ASTROPHYSICS WITH MICROARCSECOND ACCURACY ASTROMETRY

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ABSTRACT

Space-based astrometry promises to provide a powerful new tool for astrophysics. At a precision level of a few microarcsonds, a wide range of phenomena are opened up for study. In this paper we discuss the capabilities of the SIM Lite mission, the first space-based long-baseline optical interferometer, which will deliver parallaxes to 4 microarcsec. A companion paper in this volume will cover the development and operation of this instrument. At the level that SIM Lite will reach, better than 1 microarcsec in a single measurement, planets as small as one Earth can be detected around many dozen of the nearest stars. Not only can planet masses be definitely measured, but also the full orbital parameters determined, allowing study of system stability in multiple planet systems. This capability to survey our nearby stellar neighbors for terrestrial planets will be a unique contribution to our understanding of the local universe. SIM Lite will be able to tackle a wide range of interesting problems in stellar and Galactic astrophysics. By tracing the motions of stars in dwarf spheroidal galaxies orbiting our Milky Way, SIM Lite will probe the shape of the galactic potential history of the formation of the galaxy, and the nature of dark matter. Because it is flexibly scheduled, the instrument can dwell on faint targets, maintaining its full accuracy on objects as faint as V=19. This paper is a brief survey of the diverse problems in modern astrophysics that SIM Lite will be able to address.

1. INTRODUCTION

Precision astrometry is a versatile tool for many problems in astrometry. Space-based instruments offer the promise of much greater accuracy, and the ability to reach fainter magnitudes, than ground-based instruments. SIM Lite will be the first astrometric instrument capable of measurement to a precision of a few microarcseconds (μas) on faint targets. SIM Lite is based on the design for the Space Interferometry Mission (SIM) PlanetQuest, but is simpler and cheaper with only a modest reduction in overall science capability. SIM Lite is a Michelson interferometer operating in the optical waveband, with a 6m baseline, launched into an Earth-trailing orbit. It will have an accuracy of 4 μas for wide-angle astrometry (including parallax) on objects as faint as magnitude V = 19, and 1 μas in a narrow-angle frame, in a single visit to a target, as will be used for planet searches. Microarcsecond astrometry opens up a diverse range of science topics that can be addressed. This paper summarizes some of the opportunities that it represents.

SIM Lite has a Science Team comprising 15 scientists selected to conduct Key projects with the instrument, selected by NASA in 2000. The Team has worked with the project to help with the development of the instrument and operations concept for their science programs. The mission was originally called SIM PlanetQuest, and the science of that mission is described in detail in a large paper written by the Science Team (Unwin et al.[1]).

The SIM Lite design is very mature, the result of 10 years of development. In 2005 a program of technology development was completed, after extensive peer-review. SIM Lite meets the science recommendations of Astronomy and Astrophysics Decadal Surveys in 1990 and in 2000 (Bahcall[2], McKee & Taylor[3]). With almost the same accuracy as SIM PlanetQuest, SIM Lite observes about half the number of targets. By re-prioritizing science targets, the Science Team will be able to do the essentially same science problems as before.

In this paper, we outline some of the science highlights. To convey the breadth of the science, we list the Key Project topics covered by the SIM Science Team, which was competitively selected in 2000, and have been developing their science experiments and target lists. We also list the awards – 19 in all – from the recent SIM Science Studies proposal call. As examples of the details, we focus on just two topics – the search for Earthlike planets around nearby stars; and how astrometry contributes to our understanding of Dark Matter. A companion paper (Marr[4]) describes the development of the instrument, mission, and operations.

2. EXTRASOLAR PLANETS

Astrometric detection is one of the most important of several techniques for discovering and characterizing exoplanets, or planets orbiting other stars. SIM Lite detects the astrometric reflex motion of the planet on the star, allows the detection of planets that may 'hide' in the glare of the target star. Direct detection methods have the difficult task of separating the planet's like from that of the star, and the observability of a planet during only a small part of its orbit represents a major challenge, because it requires a telescope with high angular resolution as well as ultra-precision optics.

