned SIM time has been allocated to astrophysics questions. A substantial share of time remains open for future assignment.

It is the sum total of these and other scientific capabilities that led the 1990 and 2000 NRC Decadal Reports to endorse SIM as an important part of the nation's program in astronomy and astrophysics. The scientific capabilities explicitly called for by the 2000 Decadal Report were ". . . [enabling] the *discovery of planets much more similar to Earth in mass and orbit* than those detectable now, and . . . [permitting] astronomers to *survey the Milky Way Galaxy 1,000 times more accurately* than is possible now." The report emphasized the "particular attraction" of the dual capability of the new SIM.

SIM PlanetQuest will address:

- Astrometric search for brown dwarfs, massive planets, and terrestrial planets around nearby stars
- Search for newly-formed planets around young stars
- Masses and evolution of stars in close binary systems
- Accurate masses for low-mass binary stars
- Astrometric signatures of MACHO microlensing events
- Internal dynamics and ages of globular clusters
- Mass distribution in the halo of our Galaxy and its spiral structure
- Dynamics of our Local Group of galaxies including dwarf spheroidal galaxies and tidal tails
- Proper motions of nearby active galactic nuclei and the question of binary black holes
- Calibration of several components of the cosmic distance ‘ladder’

The SIM PlanetQuest design features:

- A science interferometer with 9 meter baseline
- Two guide interferometers with 7.2 meter baselines
- Optics with 325 cm^2 collecting area
- Operational limiting magnitude down to 20 at 20 μas
- Terrestrial planet-finding astrometric accuracy of 1.12 μas (single measurement)
- Global astrometric grid accuracy of 3.47 μas

In both astrophysics and planet-finding, SIM PlanetQuest is certain to provide new discoveries, refine astrophysical quantities, and re-write textbooks.

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1 Introduction

SIM PlanetQuest will exploit the classical measuring tool of astrometry with unprecedented precision to make dramatic advances in many areas of astronomy and astrophysics. Of particular importance to NASA's goal of searching for habitable planets will be SIM's surveys of the closest ~100 stars for planets of a few earth-masses to identify potential Earth analogs and determine their mass and orbital properties. SIM will also survey a few thousand stars of a much wider variety of ages, spectral types, and other properties than is possible with radial velocity studies to build up a complete understanding of the formation, evolution, and architecture of planetary systems generally. But the scientific return from SIM is far broader than searching for planets and will include improving our understanding of the physical properties of stars, determining the mass and its distribution in our Galaxy, observing the motions of the Milky Way's companions in the Local Group, and probing the behavior of supermassive black holes in other galaxies. More than half of the assigned SIM time has been allocated to astrophysics questions. A substantial share of time remains open for future assignment. It is the sum total of these and other scientific capabilities that led the 1990 and 2000 NRC Decadal Reports to endorse SIM as an important part of the nation's program in astronomy and astrophysics.

In early 2005, NASA directed the SIM Project to propose a rescoped mission to meet a revised cost-cap. This white paper describes the science capabilities and plans of the updated SIM PlanetQuest.

1.1 The Genesis of SIM PlanetQuest

SIM Planetquest has not developed in a simple, linear fashion from conception to realization. The precursor to the Space Interferometry Mission (SIM) was the Astrometric Interferometry Mission (AIM) which was a new moderate-class mission recommended by the 1990 Decadal Report (the "Bahcall Report"). The science case for AIM was built around astrophysical studies of star, the Galaxy, and the Local Group; planet detection was a significant but hardly dominant component of the program.

While NASA was developing key SIM technology and developing various mission concepts, the discovery of exo-planets dramatically changed the astrometric and scientific landscape. Detections of new planetary systems by radial velocity and other techniques gave a powerful boost to the goal of finding exo-planets via astrometry and attracted the attention of the general public. At the same time, the success of ESA's Hipparcos mission highlighted the power of precision astrometry possible only with a space mission for many other areas in astronomy and astrophysics. A field traditionally practiced by a few specialists grew rapidly to involve broader scientific communities.

The 2000 Decadal Report (the "McKee-Taylor Report") gave space interferometry high priority and highlighted the potential of finding and studying exo-planets, especially habitable planets.

The SIM PlanetQuest observatory under development today is a product of both the astrophysical and the exo-planet heritages. Several mission redesigns, most recently in 2005, have trimmed extraneous features (demonstration of nulling for future planet finding missions and extensive sparse aperture imaging) and reduced complexity. Yet SIM PlanetQuest will still carry out the exo-planet and astrophysical programs which gained it the endorsement of two consecutive decadal reviews. As described below, the Key Science program selected by peer review in 2001 includes both astrophysics (61%) and planet finding (39%), together occupying ~55% of the available science time. There remains ample SIM time for additional key projects and a vigorous GO science program.

In this overview we examine the search for planets and general astrophysics programs. In Section IV we give more detailed summaries of each of the approved Key Projects.

1.2 Reconnaissance of Nearby Planetary Systems

SIM's science return in the area of detection and characterization of planetary systems will dramatically advance our understanding of planetary systems and our search for nearby, habitable planets. SIM will:

- Exhaustively search the nearest ~75 stars for planets more massive than ~2 M_{Earth}
- Survey several thousand stars for Neptune-size and larger planets in orbits out to 10 AU
- Enumerate the planets in multi-planet systems
- Determine the orbits, including eccentricity and inclination
- Determine unambiguously masses of planets, perhaps the most fundamental property governing the evolution and fate of a planet

SIM will carry out a two-part planet survey: 1) a broad, shallow search for planets down to Neptune's mass around 2000 stars, with an expected yield of 600-1000 planet detections; 2) a narrow, deep search of the nearest 50-100 stars for planets of terrestrial mass. The number of planets that will be found cannot yet be confidently predicted, but the yield will be better determined and the search strategy further optimized as η_{Earth} is constrained by transit results from Corot and Kepler. SIM's measurements complement radial velocity searches since planets on long period orbits have larger astrometric signatures compared with smaller velocity amplitudes. For the nearby stars searched intensively, SIM will provide an exhaustive identification of planets above the detection limit (few M_{Earth}) and of periods short enough to measure during the mission length. Planets that SIM finds, or even planets that show a strong sign of a planet (3-4 sigma) are prime candidates for TPF. SIM provides an "enriched target list for TPF-C", the enrichment fact, slightly less than ~3, is mostly independent of $\eta_{Earth.}$

If radial velocity results are a reliable guide, then the detection of multiple planets in systems is to be expected. Any planets detected by SIM that do not have a radial velocity signature are sure to be interesting. Comparative study of exo-systems, critical to understanding the existence of habitable planets and the history of our own system, will gain a strong observational base.

The complete orbital characterization available from SIM will provide eccentricities, inclinations and masses, hence all of the critical information required to identify Earth-mass planets with stable orbits in the habitable zone - candidate habitable planets deserving further study by direct detection.

A second key project will study giant planets orbiting young stars. It involves a study of the role of planets in the evolution of stellar accretion disks, evolution and dispersal. The program will observe 200 nearby young, solar-type stars and will explore the early evolution of planetary systems, including planet interactions and migration.

1.3 Astrophysics with SIM PlanetQuest

SIM will extend the power of astrometry to unprecedented distances. In stellar studies, the precise determination of mass, luminosity and effective temperature will force a revolutionary confrontation between observation and the physics underlying stellar structure and evolution. Direct parallax measurement will offer a direct means to study the distribution of visible and dark matter in the Milky Way. Proper motions of stars in Local Group galaxies will build a deep understanding of each galaxy's internal motions and of the cluster dynamics.

As described in more detail in Section IV, the already selected Key Projects will investigate the following areas of astrophysics:

- The mass distribution of the Milky Way, including its dark matter
- The mass function of dark lensing objects
- The presence of supermassive black holes in the cores of galaxies
- Origin of AGN and Quasar compact optical emission
- Total mass measurements of Local Group galaxies
- Precise distances to standard candles and a 1% extragalactic distance scale
- Black hole and neutron star masses
- Globular cluster distances and ages

1.4 The Relation of SIM PlanetQuest to Other Planet Finding Missions

While SIM will create its own unique and important dataset on planets, SIM has potential additional strengths when considered in relation to the Terrestrial Planet Finder (TPF) missions. The characterization of candidate habitable planets will require critical and irreplaceable input from all three: masses and orbits from SIM (radius, internal composition, surface gravity, temperature variability), visible reflected spectrum from TPF-C (Coronagraph; thermal input, clouds, atmosphere, surface composition, biomarkers), and thermal emission spectrum from TPF-I (Interferometer; temperature, radius, energy output, atmosphere, biomarkers). Derived properties such as albedo and density as well as confirmation of habitability (or of life itself!) will come from various combinations of the data from all three missions.

If we have learned anything from the diverse and continually surprising field of planetology, it is our inability to foresee the variety of our nearby planetary neighbors. In comparative planetology, theory is a poor guide when it builds on a sample of just 9 planets. Exo-planetology is and will be an observation-driven science. At the completion of the SIM mission, our knowledge of planetary system statistics over a broad range of mass and orbital radius, around a broad range of stellar types, will be an observational result rather than the extrapolation and guesswork of today.

