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Acta Astronautica 61 (2007) 52 – 62

ACTA ASTRONAUTICA

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The SIM PlanetQuest science program

Stephen J. Edberg*, Wesley A. Traub, Stephen C. Unwin, James C. Marr IV

NASA Jet Propulsion Laboratory, California Institute of Technology, USA

Available online 18 April 2007

Abstract

SIM PlanetQuest (hereafter, just SIM) is a NASA mission to measure the angular positions of stars with unprecedented accuracy. We outline the main astrophysical science programs planned for SIM, and related opportunities for community participation. We focus especially on SIM's ability to detect exoplanets as small as the Earth around nearby stars. The planned synergy between SIM and other planet-finding missions including Kepler and GAIA, and planet-characterizing missions including the James Webb Space Telescope (JWST), Terrestrial Planet Finder—Coronagraph (TPF-C), and Terrestrial Planet Finder—Interferometer (TPF-I), is a key element in NASA's Navigator Program to find Earth-like planets, determine their habitability, and search for signs of life in the universe. SIM's technology development is now complete and the project is proceeding towards a launch in the next decade.
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1. Introduction

SIM PlanetQuest (SIM) will exploit the classical measuring tool of astrometry with unprecedented precision to make dramatic advances in many areas of astronomy and astrophysics. SIM directly serves NASA's goal of searching for habitable planets, as directed by the U.S. President's Vision for U.S. Space Exploration [1]: *Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars.* SIM will survey the closest $\sim$ 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 to build up a complete understanding of the formation, evolution, and architecture of planetary systems generally. The 2001 AASC report [2] explicitly called for scientific capabilities "... [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." SIM meets both these directives.

The scientific return from SIM will also 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 National Research Council (NRC) Decadal Reports ([3,2], respectively) to endorse SIM as an important part of the United States' program in astronomy and astrophysics including: "... *trigonometric determination of distances throughout the galaxy*,

* Corresponding author.
E-mail addresses: Stephen.J.Edberg@jpl.nasa.gov (S.J. Edberg), Wesley.A.Traub@jpl.nasa.gov (W.A. Traub), Stephen.C.Unwin@jpl.nasa.gov (S.C. Unwin), James.C.Marr@jpl.nasa.gov (J.C. Marr IV).

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doi:10.1016/j.actaastro.2007.01.036

and the study of the *mass distributions of nearby galaxies from stellar orbits*."

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

SIM observations provide fundamental astrophysical information which is needed by other missions, including Kepler, GAIA, James Webb Space Telescope (JWST), and Terrestrial Planet Finder (TPF). The synergy between SIM and these missions is discussed later.

SIM's technology has been developed over the past 10 years, and is now complete, with technology goals substantially surpassed, providing a comfortable margin for the planned observations as summarized later in this paper and presented in detail in Ref. [4].

SIM's design and performance are summarized below:

Science interferometer baseline: 9 m
Guide interferometer baselines: 7.2 m
Wavelength range: 0.4–1.0 nm
Telescope aperture: 0.30 m diameter
Astrometric field of regard: 15°
Narrow-angle field of regard: 1°
Detector: Si CCD
Orbit: Earth-trailing solar orbit
Science mission duration: 5 years
Global astrometric grid and
wide-angle astrometry: 4 μas mission accuracy
Narrow-angle and planet-finding astrometry
(1°): 1 μas single measurement accuracy
Limiting magnitude: 20 mag

More information on SIM is available at: http://sim.jpl.nasa.gov

2. Observing with SIM

The allocation of observing time on SIM has been split between investigations—key projects—selected from the first Announcement of Opportunity (AO-1) and future calls to researchers. Only about half of the available observing time has been allocated to key projects so far, with the remaining time to be allocated to Legacy and General Observer investigations in the near future. In addition, Archival Research investigations will be invited after SIM is in flight.

2.1. Legacy Projects, General Observers (GOs), and Archival Research

Legacy Projects will deliver a set of data that will be useful to a broader science community or produce tools that will be useful to that community. These data will not have as long a proprietary period, or no proprietary period, compared to key projects. These projects provide lasting science benefit for the larger community. Release of the Legacy Projects proposal call will coincide with the First GO call (see below), early in Project Phase C.