Exoplanets are such an important field, and SIM Lite's contribution so important, that up to half of the available observing may be devoted to this problem. The capability of SIM Lite is unique in that it can conduct a definitive survey of nearby stars (of all spectral types) for exoplanets with periods up to ~4 years, and masses as small as one Earth mass. In addition to detection, astrometry provides a direct measurement of the most fundamental quantity describing any astronomical object, namely its mass. Furthermore, SIM Lite delivers full orbital parameters for the planet. This is critical information for multiple planet systems, because indirect methods, such as the radial velocity (Doppler shift) method, cannot measure the orbit inclination. Masses, absent any information from RV on inclinations, are actually $M \sin i$. Measurements of mutual inclination are essential for an understanding of the formation, stability, and evolution of a multi-planet system. Such studies will greatly increase our understanding of how the planets in our local stellar neighborhood came to exist.

SIM Lite measures the star position relative to about four reference stars within about 1 deg. Its differential accuracy is 1 μas or better, achieved by rapid switching between the target and reference stars.

2.1 Exoplanet Search Program

SIM Lite has the capability to discover a significant number of terrestrial planets, for reasonable extrapolations of the frequency of planets based on today's knowledge. The number of Earthlike planets is unknown, of course. But the transit missions *CoRoT* and *Kepler* will provide key data, and allow us to optimize the SIM Lite strategy, since the instrument can be flexibly scheduled. If the frequency of 'Earths' is small, we would widen the search to many more stars, with a sensitivity of a few Earth masses. If Earths are common, then SIM Lite can focus more observing time on the closest stars, pushing to below 1 Earth mass in the most favorable cases. SIM Lite plans for exoplanets are:

1. Conduct a survey of the nearest ~60-100 stars for planets down to one Earth mass (orbit size taken here to be the middle of the 'habitable zone' of the star).
2. Measure masses. Masses are absolutely fundamental – an essential parameter defining the nature of a planet. Mass determines the ability of a planet to retain an atmosphere, which in turn may play a critical role in regulating the surface environment – perhaps a prerequisite for life.
3. Orbital dynamics. Eccentricity and inclination are important for understanding both the formation of a system, and the potential habitability of a planet. Multiple planets are of particular interest (see below), because they provide clues to the formation and stability of a system. In addition, we would of course like to know if our own Solar System is unique in some way, or is typical. Current data hints that it is unusual, but more complete and definitive data are needed.
4. Planetary diversity. SIM Lite can help us to understand the conditions under which planets form and evolve (see topic 5 below), but also the role that the parent star plays. For instance, RV surveys have not studied early-type stars. Do planets form more or less often around massive stars, and are they on average more massive? We can survey a large number of stars for