In favorable cases, TPF-C will have the capability to detect planets of radius 1 R_{Earth} or less. With the knowledge of such a planet in hand from TPF-C, data from SIM can be processed to measure the masses of these planets with an error of order 0.3 M_{Earth} . This combination of mission datasets will provide mass measurements at the 1 M_{Earth} level and, hence, offers the prospect of confidently identifying true Earth analogs.

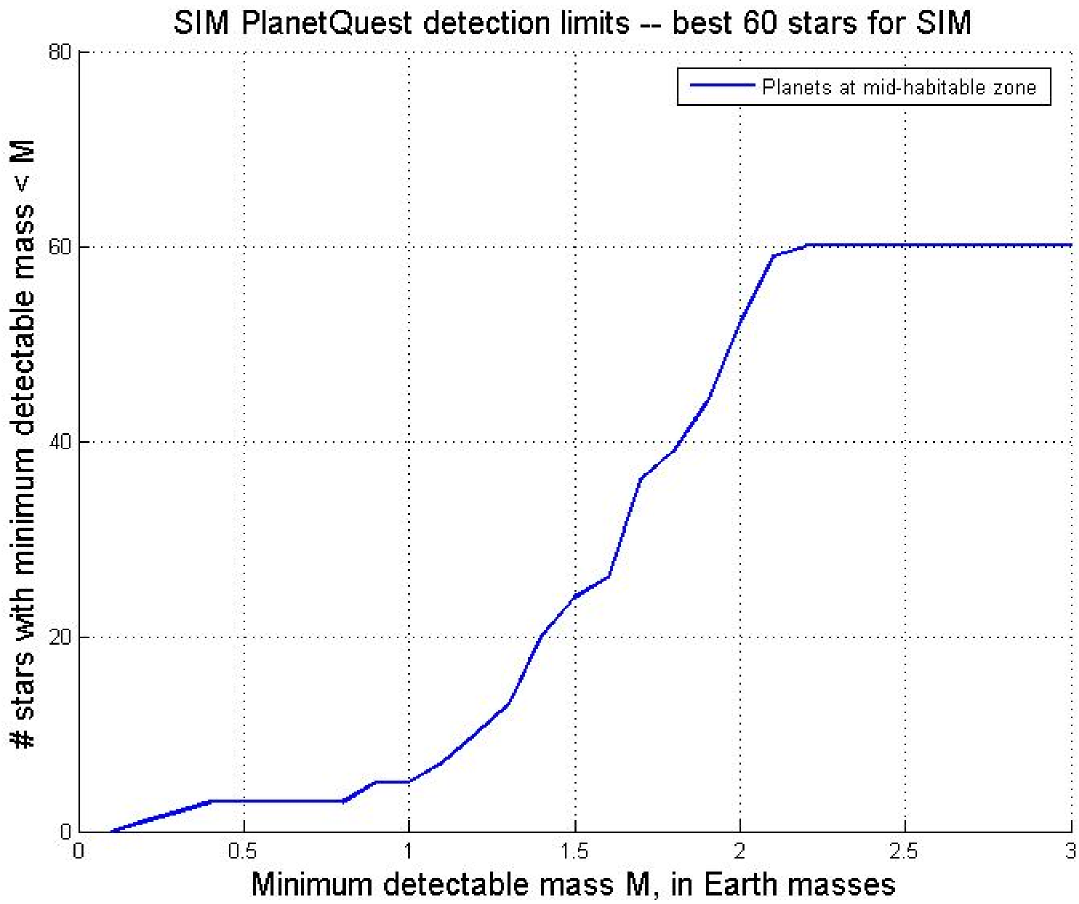

Figure 1. SIM capability for finding terrestrial planets. This is a plot of the number of stars vs. minimum mass for a planet in the middle of the habitable zone of the 60 best nearby stars for the SIM mission. This hypothetical observing program would concentrate ~17% of SIM time on these 60 stars. Minimum detectable mass is defined as a planet of a given mass whose astrometric signature is bigger than the threshold set for a 1% false alarm probability.

The Strategic Roadmap Committee studying the Search for Earthlike Planets (SRM#4) has investigated mission inter-relationships in broad overview, identifying various possible branch points depending on the success or failure of a mission, or the possible expected or unexpected science return. SIM's thorough survey of our nearest stellar neighbors will profoundly inform the selection of targets for TPF, both from the standpoint of what stars to focus on, e.g. those with definite evidence for or hints of low mass planets in the habitable zone, or those to avoid, e.g. those with gas giant or icy planets in the habitable zone.

1.5 The Relation of SIM PlanetQuest to Other Astrometry Missions

Other past or planned astrometry missions – Hipparcos, GAIA and their relatives - are survey missions which spend the same amount of time observing each unit solid angle of the sky, without respect to whether or not it is of interest. Only SIM, as a pointed mission, can carry out the on-target integrations required to obtain microarcsecond relative astrometry of bright sources, and few microarcsecond global astrometry of faint sources. Only SIM has the capability to detect Earth-mass planets, and only SIM can execute a broad range of faint-source astrophysics, such as measuring the space motions of a large selection of Local Group galaxies. A detailed comparison with GAIA is given in Section VI.

1.6 Technology Benefits From SIM

SIM will put into space for the first time a precision, long baseline optical interferometer. By demonstrating optical interferometry, SIM will break the linkage between resolving power and aperture in a manner that will lead the way for future space interferometers from infrared wavelengths to X-rays. SIM will demonstrate techniques for stabilization of structures at the nanometer level and the measurement of components of structural stability to the levels of tens of picometers. These capabilities are critical for future missions requiring precision wavelength control.

SIM's technology development is important to NASA's strategic planning for the long term. The technologies needed by SIM that have been developed in parallel with the flight design are also critical to the next generation of space-based telescopes. Dilute-aperture instruments are being studied for several future missions for extrasolar planet research, star and galaxy formation and evolution, exotic energetic objects, and early universe studies. Precision structures to carry optics, and control systems for their alignment, are being developed for SIM, but are needed for all these interferometric systems.

SIM is a pathfinder in other ways too: much of the technology and expertise developed at JPL for precision metrology, and in alignment, calibration, and thermal control of precision optics, is directly applicable to the Terrestrial Planet Finder Coronagraph (TPF-C) mission. Even though TPF-C will use a monolithic mirror as its primary optic, the telescope design as a precision system relies heavily on the technology and expertise which were developed in the SIM testbeds, and are now being applied to the flight design.

1.7 Conclusion

SIM PlanetQuest will permit a dramatic leap in our understanding of many processes in astrophysics. We will learn about the prevalence and variants of planetary systems, the masses of stars and related, extreme stars, the ages and motions of star clusters, the mass and distribution of dark matter in the Galaxy, and the behavior of the Local Group as driven by dark matter. SIM offers unique capabilities for astronomy that will not be easily replicated in any other mission.

2 Mission Description

2.1 SIM PlanetQuest Performance

In early April, 2005, the project developed a new mission design to address cost and mass issues that had arisen in the course of its formulation phase during the past 3 years. This section describes the performance that can be achieved with the new design.

The major descope that the project undertook to reduce cost, mass, and risk were to reduce baseline length from 10 to 9 meters and to reduce the photon collecting area of the instrument by ~50%, from 650 cm^2 to 325 cm^2. A backup science interferometer was also removed but this has no direct impact on performance. Although in upcoming design iterations some of the baseline length and some of the collecting aperture may be recoverable, the performance numbers refer to a design (denoted IA) with the reduced baseline and collecting area. Table 1 provides the measurement capabilities of the descoped SIM for various modes.

Scenario	Target Brightness	Observation Period	Requirement
Planet-Finding	6 mag	Single visit, 1000 s/visit	1.12 μas
Legacy Narrow Angle	10 mag	Single visit, 1000 s/visit	1.48 μas
Narrow Angle (faint)	13 mag	Single visit, 1000 s/visit	3.24 μas
Grid Stars	10.6 mag	5 year mission accuracy	3.47 μas
Legacy Wide Angle	18 mag	5 year mission accuracy	5.38 μas
Wide Angle	19 mag	Single visit, 2000 s	41 μas
2000 Decadal Review			***Floor***
Narrow Angle			3 μas
Wide Angle			10 μas

For observations of bright stars, e.g. ~7 mag stars for planet search and the stars that make up the reference grid, the reduction in accuracy is due mainly to the reduction in baseline from 10 m to 9 m, an increase of ~10% in astrometric error. For faint objects, there is an additional ~√(2) increase in error because of the 50% reduction in collecting area. While the reductions in performance are real, the SIM Science Team has endorsed the new design (Appendix 1, letter to Anne Kinney dated, 3/18/2005).