The GO Program is planned to have a series of proposal calls, the first of which (GO-1) will be simultaneous with the Legacy Proposal Call (above). Many GO-1 observing programs are expected to be in 'Snapshot' mode, most of which will require much less than five-year duration, typically two years. This allows time for allocation to a second GO proposal call (GO-2). A third GO proposal call (GO-3), with a release date approximately four years into the Baseline Mission, will be issued only if SIM is approved to continue into the second five years of mission operations.

Proposals responding to the Legacy and GO calls will be accepted for all scientific topics. The NASA Program Scientist may optionally direct the Project to set aside a portion of the offered time for investigations that directly address specific objectives that are deemed high priority science.

Archival Research programs are those that do not request specific observations, but, instead, make use of the collection of measurements accumulated over the course of the mission. Proposals for Archival Research will be invited late in the baseline mission (five years) and at intervals during the goal mission (an additional five years of operation).

2.2. 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. Copies of the proposals can be found at http://planetquest.jpl.nasa.gov/SIM/sim_team.cfm?Astro=Yes. 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 60% of the time assigned so far has been allocated to general astrophysics (Fig. 1).

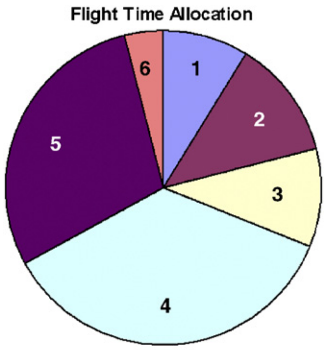

Fig. 1. The pie-chart shows the total distribution of observing time on SIM and includes both the existing program (AO-1) plus time for projects to be selected via future calls for proposals (General Observers).

The pie-chart in Fig. 1 shows the allocation of SIM time for the baseline five-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 39% of the presently allocated time and more general astrophysics programs take up 61% of the allocated time. The available time comfortably completes the revised key projects in both planet search and astrophysics.

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

2.3. Potential for future science investigations

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. Details of the approved key projects

3.1. 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 will measure masses with errors of 1% or less for roughly 200 stars, which will allow a challenge of stellar astrophysics models more severe than ever before. SIM will also investigate exotic targets such as supergiants and black holes to further understanding of these rare but intriguing objects.

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?*

3.2. X-ray binaries

Using SIM, 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.

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.

3.3. Exceptional objects

SIM'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. The circumbinary disks seem favorable sites for planet formation.

There will be a search for planets around white dwarfs, both survivors from the dwarf's 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 motion of OB/Be companions to pulsars and expand the sample of well-determined neutron star masses. Observations will be made to obtain the parallax of a transient X-ray binary, aiming for precise measurement of the neutron star radius. Proper motion and parallax measurements of certain X-ray binaries, combined with radial velocity measurements, 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. 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.

3.4. 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's astrometric measurements of the centroid, 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.

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.

3.5. Anchoring the distance scale

The SIM 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 to 0.6 Gyr, and provide a critical test of certain cosmological theories. The early star formation history of the galaxy will also be probed.

To achieve these goals, the following SIM 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.

3.6. Open and globular cluster distances

SIM'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, 1% 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.

3.7. Taking measure of the Milky Way

The SIM 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;
   (c) the relative contribution of the disk and halo to the overall gravitational potential;
   (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.

3.8. Proper motions of galaxies

SIM'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 six-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.

This project will derive distances at the level of 7% 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.

3.9. Binary black holes and relativistic jets

The SIM 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. With global astrometry, radio (International Celestial Reference Frame) and optical (SIM) positions of radio-loud quasars can be compared at the sub-milliarcsecond level (radio $\sim$ 70–100 μas; optical $\sim$ 4–10 μas). 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 μas or more (readily detectable with SIM) may be present in a number of AGN.

3.10. 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 observations. 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 photocenters 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)?

3.11. Optical synthesis imaging

SIM 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's two baselines and combine observations taken at many small increments in roll angle to image a field of view of $\sim 1''$ in with a resolution of FWHM approximately $0.008''$ in at a wavelength of 500 nm.

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.

3.12. New approach to astrometry with SIM

The SIM 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.

GNAA with SIM is simply the application of traditional single-telescope narrow-angle techniques to SIM's narrow-angle optical path delay measurements. 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.