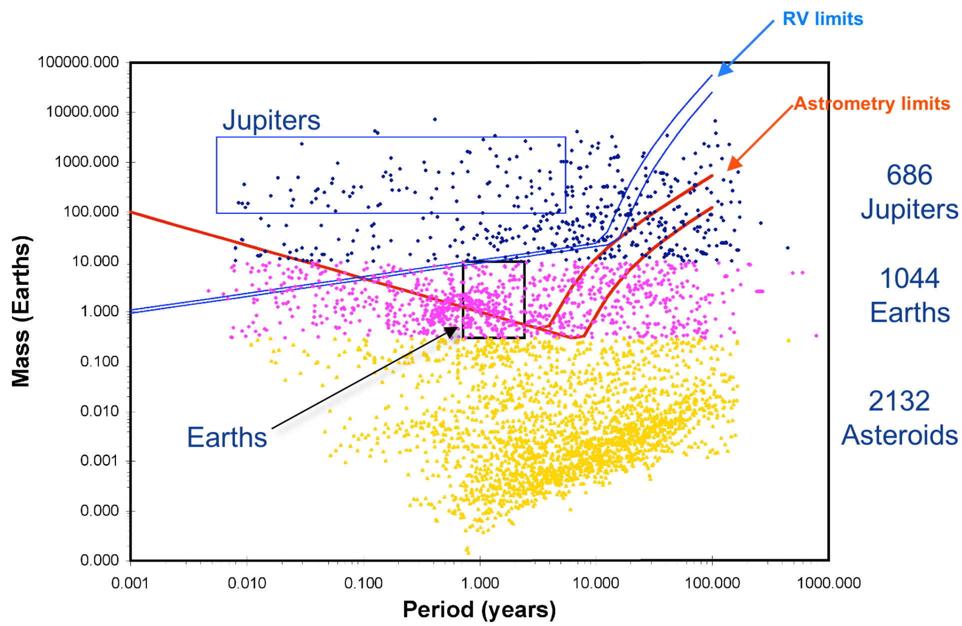

Figure 1 – The simulation data pool. The five data-generation teams made systems drawn from the population of objects shown here: a total of 3862 Objects orbiting 527 stars. Although one group added asteroids for completeness, as expected, none were detected in the simulations. The above distribution is consistent with the with the known distributions from observation (primarily RV), and that ~10% of stars have Jupiters (Cumming et al. [5]).

Neptune mass planets, and gather statistics that help to complete the overall picture of planetary systems.

5. Young planets. By searching for planets around young stars, with ages 1 – 100 Myr, we can learn much about young planets. When do they form, and in what orbits? Is migration actually seen in such systems? These are hard measurements to make because of stellar activity and circumstellar dust, but the astrometric method is much more robust than direct methods.

2.2 Multiple Planet Systems

2.2.1 A Double-Blind Simulation

SIM Lite recently completed a major simulation of its astrometric planet-finding capabilities. This was conducted in the framework of a *double blind test*, and the results were independently reviewed by a team of astronomers not involved with the creation of systems to test the instrument with, the generation of simulated data that SIM Lite would collect on such systems, or the analysis of the data and extraction of planetary signals. This powerful methodology of the double blind test has been used by the gravitational wave detection mission *LISA*, to verify the detectability of wave signals in realistic cases. Indeed, this approach to verifying the performance of any fundamentally new instrument which is yet to be build is key to building confidence that the requirements are properly defined, and that the instrument, once built, will deliver the intended science performance.

In all, this effort involved more than 30 astronomers during a period of several months. This work is just now being completed, and several papers are being written, but not available for reference yet.

Multiple planets are known to be fairly common, from RV studies (Butler et al.[6]). For each nearby star, there are either RV surveys underway or they will be added to existing observing programs. So, for the simulations, RV data were combined with SIM Lite data. These proved to be especially valuable in characterizing long-period orbits for which the duration of the mission limits the accuracy of parameter estimation (Eisner & Kulkarni[7]). SIM Lite observations can be spaced in time to provide sensitivity to planets of unknown period, over a wide range of periods (Ford[8]), although this was not done during the first phase of these simulations.

2.2.2 Simulation Description

Astrometric and RV data were generated for a total of 48 systems. Figure 1 shows the distribution of planet masses and orbit periods. One group included a population of asteroids for completeness. None were detectable by SIM Lite, and none were detected in the tests.

The simulations confirmed the level of signal-to--noise ratio (SNR) expected for detection from analytical calculations. Defining the SNR as the ratio of the astrometric signature divided by the 'mission noise' (effectively, the position error of an isolated star, in the local reference frame of the reference stars), we found a sharp transition at SNR 5.5 - 6 (Figure 2).

Five teams, working independently, developed model planetary systems. These were, reasonably enough, constrained to be consistent with the known (albeit incomplete) statistics of extrasolar planets. There is a potentially huge parameter space, so this was a necessary restriction.

Simulated astrometric data were generated by a team at the Michelson Science Center, taking these systems as input, and applying a realistic observing program as might be conducted by the actual SIM Lite instrument. The instrument measurement process was simplified to make the task tractable, but it retained all the relevant