3 Observing With SIM

3.1 Allocation of Observing time

The SIM Science Team was selected via a NASA Announcement of Opportunity (AO), in November 2000. The Team comprises the Principal Investigators of ten Key Projects and five Mission Scientists contributing their expertise to specific areas of the mission. Their science programs cover a wide range of topics in Galactic and extragalactic astronomy. Besides the planet searches mentioned above, they include: the formation and dynamics of our Galaxy, calibration of the cosmic distance scale, and fundamental stellar astrophysics. All of the science observing on SIM is competitively awarded; the present Science Team programs total about 36% of the total mission time available, and the remainder will be assigned via future NASA competitions. More than 61% of the time assigned so far has been allocated to general astrophysics (Figure 2).

The pie chart in Figure 2 shows the allocation of SIM time for the baseline 5-year mission. Within the selected program of Key Projects, the distribution of observing time between the various Key Projects is summarized there. Planet finding programs together take up 38% of the presently allocated time and more general astrophysics programs take up 62% of the allocated time. The available time comfortably completes the revised key projects in both planet search and astrophysics.

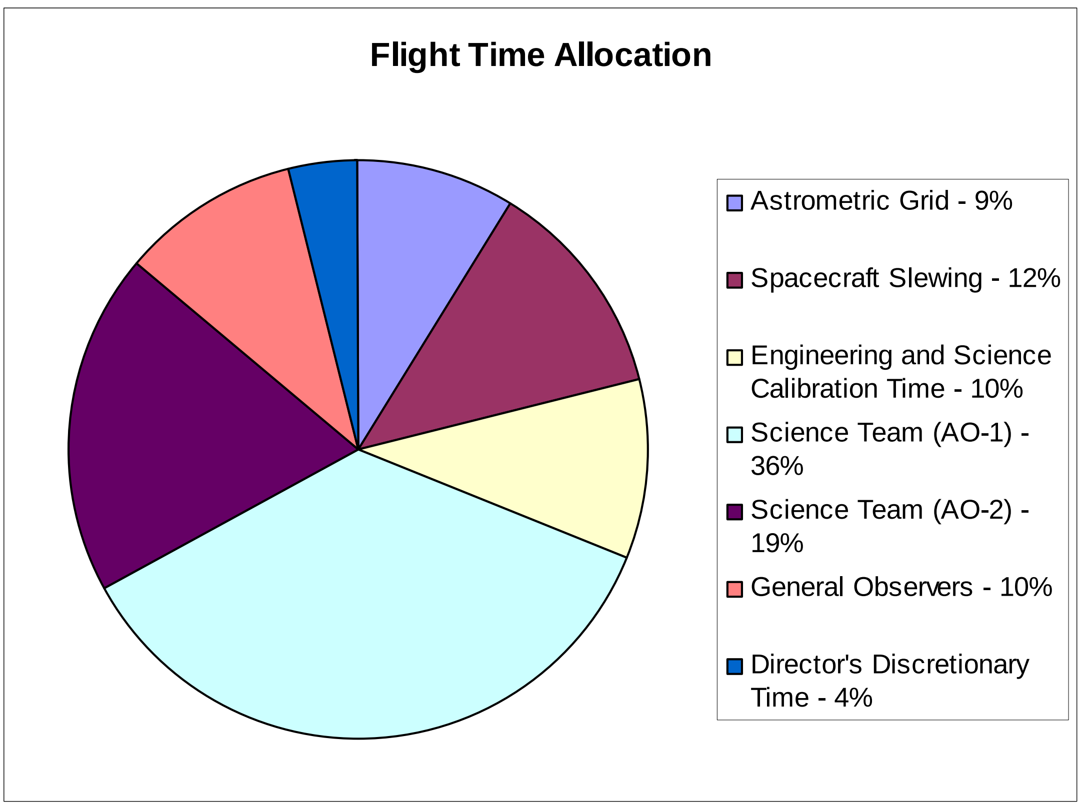

Figure 2. The pie-chart shows the total distribution of observing time on SIM and includes both the existing program (AO-1) plus time for projects to be selected via future calls for proposals.

SIM is designed with an expendables-life of at least 10 years, to leave open the option of a longer mission. Under a 10-year mission scenario, there would be the possibility of entertaining many additional projects, greatly increased GO time, further improvements in the grid, and benefits including improvements to the orbit determinations, proper motions, and parallaxes.

Several types of measurements would greatly benefit from a 10 yr mission, in some cases far beyond a nominal factor of two. Terrestrial planets discovered by SIM (or potential discoveries, 4 sigma) and confirmed by TPF would receive in depth scrutiny to obtain accurate orbits and masses. In general, proper motion measurements would improve by $T^{1.5}$ and non-linear motion of a star, an indicator of a long period companion would be more sensitive by $T^{2.5}$, a factor of ~5.6.

Mission Duration	**Position Accuracy**	**Parallax Accuracy**	**Proper Motion Accuracy**	**Acceleration Knowledge***
5 Years	3.47 μas	3.81 μas	2.4 μas/yr	0.46 μas/yr^2
10 Years	2.46 μas	2.70 μas	0.85 μas/yr	0.082 μas/yr^2

* Non-zero acceleration is an indicator of a long-period planet.

The following two science sections, on Planetary Science and Astrophysics, are based on only the accepted AO-1 key projects. A second AO and a call for General Observer projects will be made over the next 2 - 3 years (Section III.C).

3.2 Summary of the Approved Program

In its wide-angle astrometric mode, SIM will yield 4.4 μas absolute position and parallax measurements. Astrometric planet searches will be done in a narrow-angle mode, with an accuracy of 1.44 μas or better in a single measurement. SIM will define a new astrometric reference frame, using a grid of approximately 1304 stars with positions accurate to 4.4 μas. As a pointed rather than a survey instrument, SIM will maintain its astrometric accuracy down to the faintest magnitudes, opening up the opportunity for astrometry of active galactic nuclei to better than 10 μas.

The masses of stars will be determined to unprecedented precision by several of the selected AO-1 projects. Mass measurements will span the range from substellar (even planetary) masses through the H-R diagram to the most massive stars and exotic objects such as neutron stars and black holes. SIM measurements will address the mass question via direct measurements of the orbits of binaries (using the precision being used by the planet searches) for a variety of stars spanning the H-R diagram in spectral type, evolutionary age, and metallicity. Exotic objects will yield their secrets in this manner as well. Gravitational microlensing measurements permit the determination of the masses of individual objects as well as providing a column density of such objects in the search direction.

Astrometric measurements of the distances of distance scale standard candles and the motions of stars in open and globular clusters yield valuable information. Parallaxes of standard candles will tie down distances to a wide range of Population II objects, including clusters and the Milky Way's halo. The ages of clusters are tied to their populations, and the dynamics of clusters can be characterized with SIM. Are the Milky Way's globular clusters the sources of the metals observed in later stellar populations?

SIM will be a unique tool for studying the nature of dark matter, which dominates the mass of the Milky Way and the Universe as a whole. SIM will map the gravitational potential of the Milky Way's dark halo, using the motions of individual stars, star clusters, and dwarf galaxies to pin down the halo's total mass, spatial extent, radial profile, and three-dimensional shape. The distant tidal streams emanating from dwarf spheroidal satellites and globular clusters will provide especially powerful constraints on departures from spherical symmetry and the presence of substructure, both of which tend to thicken the streams as they spread away from their source.

Other extragalactic measurements are planned as well. The photocenters of active galactic nuclei (AGN) and quasars can be studied in exquisite detail. What is the source of AGN optical emission? How does the radio emission behave in comparison to the optical emission, and how does that affect the reference frame tie? Do binary, supermassive black holes exist from galaxy mergers? For how long?