3.13. Young stars and planets

The SIM 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 1–5 AU, this investigation will develop a data set 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. 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 (< 5 AU or 30 milliarcsec at Taurus) impossible even for advanced Adaptive Optics systems.

Among the questions addressed are:

- What is the incidence of gas giant planets around young, solar-mass stars in the orbital range 1–5 AU? When and where do gas giant planets form?
- What is the origin of the apparent dearth of companion objects between planets and brown dwarfs seen in mature stars?

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.

3.14. Planets around nearby stars (1)

The SIM 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 2 targets will consist of $\sim$ 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.

3.15. Planets around nearby stars (2)

The SIM 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 co-planarity in known multiple systems.
5. Reconnaissance for the 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 have 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. Synergy of SIM and other missions

In this section we discuss the scientific connections and synergy between SIM and four specific future missions, Kepler, GAIA, JWST, and TPF. This topic has also been addressed in Traub et al. [5] and Beichman et al. [6].

COROT, Kepler, and SIM will provide the many order-of-magnitude improvements in sensitivity and resolution (Fig. 2) relative to ground-based efforts needed to detect other Earths in the habitable zones of their parent stars using indirect techniques of transits, radial velocity, and astrometry. Once we have detected these planets via indirect means, we will need a number of missions to characterize these planets physically and to search for evidence of life in any atmospheres these planets may possess.

The combination of transit photometry with COROT and Kepler, follow-up spectrophotometry from JWST and follow-up radial velocity data give unique information on planetary mass, radius, density, orbital location, and, in favorable cases, composition of the upper atmosphere. These data, available for large numbers of planets, will revolutionize our understanding of gas-giant and icy-planets. While less information will be available for smaller, rocky planets, a critical result of

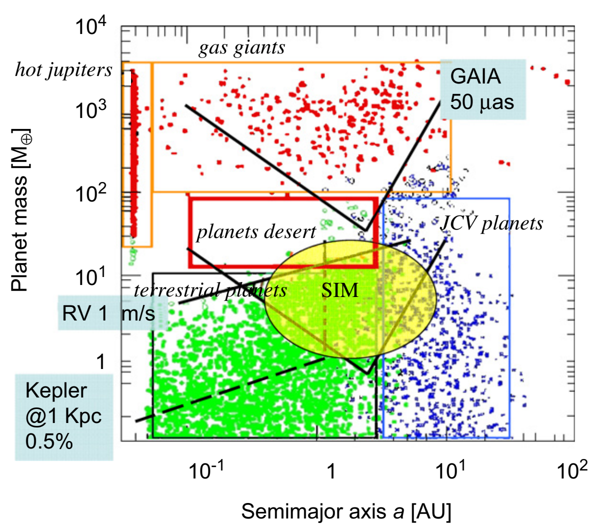

Fig. 2. The planet discovery potential for ground-based and space mission searches. RV stands for ground-based radial velocity measurements. SIM will find and determine orbits of terrestrial planets other methods cannot. After Ida and Lin [7].