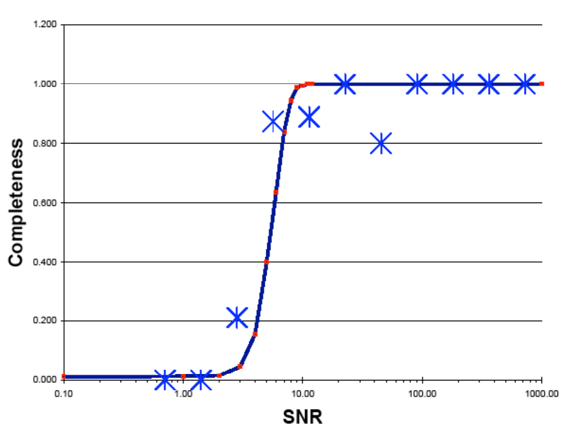

Figure 2 - Detected fraction of planets vs signal to noise in the simulated SIM Lite measurements

characteristics, which test the ability of the instrument to deliver planets from the simulated data. A second phase of the double-blind tests is planned for later in 2008, which will allow more of the parameter space to be explored, and a wider array of questions about planetary system detection to be addressed.

Another set of five teams, each working independently, and with no knowledge of the actual contents of the planetary systems in the data, analyzed the data, extracted planets with their key parameters (mass and orbit period), and an estimate of the confidence in each detection. There were differences in analysis methods, some proving to be more effective than others; the details are beyond the scope of this summary. Since the actual SIM Lite mission will of course learn from the experience gained, the true performance can be compared to that of the most successful team; this was a test of SIM Lite capability, not the skill of the independent teams

2.2.3 Simulation Results

There are many possible questions that could be posed of such a rich dataset. We restricted the problem, for the first phase of the double-blind tests to the following:

- What is the detection threshold (expect SNR~5.8 needed to detect a planet)
- Do other planets in the system interfere with the detection of terrestrial planets in the habitable zone?
- What is the reliability of a claimed detection? How many detections, divided by the number of detections plus false alarms?
- What is the completeness? (number detected divided by the number that were actually detectable)

We can ask the above questions for:

- All planets,
- Terrestrial planets,
- Habitable zone planets and
- Habitable Terrestrial planets.

Briefly, the results were as follows.

Indeed, a SNR ~ 5.5 is needed for detection (Fig. 2), and as expected, the transition is fairly sharp.

Perhaps the most important result is that multiple planets had little impact on the ability of SIM to find terrestrial planets in the habitable zone of a star. The impact of 'adding' planets to the detectability was no more than 10%. The cases in which the complexity overwhelmed the ability of the teams to correctly characterize the system were rare. In general, the parameters of very long-period planets were poorly constrained. A fairly sharp boundary exists at about 80% of the mission duration; reasonably enough, this corresponds roughly to having at least one 'closed' orbit. Long-duration RV data help a lot (all likely SIM Lite targets are already, or will be, the subject of such programs). For this study, the long-period planets were there as tests of the ability to extract terrestrial planets.

The reliability of detection varied between the teams, with three of the teams above 80%. One team achieved 98%. As noted above, it is reasonable for the mission to base its actual analysis on the methods of the most successful team.

Completeness was typically around 80%, but the best team actually achieved 100%, for terrestrial habitable-zone planets. This high level of completeness indicates the detection algorithms are very efficient – missing very few, while generating a minimal number of false alarms. Missing a few is of course not very significant for a groundbreaking mission like SIM Lite, which is exploring unknown territory. False alarms are bad if the occurrence is low (few stars harbor terrestrial planets), but in a catalog of many such detections, an occasional false alarm is entirely acceptable, and indicates that the data are being used efficiently.

2.3 Exoplanet Discovery Space

Returning to the likely prospects for the discovery of terrestrial planets, it is useful to view the search space as a period-mass plot (see Fig. 3). It illustrates the important point that for any given star, the SIM Lite dataset allows the detection of planets with a wide range of periods