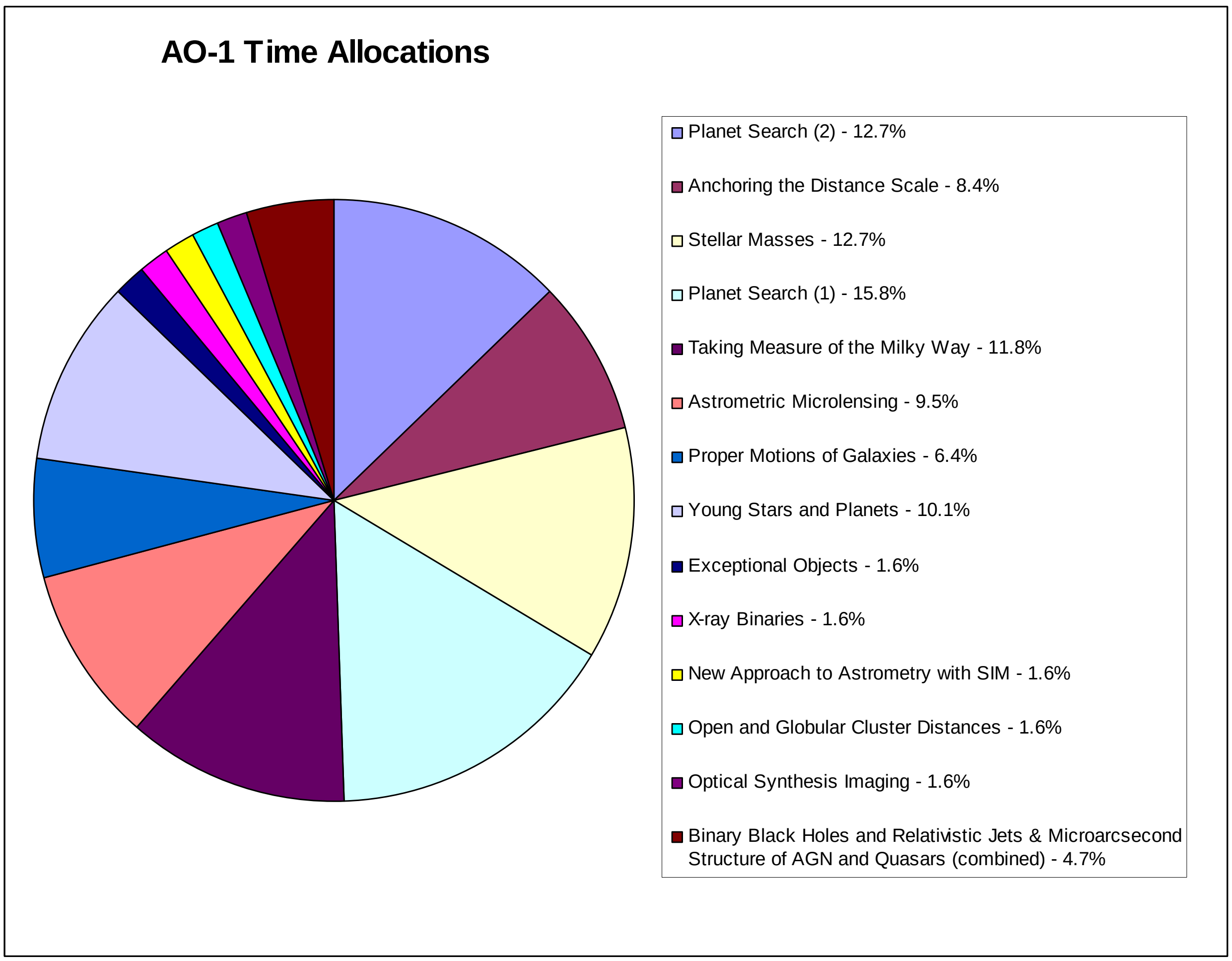

Figure 3. Within the time allocated through the first Announcement of Opportunity (AO-1), a wide variety of science programs, including planet finding and general astrophysics, are planned.

The optical tie with the radio-measured International Celestial Reference Frame requires SIM measurements for completeness. The quasar studies mentioned above have bearing on this problem. Other sources used for the frame tie, including asymptotic giant branch stars and others will be studied to better understand their radio emission sources and their relationship to their optical sources

SIM PlanetQuest will also demonstrate new methods of investigation. High precision astrometry without the benefit of a background grid will utilize SIM's interferometer in a number of fields. Optical synthesis imaging will utilize SIM's science *and* guide interferometers to make multiple measurements of selected sources and then apply the techniques perfected by radio astronomers to construct an exquisitely detailed image.

3.3 Potential for Future Science Investigations

3.3.1 Additional Key Projects

While the power of SIM is well-illustrated by the approved programs, the potential with SIM is far from exhausted. Two examples, at extremes of distance, include the rotational parallaxes of nearby spiral galaxies and general relativistic effects due to the Sun and planets. Rotational parallax measurements involve the determination of the proper motions of sets of stars in intermediate to late-type spirals. These data, combined with ground based spectral data, permit the determination of distances to accuracy of a few percent and with complete independence from luminosity-based distance indicators (and thus providing a means for further calibrating the latter).

There are many areas of galactic astronomy where SIM offers potential break-through measurements. The capability of SIM to measure distances and hence absolute luminosities of sources anywhere in the galaxy can be extended to study of countless rare and poorly understood types and evolutionary stages of stars, systems and phenomena. The field of binary stars offers a rich range of opportunities for programs to better understand their dynamics and evolution.

3.3.2 General Observer Opportunities

A call for General Observer proposals will be issued by the Michelson Science Center (MSC) for science investigations requiring microarcsecond astrometry. The MSC will assist observers with experiment planning and will deliver standard astrometric products: e.g., positions, proper motions, and parallaxes.

Selected GO proposals may receive funding for target selection before launch, and all will receive support for analysis and publication of SIM PlanetQuest data and results.

GO proposals will fall into the "Small" or "Medium" categories to observe either a modest number of at full SIM precision or in a 'Snapshot Mode' that will be optimized for efficient measurement of parallax and proper motion or binary orbits, etc. Typical parameters for Snapshot Mode might be, position ~10 µas (1-sigma), parallax ~15 µas, and proper motion (for a 2-year baseline) ~17 µas for objects brighter than 16 mag.

4 Details of the Approved Key Projects

The SIM Science Team was selected via a NASA Announcement of Opportunity, in November 2000. The Team comprises the Principal Investigators of ten Key Projects, and five Mission Scientists contributing their expertise to specific areas of the mission. Their science programs cover a wide range of topics in Galactic and extragalactic astronomy. They include: searches for low-mass planets - including analogs to our own solar system - the formation and dynamics of our Galaxy, calibration of the cosmic distance scale, and fundamental stellar astrophysics. Copies of the proposals can be found at http://planetquest.jpl.nasa.gov/SIM/sim_team.html .

All of the science observing on SIM is competitively awarded; the Science Team programs total about 36% of the total available, and the remainder will be assigned via future NASA competitions.

4.1 Young Stars and Planets

The SIM PlanetQuest Young Stars and Planets Project (Charles A. Beichman, P. I.) will investigate the frequency of giant planet formation and the early dynamical history of young stars. Its goal is to understand how the diverse architectures of our own and other planetary systems had their origins in the formation processes of cloud collapse, disk formation and accretion, planet formation and migration, and disk dispersal. By detecting Jupiter-mass planets orbiting young stars in the critical orbital range of 1 to 5 AU, this investigation will develop a dataset for comparison with the planetary systems found around mature stars discovered with other SIM Key Projects, and with planets in distant orbits (50-100 AU) found around young stars (<10 Myr) through AO imaging.

The bulk of this program is a planet search around 200 of the nearest (<150 parsecs [pc]) and youngest (0.5-100 Myr) solar-type stars. This investigation expects to find at least between 20 and 50 previously unknown planetary systems. Only astrometry with SIM can find these planets because a) photospheric oscillations limit radial velocity measurements to ~100 times worse sensitivity than for mature stars; and b) the great distance to these stars (25-150 pc) makes direct imaging of the inner solar system (<5AU or 30 milliarcsec at Taurus) impossible even for advanced AO systems.

Among the questions addressed are:

- *What is the incidence of gas giant planets around young, solar-mass stars in the orbital range 1 AU to 5 AU? When and where do gas giant planets form?* By searching for planets around ~200 pre-main sequence stars carefully selected to span an age range from 0.5 to 100 million years, SIM will learn at what epoch and with what frequency giant planets are found at the water-ice "snowline" where they are expected to form. This will provide insight into the physical mechanisms by which planets form and migrate from their place of birth, and about their survival rate.

- *What is the origin of the apparent dearth of companion objects between planets and brown dwarfs seen in mature stars?* This survey for young planets and observations of young binaries will determine whether the "brown dwarf desert" is the expression of two different kinds of formation mechanisms, or the result of dynamical evolution acting on bodies made via a common process.

In a second part of this program, SIM will measure distances and orbital properties of ~100 stars precisely enough to determine the masses of single and binary stars to an accuracy of 1%. This information is required to calibrate the pre-main sequence tracks that serve as a chronometer ordering the events that occur during the evolution of young stars and planetary systems. The current uncertainty of a factor of two or more in the masses of pre-main sequence stars results in comparable or larger uncertainties in determinations of mass functions, ages, circumstellar disk lifetimes, and star forming histories of young clusters. SIM will determine the distances, masses and luminosities of ~100 pre-main sequence stars in binary systems, covering a range of three in mass and 100 million years in age. With accurate distances and companion information from SIM it will possible to determine precise stellar masses and thus provide the most reliable calibrations of pre-main-sequence evolutionary tracks.

4.2 Planets Around Nearby Stars (1)

The SIM PlanetQuest key project Extrasolar Planet Interferometric Survey (EPIcS) (Michael Shao, P. I.) 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 Tier 1 survey is designed primarily to address the first objective, the detection of Earth-like planets around nearby stars. The Tier 1 targets will consist of ~75 main sequence 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 main sequence 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 main sequence 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 the findings are statistically robust.

4.3 Planets Around Nearby Stars (2)

The SIM PlanetQuest key project Discovery of Planetary Systems with SIM (Geoffrey W. Marcy, P. I.) team has the following goals:

1. Detect terrestrial planets of 1 – 3 M_{Earth} around stars closer than 8 pc.

2. Detect 3 – 20 M_{Earth} planets around stars at a distance of 8 – 30 pc.

3. Determine absolute masses of planets previously detected with radial velocity studies and search for additional planets

4. Determine the degree of coplanarity in known multiple systems

5. Reconnaissance for TPF

This investigation seeks to determine:

- The occurrence rate and mass distribution of terrestrial planets
- The architecture of planetary systems
- Eccentricities of the orbits of low-mass planets
- The occupancy rate of the habitable zone

and ask

What fraction of stars has planetary systems? How many planets are there in a typical system? What is their distribution of masses and orbital semi-major axes? How common are circular orbits? How commonly do planetary systems have architecture similar to that of our Solar System?