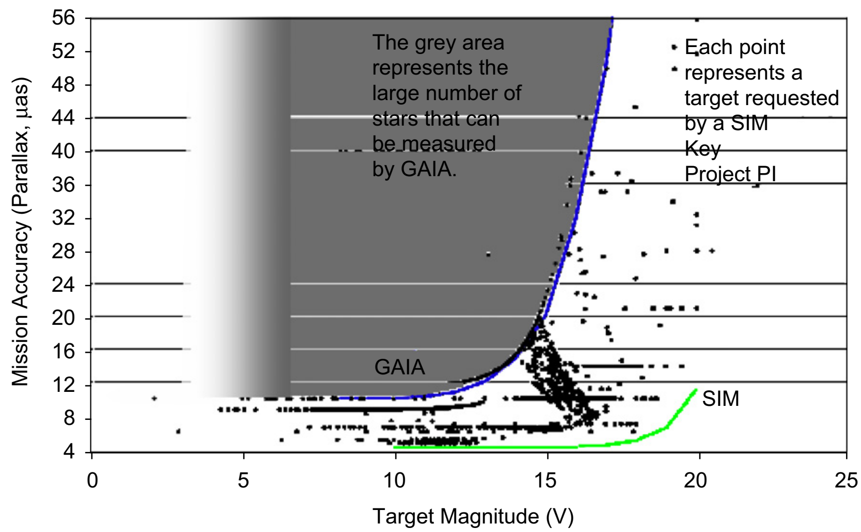

Fig. 3. SIM Science Team selected targets are shown on this plot of desired mission accuracy vs. target brightness. The targets are selected to exploit the new parameter space that SIM opens (green curve). For comparison, GAIA will observe a very large number of targets (grey area) to the left of the GAIA curve (blue). The transitional zone represents GAIA's bright star limit ranging from magnitude ∼ 3–7.

the transit surveys will be the frequency of Earth-sized planets in the habitable zone. Since the angular resolution and collecting area needed for the direct detection of nearby planets are directly related to the distance to the closest host stars, the frequency of terrestrial planets will determine the scale and cost of missions to find and characterize those planets.

Subsequent to the transit surveys, we will embark on the search for and the characterization of nearby planets, and the search for a variety of signposts of life.

We will ultimately require three complementary data sets: masses via astrometry (SIM); optical photons (TPF-Coronagraph); and mid-IR photons (TPF-Interferometer/Darwin). JWST will play an important role in follow-up activities looking at ground-based, COROT, and Kepler transits; making coronagraphic searches for hot, young Jupiters; and studying protoplanetary and debris disks.

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 ($> 4\ M_{\mathrm{Earth}}$), even if only a handful are in the habitable zone.

GAIA is an ESA space astrometry mission, a follow on and major upgrade of the very successful Hipparcos mission. While GAIA and SIM both make very precise position measurements of stars, the capabilities of the two missions are quite different (Fig. 3). 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

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 is ∼ 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.

JWST, expected to launch in 2013, will offer coronagraph modes for its two infrared imaging instruments. Even though JWST's segmented primary mirror is poorly suited to high contrast coronagraphy, JWST's coronagraphs can access the bright 4.8 μm emission feature expected in the spectra of giant planets and brown dwarfs enabling the detection of substellar companions at contrast ratios of 10^{-5}–10^{-6}. Detailed performance estimates show that JWST should be able to detect warm planets in nearby young stellar associations at radii greater than 0.7 arcsec, and perhaps even a few old (5 Gyr) Jupiter-mass planets around nearby, late-M type stars (Green et al., 2005). JWST will study early and late phases of planet system evolution revealed by emission from pre-planetary disks and debris disks. The presence of planets by their gravitational effect on debris disk structure in systems which are too dusty for study by SIM and TPF may be inferred from JWST observations. JWST may obtain intrinsic spectra of hot young gas giants in favorable cases. It will be able to follow-up on Kepler transits of giant planets to study the absorption spectrum of any planetary atmosphere.

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. 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.

5. SIM's technology development and current status

5.1. Technology completed

SIM's technology development was completed in July 2005, following a 10-year program that resulted in component, subsystem, and system-level demonstrations of full SIM instrument capability to achieve better than 1 μas single-measurement astrometric performance over small (∼1°) fields of regard (current estimate is 0.7 μas) and better than 4 μas five-year mission accuracy over the full sky (current estimate is 2.3 μas), to visual magnitude 20 stars and with instrument systematic errors below 0.1 μas. Further details of the SIM technology development program are presented at this conference by Laskin et al. [8]. An overview of the SIM project, including an instrument description, is provided at this conference by Marr et al. [4].

5.2. Project status

While the project is technically ready to proceed to a launch as early as 2011, and presently has the team in place to do this, NASA's changing priorities have resulted in SIM's launch being delayed, perhaps by as much as four years. SIM's ultimate launch date will be determined by funding availability.

6. SIM science summary

SIM science is compelling and not duplicative of any other NASA or ESA mission flying or in planning. SIM will be a facility-class instrument supporting those interested in ultra-precise distances to and proper motions of stars and galaxies. With SIM's ultra-precision astrometry there will be many serendipitous discoveries. A brief recap of SIM's science capabilities follows:

Exploring new Worlds

- 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 5–10 AU.
- Perform the only census for gas giants near the habitable zone 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

- 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.

Acknowledgments

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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