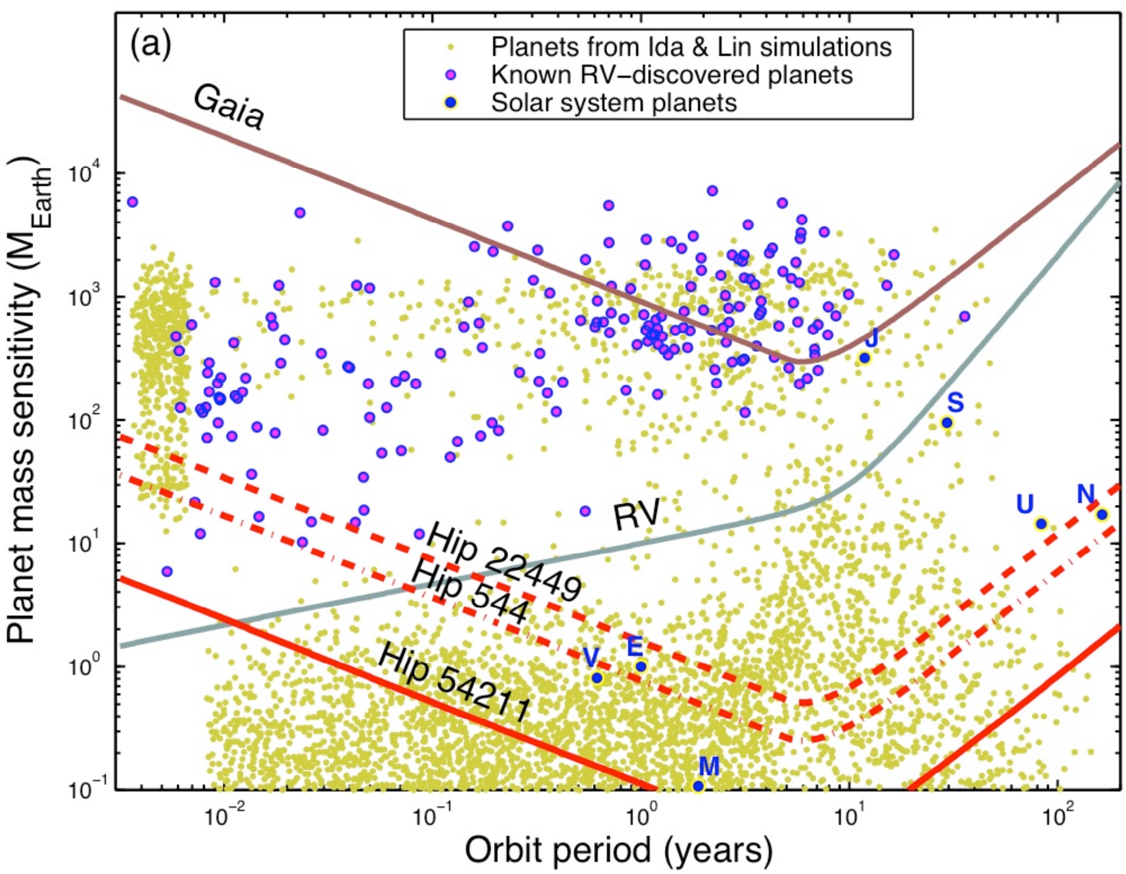

Figure 3 – The search space for extrasolar planets showing SIM Lite sensitivity. Shown as small dots are simulated planet distributions from the models of Ida & Lin[9]. The three curves labeled with Hipparcos numbers show the first, median, and last star in the SIM Lite sample, sorted according to planet detectability. Also shown are the typical sensitivities of GAIA, and radial velocity surveys. SIM Lite does not detect hot Jupiters, but explores deeply into the regime of terrestrial planets, ice giants, and gas giants at a wide range of orbital periods.

and masses. At short periods, the signature is smaller (and RV detection is more effective, as witnessed by the discovery of a large population of 'hot Jupiters'). RV has very limited capability for detecting ice giants, and terrestrial planets are likely not detectable except perhaps around a few M dwarfs and sub-stellar objects. At long periods, as noted above, the astrometric detectability (and ability to accurately measure parameters) is limited by the lack of complete orbit. From the ground, astrometric detection is less accurate and limited to the detection of giant planets and brown dwarfs (Han, Black & Gatewood[10]). For a 5-year nominal mission, the best sensitivity is slightly beyond the middle of the habitable zone. But note that for the closest stars, this allows the detection of sub-Earth mass planets, if such bodies exist. The scope for such discoveries with SIM Lite makes this an exciting mission.