4.4 Stellar Masses

It is crucial to our understanding of stellar astrophysics that stellar masses be determined to high accuracy. Knowing the masses of main sequence stars answers basic stellar astrophysics questions such as, *What is the biggest star? How is the mass of a stellar nursery partitioned into various Types of stars?* and, *What is the mass content of the Galaxy and how does it evolve?*

The principal goals of the MASSIF (Masses and Stellar Systems with Interferometry, Todd J. Henry, P. I.) key project are to (1) define the mass-luminosity relation for main sequence stars in five fundamental clusters so that effects of age and metallicity can be mapped (Trapezium, TW Hydrae, Pleiades, Hyades, and M67), and (2) determine accurate masses for representative examples of nearly every type of star, stellar descendant, or brown dwarf in the Galaxy. To reach these goals SIM PlanetQuest will measure masses with errors of 1% or less for roughly 200 stars, which will allow a challenge of stellar astrophysics models more severely than ever before. The extrema of the H-R Diagram will receive intense scrutiny to understand just where the stellar main sequence begins and ends. SIM will also investigate exotic targets such as supergiants and black holes to further understanding of these rare but intriguing objects. In the process of carrying out this investigation, SIM will develop a well-stocked toolbox of mass-luminosity relations at optical and infrared wavelengths that can become the standards against which all stars are measured.

An ensemble of mass-luminosity relations will allow accurate estimates for the masses of stars with extrasolar planets, and consequently, accurate estimates for the planet masses.

In addition, because the proposed observations will target 100 or more relatively close binary systems (separated by tens of AU or less), a search for planets in those systems will be carried out. Currently, there is no understanding of planetary survival in stellar binaries that have separations similar to our solar system. Thus, through the MASSIF effort, perhaps SIM can finally answer the question, *Is it possible to have two nearby Suns hanging in the sky of a world?*

4.5 X-ray Binaries

Using SIM PlanetQuest, the Masses and Luminosities of X-Ray Binaries (Andreas Quirrenbach, P. I.) project will perform narrow-angle observations of several X-ray binaries to determine their orbits, and will observe 25-30 X-ray binary systems in wide-angle mode to measure their distances and proper motions. The project will:

- Determine the orbits of two black hole systems to measure the black hole masses.
- Obtain precise mass measurements for two neutron star systems to constrain neutron star equations of state.
- Determine the distances and thus luminosities of selected representatives of various classes of X-ray binaries (black holes, neutron stars, jet sources).
- Measure proper motions, allowing for an estimate of the age of the population.

Narrow-angle observations of black hole systems provide a direct test of the dynamical mass estimates on which the black hole evidence is based. When combined with X-ray data, mass measurements may provide additional constraints on the black hole spin. Precise mass determinations of neutron star systems can address the question of whether neutron stars can be significantly more massive than 1.4 solar masses, which would eliminate soft models of the neutron star equations of state.

The wide-angle observations will probe the Galactic distribution of X-ray binaries through parallaxes and proper motions. They will also eliminate the uncertainties in the luminosities of individual sources, which is currently up to a full order of magnitude. This will enable more detailed comparisons of X-ray observations to physical models.

4.6 Exceptional Objects

SIM PlanetQuest's project Exceptional Stars Origins, Companions, Masses and Planets (Shrinivas R. Kulkarni, P. I.) will study the formation, nature, and planetary companions of the exotic endpoints of stellar evolution. This project will determine the parallax and orbital inclination of several iron-deficient post-AGB stars, whose peculiar abundances and infrared excesses are evidence that they are accreting gas depleted of dust from a circumbinary disk. Measurement of the orbital inclination, companion mass, and parallax will provide critical constraints. The circumbinary disks seem favorable sites for planet formation.

There will be a search for planets around white dwarfs, both survivors from the main-sequence stage, and ones newly formed from the circumbinary disks of post-AGB binaries or in white dwarf mergers.

This investigation will find the true nature of runaway OB stars from their proper motion and parallax (or limit thereto). It will measure the orbital reflex of OB/Be companions to pulsars, determine natal kicks and pre-supernova orbits, and expand the sample of well-determined neutron star masses. Observations will be made to obtain the parallax of a transient X-ray binary, whose quiescent emission may be thermal emission from the neutron star, aiming for precise measurement of the neutron star radius. A few neutron stars whose kicks are suitably oriented can remain in low-mass X-ray binaries. Proper motion and parallax measurements, combined with radial velocity, fix their true space velocities, and thus test the scenarios for their formation.

This project will measure the reflex motions of the companion of what appear to be the most massive stellar black holes. The visual orbits will determine natal kicks, and test the assumptions underlying mass estimates made from the radial velocity curves, projected rotation, and ellipsoidal variations. In addition, this project will attempt to observe the visual orbit of SS 433, as well as the proper motion of the emission line clumps in its relativistic jets.

As part of this project, contributions to the mission include:

- A tie of the SIM frame to the ecliptic (Solar System ephemeris) frame with better than 20 microarcsec precision.
- A study of the problem of amplitude calibration for SIM, and the requirements for precision work on binary stars unresolved by the individual SIM apertures.
- A study of the effects of distant companions to grid stars, in particular on SIM's sensitivity to long-period binaries, and suggestions for avoiding these effects.

4.7 Astrometric Microlensing

The primary goal of the Stellar, Remnant, Planetary, and Dark-Object Masses from Astrometric Microlensing (Andrew P. Gould, P. I.) key project is to make a complete census of the stellar population of the Galaxy, including both ordinary stars and dark stars.

The only way to examine the field population of these stars is through microlensing, the deflection of light from a visible star in the background by an object (dark or not) in the foreground. When lensed, there are two images of the background star. Although these images cannot be resolved when the lens has a stellar mass, the lensing effect can be detected in two ways: photometrically, i.e. by measuring the magnification of the source by the lens, and astrometrically, i.e. by measuring the shift in the centroid of the two images. With SIM PlanetQuest, it is possible to break the microlensing degeneracy and allow detailed interpretation of individual microlensing events. This investigation will thus develop a detailed census of the dark and luminous stellar population of the Galaxy.

SIM PlanetQuest will measure the centroid of light of the two blended images generated by the lensing object. The centroid will be shifted slightly from the true position of the source toward the brighter image during the lensing event, typically by about 100 microarcseconds. With its 4 microarcsecond precision, SIM will be able to accurately measure this shift.

To measure the other necessary parameter, two telescopes are needed, one on Earth, and one elsewhere in the solar system. From the difference in the event as seen by these two telescopes, one can reconstruct this value. Since SIM will be in a trailing solar orbit, moving away from the Earth at 0.1 AU/yr, SIM photometry (a byproduct of its astrometric observations) can be used to determine it.

The present day mass function of luminous objects is reasonably well determined, but that of dark objects is totally unknown. With microlensing measurements, the contributions of these dark objects to the mass of the Galaxy will be uncovered, as will some details of their individual mass functions.

In addition to the mass of the lens, this investigation will also be able to measure its distance and transverse velocity. Whereas in the past, using purely photometric microlensing, observers were merely able to say that there was a lens somewhere along the line of sight, one will now be able to sort each lens by Galactic component as well as by mass, leading to further insights into the structure of the Galaxy. These results are applicable to MACHO (Massive Compact Halo Objects) collaboration results for the microlensing optical depth toward the Large Magellanic Cloud. Furthermore, these measurements provide an independent means of obtaining stellar masses, and the only means for single stars.

4.8 Anchoring the Distance Scale

The SIM PlanetQuest key project Anchoring the Population II Distance Scale: Accurate Ages for Globular Clusters (Brian C. Chaboyer, P. I.) will obtain accurate parallaxes to a number of Population II objects (globular clusters and field stars in the halo) resulting in a significant improvement in the Population II distance scale. Supporting theoretical work and ground-based observations will diminish the error in the measured ages of the Galaxy's oldest stars from 2 Gyr to 0.6 Gyr, and provide a critical test of LCDM cosmology. The early star formation history of the Galaxy will also be probed.

To achieve these goals, the following SIM PlanetQuest observations will be obtained:

1. Parallax and proper motion measurements of at least 20 different globular clusters. These clusters have been chosen to span a range in metallicities, horizontal branch types, number of RR Lyrae stars and RR Lyrae pulsation properties.

2. Parallax measurements to a selected sample of at least 60 field RR Lyrae stars.

3. Parallax and proper motion measurements to at least 60 metal-poor subgiant branch stars in the field, allowing the determination of ages independently of the helium abundances for a larger sample of “datable" objects and in comparison with the clusters.