Another unique contribution of SIM Lite will be its study of giant planets orbiting young stars. This program will determine the occurrence of Jupiter-mass planets around a sample of young stars with a range of ages. The objective is to understand the formation and evolution of planetary systems by observing young systems before they reach long-term equilibrium. Virtually all of our current knowledge is based on very mature systems which may have ceased any significant evolution. SIM Lite will observe about 200 nearby young, solar-type stars and will explore the early evolution of planetary systems, including planet interactions and migration.

3. GALACTIC DYNAMICS AND LOCAL DARK MATTER

Astrometry of stars as tracers of the mass distribution of the galaxy with SIM Lite will enable important and unique contributions to the understanding of Local Group dynamics and dark matter in the nearby universe.

The concordance Cold Dark Matter (CDM) model for the formation of structure in the Universe, while remarkably successful at describing observations of structure on large scales, continues to be challenged by observations on the scale of an individual galaxy. Fortunately, CDM models and their various proposed alternatives make a rich variety of testable predictions that make the Local Group and our own Milky Way galaxy key laboratories for exploring dark matter (DM) in this regime. Some of the most definitive tests of local DM require microarcsecond astrometry of faint sources, an astrometric regime that is a unique niche of the SIM Lite.

SIM Lite will address the following specific problems in galactic dynamics:

(1) Measuring the shape, orientation, density law and lumpiness of the dark halo of the Milky Way and other nearby galaxies;

(2) Determining the orbits of Galactic satellites, which may be representatives of late infall from the hierarchical formation of the Milky Way;

(3) Ascertaining the distribution of angular momentum and orbital anisotropy of stars and globular clusters in the outer Galactic halo, which hold clues to the early hierarchical formation of these systems;

(4) Measuring the physical nature of dark matter by measuring the phase space density in the cores of nearby dSph galaxies; and

(5) Reconstructing the dynamical history of the Local Group through the determination of orbits and masses of its constituent galaxies.

Here we illustrate just one of the ways in which SIM Lite astrometry can use fundamental dynamical measurements of galaxies to trace the influence of dark matter. Further examples may be found in the large science review paper by Unwin et al.[1]

Dark Matter in Dwarf Spheroidal Galaxies

Dwarf spheroidal galaxies can be used as a laboratory to test models of dark matter. Cold dark matter particles are described by small residual velocity dispersion and high phase-space density, resulting in steep density cusps in the central regions of galaxies (Navarro et al.[12]). Alternative models broadly classified as warm dark matter often predict constant density cores in galactic halos (Tremaine & Gunn[13]). They feature reduced phase space densities and higher velocity dispersions. Precisely measuring the log-slope of the central dark matter density profile places important constraints on the nature of dark matter.

Dwarf spheroidals are also unique among all classes of galaxies in their ability to probe the particle nature of dark matter, because phase-space cores resulting from the properties of the dark matter particle are expected to be most prominent in these small halos. Figure 4 explains

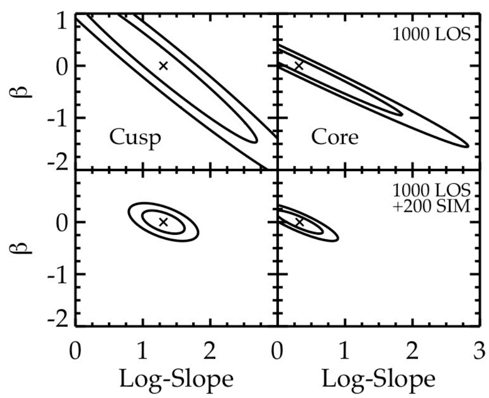

Figure 4. --Testing the nature of dark matter using observations of Sph stars, from analytical modeling by Strigari et al.[10]. Each panel shows the 68% and 95% confidence regions for the errors in the measured dark halo density profile (log) slope (measured at twice the King core radius) and velocity anisotropy parameter β for a particular dSph. In the upper plots, derived from line-of-sight (RV) velocities for 1000 stars, the two parameters are highly degenerate, for both a cusp model (left panel), and core model (right panel). The addition of 200 proper motions from SIM providing 5 km/s precision transverse velocities (lower panels) dramatically reduces the uncertainty in both parameters.

the significance of the astrometric observations of stars in a dwarf spheroidal, in distinguishing between a cusp and a core, which are key discriminants between CDM and warm dark matter.