4.9 Open and Globular Cluster Distances

SIM PlanetQuest’s Open and Globular Cluster Distances for Extragalactic, Galactic, and Stellar Astrophysics (Guy S. Worthey, P. I.) project obtains parallax distances to a set of star clusters. One important goal is to pinpoint the zero point of the distance scale for main-sequence fitting. Another goal is to improve stellar evolutionary isochrones and integrated light models. The clusters themselves will be used to address unsolved problems of late-stage stellar evolution and Galactic and extragalactic chemical evolution. The clusters to be observed are chosen to span the widest possible range of abundance and age, to be as rich as possible, and to be as well-studied as possible.

This project will solve all distance-scale issues involving main-sequence fitting. It will also vastly improve the precision of distance measurement techniques that depend on stellar colors or luminosity functions such as the surface brightness fluctuation magnitude method for local galaxies. In combination with other (guest observer) SIM projects to pinpoint RR Lyrae and Cepheid distances, one-percent extragalactic distances will be within grasp, with a corresponding improvement in the precision of measurements of galaxy luminosities, sizes, large-scale flows, and dark matter content and a corresponding improvement in the cosmological parameters.

In addition to these science goals, the open and globular cluster project will support cluster age studies, Galactic chemical evolution studies through tie-ins to data on the rest of the Galaxy’s open and globular clusters, extragalactic chemical evolution studies through synthetic integrated-light studies, and stellar evolution studies of the helium-burning stages of stellar evolution as manifested in the target clusters.

4.10 Taking Measure of the Milky Way

The SIM PlanetQuest key project Taking Measure of the Milky Way (Steven R. Majewski, P. I.) will make definitive measurements of fundamental structural and dynamical parameters of our home galaxy, the Milky Way. The suite of experiments will utilize observations of distant giant stars in clusters and satellite galaxies, complemented by data for SIM Astrometric Grid stars, to characterize all of the major components (bulge, disk, halo, satellite system) of the Milky Way.

Specifically, the goals are:

1. To determine the mass distribution of the Galaxy, which is dominated by the presence of dark matter. SIM will measure

   a. tidal debris from dwarf satellites, notably the Sagittarius dwarf, mapping the shape, mass and extent of the Milky Way’s dark halo out to 250 kpc;
   b. transverse motions for globular clusters not included in the Population II distance scale key project, mapping the Milky Way’s inner halo; by determining the orbits of the clusters,

these data will illuminate the formation and subsequent evolution of the Galaxy's globular cluster population;

c. the relative contribution of the disk and halo to the overall gravitational potential; in particular, these data will constrain the relative contributions of disk and dark halo to the mass inside the Solar radius, thereby addressing whether the concordance cosmological model correctly predicts the dark-matter structure in the inner regions of galaxies;
d. the local volume and surface mass-density of the disk, for model-independent comparisons with inventories of stars and gas in the solar neighborhood.

2. To measure fundamental dynamical properties of the Milky Way, notably

   a. the pattern speed of the central bar;
   b. the rotation field and velocity-dispersion tensor in the disk;
   c. the kinematics (mean rotational velocity and velocity dispersion tensor) of the halo as a function of position

3. To provide independent, high-accuracy determinations of two fundamental parameters that play a central role in virtually every problem in Galactic astronomy, namely

   a. the Solar Radius or the distance to the center of the Milky Way, R_0
   b. the Sun's angular velocity around the Galactic center, ω_0

4.11 Proper Motions of Galaxies

SIM PlanetQuest's key project Dynamical Observations of Galaxies (SIMDOG) (Edward J. Shaya, P. I.) will be used to obtain proper motions for a sample of 27 galaxies; the first optical proper motion measurements of galaxies beyond the satellite system of the Milky Way. SIM measurements lead to knowledge of the full 6-dimensional position and velocity vector of each galaxy. In conjunction with new gravitational flow models, the result will be the first total mass measurements of individual galaxies. This SIM study will lead to vastly improved determinations of individual galaxy masses, halo sizes, and the spatial distribution of dark matter.

Through other key projects, SIM will determine precise distances to Cepheid variable stars and the red giant and horizontal branch stars that serve as standard candles. Bootstrapping on these calibrations, and in the course of a program of support observations for SIM, this project will derive distances at the level of 7 percent for all the target galaxies using two methods: from the luminosity of the tip of the red giant branch of old metal-poor stars and from the Balmer line equivalent widths of A,B supergiants, the very stars used for the SIM proper motion studies. With this anticipated level of accuracy, we will locate galaxies to better than 300 kpc across the ~4 Mpc region of interest. This galaxy localization uncertainty is comparable to the anticipated dimensions of halos. One can expect to resolve the mass of groups into the masses of individual galaxies.

This key project directly addresses the first and second fundamental questions of the NASA OSS Strategic Plan for "Origins, Evolution, and Destiny": 1) How *did the Universe begin and what is its ultimate fate?* and, 2) *How do galaxies, stars, and planetary systems form and evolve?* On large scales, these processes are controlled by dark matter. Full 3-dimensional information on the orbits of galaxies, albeit initially only for the nearest galaxies, leads to an understanding of the mass composition and evolution of galaxies and large-scale structure. These data also illuminate the future paths of galaxies, which tells how rapidly galaxies in groups are merging into fewer, more massive systems and, specifically, when the Andromeda galaxy will collide with the Milky Way.

4.12 Binary Black Holes and Relativistic Jets

The SIM PlanetQuest key project Binary Black Holes, Accretion Disks and Relativistic Jets: Photocenters of Nearby Active Galactic Nuclei (AGN) and Quasars (Ann E. Wehrle, P. I.) will address the following three key questions.

1. *Does the most compact optical emission from an AGN come from an accretion disk or from a relativistic jet?*

2. *Does the separation of the radio core and optical photocenter of the quasars used for the reference frame tie change on the timescales of their photometric variability, or is the separation stable at the level of a few microarcseconds?*

3. *Do the cores of galaxies harbor binary supermassive black holes remaining from galaxy mergers?*

Questions 1 and 2 will be answered with global and differential astrometry as follows. First, note that the SIM fringe spacing (resolution) is a few milliarcseconds, so most AGN cores will be unresolved. However, with global astrometry, radio (ICRF) and optical (SIM) positions of radio-loud quasars can be compared at the sub-milliarcsecond level (radio ~70-100 microarcseconds; optical ~4 -10 microarcseconds). Changes in radio structure originate in moving relativistically beamed features in a jet; it is to be expected that similar behavior will be observed in optical structure. SIM will also measure any color-dependent position shifts across the optical waveband. This will prove to be a powerful diagnostic tool for AGN structure on scales of a few microarcseconds. Interior motion and associated photocenter changes of the objects in the reference frames affects the quality of the frame tie, hence, it is critical that the underlying physics should be studied in detail using bright archetypal objects such as 3C273 and 3C345, as representatives for the radio-loud core-dominated quasar class.

Question 3 has central importance to understanding the onset and evolution of non-thermal activity in galactic nuclei. An entire AGN black hole system may be in orbit about another similar system, as might occur near the end of a galactic merger. How large is the astrometric signature? Rough estimates, based on the circumstantial evidence currently available, indicate that displacements of 10 microarcseconds or more (readily detectable with SIM) may be present in a number of AGN.

4.13 Microarcsecond Structure of AGN and Quasars

The Astrophysics of Reference Frame Tie Objects (Kenneth L. Johnston, P. I.) key project will investigate the underlying physics of SIM grid objects. This project assists the SIM team in general to establish an absolute coordinate system for all SIM PlanetQuest observations, which is a crucial requirement for some other Key Projects.

Extragalactic objects in the SIM grid will be used to tie the SIM reference frame to the quasi-inertial reference frame defined by extragalactic objects and to remove any residual frame rotation with respect to the extragalactic frame. The following questions concerning the physics of reference frame tie objects will be investigated.

1. *What is the origin of optical emission in quasars?*

2. *Are the optical photo-centers of quasars compact and positionally stable on the microarcsecond level?*

3. *Are binary black hole mergers responsible for quasars?*

4. *What is(are) the emission mechanism(s) responsible for generating radio emission in chromospherically active stars. Is the emission thermal, relativistic synchrotron or gyro-synchrotron?*

5. *What causes the transition of spherically symmetric Asymptotic Giant Branch (AGB) stars to asymmetric planetary nebulae (PNe)?*

4.14 Optical Synthesis Imaging

SIM PlanetQuest will be the first space astrophysics instrument to provide a capability for synthesis imaging at optical wavelengths, offering the promise of imaging high-surface-brightness targets with more than 4 times the best resolution attainable with the Advanced Camera on the Hubble Space Telescope. Synthesis Imaging at Optical Wavelength with SIM (Ronald J. Allen, P. I.) will collect data from SIM PlanetQuest's two baselines and combine observations taken at many small increments in roll angle to image a field of view of ~1" with a resolution of FWHM approximately 0.008" at a wavelength of 500 nm. The point spread function (PSF) of the images produced directly from this data show many low-level spurious responses spread over the entire image. However, the truly incredible phase stability of SIM's interferometers means that these responses can all be calculated to a very high degree of accuracy, opening the way for the application of image restoration algorithms such as those popular in radio astronomy.

SIM imaging will be especially useful on crowded fields containing many high-brightness targets. Such fields include the central regions of galaxies out to the Virgo Cluster (including active nuclei and jets), and the swarms of stars in the cores of Galactic globular clusters. There are indications that the central regions of some globular clusters may contain black holes, similar to the situation currently thought to occur in the centers of many galaxies. These massive objects dramatically affect the motions of nearby stars. Images made with SIM at several epochs spread over the lifetime of the mission will yield positions, proper motions, and perhaps even accelerations of cluster stars, providing unique new information on the masses of central black holes. If SIM were to fly tomorrow, the plan would be to observe the nucleus of the nearby spiral M 31 and the central core of the Galactic globular cluster M 15.

4.15 New Approach to Astrometry with SIM

The SIM PlanetQuest project A New Approach to Microarcsecond Astrometry with SIM Allowing Early Mission Narrow Angle Measurements of Compelling Astronomical Targets (Stuart Shaklan, P. I.) demonstrates a technique for narrow angle astrometry that does not rely on the measurement of grid stars. This technique, called Gridless Narrow Angle Astrometry (GNAA) can obtain microarcsecond accuracy and can detect extra-solar planets and other exciting objects with a few days of observation.

Gridless narrow angle astrometry with SIM is simply the application of traditional single-telescope narrow angle techniques to SIM's narrow angle optical path delay measurements. The technique allows one to perform microarcsecond astrometry without solving for baseline length, precise baseline orientation, or the metrology constant term. In GNAA, a set of reference stars and a target star are observed at several baseline orientations. A linearized model is used to solve for reference star positions and baseline orientations. The target star position is determined using the estimated baseline orientations. Then the process is repeated at a later time and a conformal transformation is applied to relate the reference target stars to a common reference frame.

The GNAA technique will be used to observe short-term periodic signals, including known and potential extra-solar planets, the black-hole Cyg X-1 (P = 5.6 d), as well as radio and X-ray binary systems, e.g. the Be star LSI 61303 (P = 26.5 d), and similarly V725 Tau, X Per, V801 Cen, HD 63666, HD 91188, all with periods < 35 d.

One of the hallmarks of SIM's few-milliarcsecond astrometric precision is its ability to obtain accurate parallax measurements across more than half of the Galaxy. SIM's astrometric precision will allow parallax distances to be measured with 5% accuracy well past the Galactic center, and distances of stars within ~3 kpc to be measured with less than 2% uncertainty. This 3 Kpc shell contains the near half of the traditional extragalactic distance ladder: RR Lyrae variables and Cepheid variables that range over all [Fe/H], plus many star clusters used for main-sequence fitting.

5 Synergy with Other Planet Finding Programs

The most prominent science program for the SIM mission is to search for planets around nearby stars. The SIM spacecraft is extremely capable in searching for planets around nearby stars that subsequently can be observed by the TPF-C and TPF-I missions with direct imaging in the visible and thermal IR, and even more important, moderate resolution spectroscopy of the light from the planet.

SIM PlanetQuest represents about a factor of 300-1000 increase in accuracy over other astrometric instruments, and it is expected to reap a bountiful harvest of planets, from barely substellar brown dwarfs to terrestrial planets in the habitable zone. To fully optimize the use of SIM time, especially for terrestrial planets, the PI's of the planet search key project will make full use of data from all available sources: ground based radial velocity and ground based long baseline interferometry as well as statistics from Kepler mission transits. Careful planning is important to making the best use of SIM science observation time.

In this section we first discuss what SIM can do by itself and then describe how SIM and TPF-C interact in a synergistic, positive feed back way that enables more science than the sum of the two missions.

5.1 SIM Alone

SIM has a "two tier" planet search program, the first at ~4-5 μas, single measurement accuracy, aimed at planets of a Neptune-mass and above, and the second at ~1 μas accuracy aimed at terrestrial planets. The throughput of SIM in terms of the number stars searched is vastly different for these two programs. From a photon noise point of view, the integration time needed to get 5 μas is 1/25 the time needed to get to 1μas. In addition, at 5 μas we can use the SIM grid as a reference frame instead of spending time observing nearby reference stars. The difference is almost a factor of 50 in the number targets that can be observed at 5 μas vs. 1 μas.

The current plan is for SIM to spend ~5% of its time on ~2000 stars looking for planets of Neptune-mass and larger, and about 15% of its time searching the nearest 50-200 nearby stars for terrestrial planets.

The two major radial velocity planet search teams (Berkeley and U. Geneva) who together have found >90% of the exoplanets are key participants in the SIM planet search program. The ground based radial velocity search has been extremely fruitful and their results have created the subfield of exoplanet research. About 7-10% of single stars are known to have Jovian mass planets in orbits ranging from 3 days to 3-4 years. There is considerable data, not published, of longer period Jovian planets. RV searches are less sensitive as the planet orbital period increases but astrometric searches are more sensitive. Statistical analysis of the known extra-solar planets can be used to roughly bound the number of Neptune and more massive planets detectable with SIM. SIM with 5% of its time might find an additional 600-1000 ice giant/gas giant planets.

With this many new planets one extremely interesting new science area will be multiple planetary systems. Astrometry, unlike radial velocity, measures all of a planet's orbital parameters (and the planet's mass). The ability to measure the inclination of the orbital plane of planets in a multi-planet system will give us the first direct evidence that planetary systems like our own are or are not common. With the huge advance in measurement capability that SIM provides, maybe the only thing we can predict is that we will be surprised. Radial velocity searches went on for years, concentrated on finding Jovian planets in 12-year orbits. Yet the first planets discovered outside our solar system were found circling a pulsar, and the first planet found orbiting a Sun-like star was a hot Jupiter orbiting 0.05 AU from its parent star.

The exact observing plan for SIM's planet searches will make use of data from precursor missions, COROT and Kepler in particular. For example, if the number of Earths in the habitable zone proves to be high (~10%), SIM might best spend its time on a relatively small sample of, say ~50 stars, searching down to ~1.5 M_{Earth} to find those planets most like the Earth. But if COROT/Kepler show that such planets are relatively rare (1-2% in the habitable zone), SIM might better look at a larger number of stars for higher mass planets since every factor of two decrease in the mass of the planet is a factor of four in the number of stars SIM can search. SIM will find many 1-10 M_{Earth} planets outside the habitable zone where Kepler and RV surveys are unlikely to have much success. In the "pessimistic estimates," a search of 200 stars might yield a relatively rich harvest of 60-140 terrestrial-mass planets (>4 M_{Earth}), even if only a handful are in the habitable zone.

5.2 SIM and TPF synergy

SIM and TPF observations complement each other in several ways. Just as SIM's science program is enhanced by the use of Kepler data, SIM data will enhance the science from TPF. Most importantly, SIM will complement TPF scientifically by determining masses for many planets identified by TPF (Section I.D). Perhaps just as important, SIM will identify planetary systems for TPF to avoid. These include planetary systems where a Jovian planet would dynamically preclude the existence of a terrestrial planet in the habitable zone. TPF-C can detect planets down to and perhaps slightly less than 1 Earth radius, but for some nearby stars, those whose habitable zone is very large, SIM sensitivity is sufficient so that non-detection can preclude a planet detectable at the nominal contrast of 10^{-10}. Such a system might not be a good one for an intensive TPF-C program.

An extensive Monte Carlo simulation shows that the use of SIM data can increase the number of planets TPF can identify. The improvement in observing efficiency depends on the unknown frequency of earths, but the increased knowledge from SIM about specific targets and overall confidence in outcome of a TPF-C observation represents a significant risk reduction for the overall planet-finding program.

5.3 Orbit Determination

SIM astrometry can measure all the orbital parameters of a planet, information critical to assessing the habitability of a system. For example, orbital inclination in a multi-planet system relates to the long-term stability of the planetary orbit while eccentricity determines the maximum and minimum temperature the planet is likely to experience over a year.

It will be hard to determine orbits with direct imaging since a planet will not be detectable inside an inner working angle ~4 λ/D for TPF-C. A planet in a circular inclined orbit will spend much or most of its time inside the inner working angle of a coronagraphic telescope and even when it's outside the inner working angle, in the detection zone up to 1/2 the time will be spent with the starlit side of the planet facing away from the telescope. Some orbital parameters are difficult or impossible to measure. In cases where SIM has even a coarse orbit determination, these data can assist TPF by significantly reducing the TPF search time. If the SIM detection is good enough (6-7 sigma), the orbital uncertainties will be small enough to let TPF find the planet on the first try. With a 7 sigma detection, the orbital phase, where the planet is in its orbit should be known to +/-20 days (for a 360 day year).

5.4 Planet Mass

Of the numerous techniques that exist for detecting planets, astrometry is the only one that measures the mass of the planet directly. Its mass determines a planet's ability to hold on to an atmosphere or to have tectonic activity capable of driving atmospheric change. Mass determines whether the planet is a rocky planet, an ice giant like Neptune or Uranus or a gas giant like Jupiter.

While a clear detection of a planet by SIM will produce a good mass measurement down to ~2 M_{Earth}, a marginal detection by SIM aided by TPF observations can determine more accurate mass estimates. The mass of a planet is measured by observing its gravitational interaction with the parent star. But a few direct detections with a ~5 mas position uncertainty in an orbit with a 100 mas radius constrains many orbital parameters to ~5%. Just a few direct detections by direct imaging would constrain many of the orbital parameters of the planet (except mass) ~25X better than possible with SIM alone. Thus augmented, SIM data could set error bars on the planet mass at ~0.3 Earth mass level.

Two planets in our solar system, Jupiter and Saturn, can provide an example of how the combination of SIM and TPF can lead to correct scientific conclusions where data from just one source would be incomplete. If Saturn were at 5AU, the rings of Saturn would make it much brighter than Jupiter even though Jupiter is 3 times the mass of Saturn. If one of the exo-terrestrial planets has a ring, the brightness might lead us to think the planet is much more massive than it actually is. In addition, a cursory inspection of the spectra will reveal the rock or ice that the rings are made of. One might conclude this planet is like Mars but 6-7 M_{Earth} and having very little atmosphere. But if the rings are just a bit brighter than the planet, increasing the integration time on TPF by a factor of 4-6 might reveal the atmosphere of the planet, partially hidden by the glare of the rings. A direct measurement of the mass of a planet showing an inconsistency with indirect methods of "guessing" the mass would lead to a totally different and interesting interpretation of a new discovery.

6 Comparison with GAIA

GAIA is an ESA space astrometry mission, a follow on and major upgrade of the very successful Hipparcos mission. While GAIA and SIM PlanetQuest both make very precise position measurements of stars, the capabilities of the two missions are quite different. GAIA's strength is in numbers. The mission will survey ~1 billion stars, with both astrometric and radial velocity measurements. GAIA is a global astrometric mission, with a goal of ~16 μas at 15 mag. The nominal mission for GAIA is launch in 2011 and end in 2020, a mission life of ~9 years. http://www.rssd.esa.int/index.php?project=GAIA&page=Info_sheets_accuracy

SIM PlanetQuest accuracy is selectable by the PI. Perhaps the easiest comparison is with the SIM grid. The rescoped SIM mission will have a grid accuracy of 4.4 μas (for the baseline 5 yr mission). NASA has instructed JPL to design a mission capable of operating ten years (for consumables) as well as to develop a budget for ten years of mission operations. If SIM is operated for nine years, the Grid accuracy will be 3.3 μas, to be compared to GAIA's accuracy over a similar mission life.

At fainter magnitudes GAIA accuracy degrades significantly because of CCD read noise and dark current and the relatively short integration time spent per object. At 18 mag the accuracy falls to ~200 μas whereas SIM will still be capable of 6 μas accuracy. Brighter than 15 mag, GAIA's accuracy ~10 μas The accuracy of GAIA for bright stars is a rather complex function. GAIA is a survey instrument and observes all stars in the same way. Bright stars saturate the CCDs and useful astrometric information is degraded unless the target drifts through a small number of CCDs that have neutral density filters.

6.1 Planet Search Around Nearby Stars

If we assume the GAIA mission accuracy is 4 μas (nine year mission duration), that could be compared a 10 yr SIM narrow angle astrometry program. The SIM program would involve ~200 2D visits (i.e., measurements made with two very different baseline orientations) which would have an equivalent mission accuracy of 0.11 μas. SIM's deep search would be able to detect planets 1/40 as massive as GAIA.

6.2 Global Astrometry of Faint Stars

In a nine year mission, the discovery space unique to SIM would be in the difference between the 3.3 μas accuracy of the SIM mission and the ~16 μas accuracy (for 15 mag stars) of the GAIA mission.

For astrometry of extragalactic targets, at 18 mag SIM's advantage is very large, similar to its advantage for planet search. The measurement of proper motion of nearby galaxies will be an order or magnitude more accurate with SIM. One component of the "Taking the measure of the Milky Way" key project will look at stars that form tidal debris of dwarf galaxies that orbit the Milky Way. These targets are also faint, and although the full 4-5 μas accuracy of SIM is not needed, 20-30 μas is needed and is beyond the capability of GAIA.

6.3 Time Critical Observations

SIM is a targeted mission and can make observations of any target at any time (limited to solar exclusion constraints). GAIA is a scanning mission with a fixed observing schedule for the full mission. Targets of opportunity, such as those required by the SIM Key Project on microlensing would not possible with GAIA. The ability to select a time to make observations is also important for very short period or highly eccentric orbits of planets, stars, and exotic objects.

6.4 Angular Resolution/Target Confusion

SIM, with an angular resolution of ~10 mas will see two objects 10 mas apart as two objects instead of measuring the photocenter of the sum of the two objects. This capability is used in the MASSIF key project (described later in this white paper) to measure the masses of stars in close binary systems. Avoiding confusion is also an advantage when measuring the motion of bright stars in nearby galaxies.

6.5 Common Capabilities

For global astrometry targets brighter than 15 mag, the difference between SIM (3.3 μas for a nine year mission) and GAIA (4-10 μas) is present but not strikingly large. But it's likely that both GAIA and SIM will make numerous important discoveries and independent confirmation is an important part of science. Several years ago, Hipparcos announced a parallax to the Pleiades cluster, the implication of which was that most of conventional stellar evolution theory was wrong. Several years after the publication of that paper, ground based observations (some from ground based interferometers) began to poke holes in the Hipparcos conclusions and it is now accepted that conventional stellar evolution theory is intact. While the glory goes to the scientist who gets there first, independent confirmation is the bedrock of modern science. If SIM launches 1-2 years ahead of GAIA, with capabilities (in this overlap region) that are a factor of sqrt(2) better, SIM might get there first, most of the time. Of course in science topics that require 1 million or 100 million targets GAIA is unchallenged.

7 SIM PlanetQuest Science Summary

As one of the most important NASA astrophysics missions in the coming decade, SIM PlanetQuest is featured prominently in the 2005 Universe Division Roadmap. The breadth of science that SIM PlanetQuest will address is captured in the summaries to each of the major Roadmap science chapters:

EXPLORING NEW WORLDS

SIM PlanetQuest will:

- search for terrestrial planets around nearby stars, and measure planetary masses
- characterize the orbital ellipticity and inclination of multiple-planet systems, to determine the stability and the evolution of planetary systems
- search for "Solar System analog" systems with giant planets at 5-10AU
- perform the only census for gas giants near the HZ around young stars (1-100 Myr)
- investigate formation and migration scenarios that might explain the puzzling presence of 'hot Jupiters' in very short-period orbits
- optimize target selection for TPF-C

ORIGIN AND DESTINY OF STARS

SIM will:

- Associate stars with their sites of formation to advance studies of their evolution
- Assist in measuring the masses and luminosities of compact stellar remnants
- Probe the formation of binary stars

ORIGIN AND EVOLUTION OF COSMIC STRUCTURE

SIM will:

- Reveal the early assembly and enrichment history of the Milky Way galaxy by accurately determining distances and ages of stars and star clusters.
- Map the gravitational potential of the Milky Way's stellar disk and dark matter halo.
- Test the leading hypothesis for the nature of dark matter by measuring the shape and lumpiness of the dark halo.
- Determine distances and velocities of galaxies in the Local Supercluster, enabling reconstruction of the history of our cosmic neighborhood.
- Conduct the first survey of all objects, dark and luminous, in the Milky Way disk and bulge, and determine the nature of objects causing microlensing towards the Magellanic Clouds.

8 Appendix 1. Letter from SIM Science Team to Dr. Anne Kinney

SCIENTIFIC DIRECTOR
UNITED STATES NAVAL OBSERVATORY
3450 MASSACHUSETTS AVE., NW
WASHINGTON, D.C. 20392-5420

March 18, 2005

Anne Kinney
Division Director
Universe Division
NASA Headquarters
300 E Street SW
Washington, DC 20546-0001

Dear Anne:

This letter is to inform you of the excellent progress being made in the redesign of the SIM PlanetQuest mission. A SIM Science Team meeting was held recently, March 15-16 at the Naval Observatory in Washington DC. The major topic of the meeting was the redesign effort for the SIM mission.

The SIM Science Team fully endorses the SIM rescoping of the mission architecture, which shrinks the baseline from 10m to 9m and reduces the collecting area by 50%. The redesigned mission will achieve excellent science in both planet finding and general astrophysics. This was presented as redesign option 1a. This rescoping requires no new technology development and keeps the mission on schedule for a 2010 launch. The Science Team acknowledges that with the present design, SIM's performance depends critically on its baseline length and aperture area: the system cannot be further descoped without a large impact on the mission's science return. Conversely, even small improvements in either aperture size or baseline would significantly improve the number of targets SIM could study. The Science Team encourages the Project Team to investigate ways to improve the science to be achieved with faint (visual magnitudes > 18) and to investigate ways to improve the throughput of the instrument. The Science Team will continue to work with the Project team to achieve this.

The Science Team thanks Dave Gallagher and the entire Project Team for their excellent work in the redesign effort. We look forward to the completion of the redesign effort so we can continue towards the realization of the SIM mission.

Sincerely,

Ken

Kenneth Johnston for SIM Science Team

Copy: Lia La Piana
Phil Crane
SIM Science Team