4. SCIENCE TEAM PROJECTS

The SIM Lite Science Team comprises 15 members, and more than 60 co-investigators and collaborators, selected via NASA Announcement of Opportunity in 2000. Ten members lead Key Projects, which are major investments of SIM observing time. Five members are Mission Scientists, with smaller observing programs; these scientists were selected for specific expertise recognized to be of value in the development of the instrument and mission.

Here we list the investigations; the proposal summaries and full texts are available on the SIM Lite website[14]:

SIM Lite Key Projects

"Discovery of Planetary Systems", Geoffrey W. Marcy, University of California Berkeley

"Extrasolar Planets Interferometric Survey", Michael Shao, JPL (Project Scientist)

"The Search for Young Planetary Systems and the Evolution of Young Stars", Charles A. Beichman, California Institute of Technology

"Stellar, Remnant, Planetary, and Dark-Object Masses from Astrometric Micro-lensing", Andrew P. Gould, Ohio State University,

"Dynamical Observations of Galaxies", Edward J. Shaya, University of Maryland

"Astrophysics of Reference Frame Tie Objects", Kenneth J. Johnston, U.S. Naval Observatory

"Anchoring the Population II Distances and Ages of Globular Clusters", Brian C. Chaboyer, Dartmouth College

"Determining the Mass-Luminosity Relation for Stars of Various Ages, Metallicities and Evolutionary States", Todd J. Henry, Georgia State University

"Taking the Measure of the Milky Way", Steven R. Majewski, University of Virginia

"Binary Black Holes, Accretion Disks and Relativistic Jets: Photocenters of Nearby Active Galactic Nuclei and Quasars", Ann E. Wehrle, California Institute of Technology

SIM Lite Mission Scientists

"Open and Globular Cluster Distances for Extragalactic, Galactic, and Stellar Astrophysics", Guy P. Worthey, Washington State University

"Masses and Luminosities of X-Ray Binaries", Andreas Quirrenbach, Leiden University

"A New Approach to Micro-arcsecond Astrometry with SIM Allowing Early Mission Narrow Angle Measurements of Compelling Astronomical Targets", Stuart Shaklan, JPL

"Exceptional Stars Origins, Companions, Masses and Planets", Shrinivas R. Kulkarni, California Institute of Technology

"Synthesis Imaging at Optical Wavelength with SIM", Ronald J. Allen, Space Telescope Science Institute

5. SIM SCIENCE STUDIES

In 2008 the SIM Lite project and the Michelson Science Center (MSC) invited proposals to the "SIM Science Studies". The purpose of this proposal call was to enhance the science return from SIM Lite by inviting astronomers to study new science ideas and concepts for novel experiments.

A total of 19 proposals were accepted for one-year studies. The awards cover a wide range of topics in astrometry. Some of these build on the science themes defined by the SIM Science Team (see above). Others will explore other science areas not already covered. The most effective use of this new capability requires not only careful selection of science targets and observing strategies, but also community input as to innovative ideas that take full advantage of SIM's precision, sensitivity, and flexibility.

These studies are just now getting underway. Although no SIM Lite observing time is assigned to the studies, the science concepts that they explore will be prime candidates for the Guest Observer Program which will be announced approximately 2-3 years before SIM launch. As noted above, SIM Lite is a flexibly scheduled observatory: a Guest Observer Program is a recognized and effective way for the community to participate in a facility instrument.

Details of the 19 SIM Science Study awards may be found on the MSC website[15]; listed here are the Principal Investigators and study titles, loosely grouped according to topic:

<u>Extrasolar Planets and Planetary Systems</u>

Eric Ford, University of Florida – Detection and Characterization of Resonant Planetary Systems with SIM

Bernard Gaudi, Ohio State University – Measuring the Astrometric Signature of Transiting Planets with SIM

John Subasavage, Georgia State University – SIM's Search for Planets Orbiting White Dwarfs

Angelle Tanner, JPL/SBAR – Detecting Terrestrial Mass Planets Around M-dwarfs: Is SIM Competitive?

Keivan Stassun, Vanderbilt University – Planets in Binary Star Systems: A Catalog of Wide, Low-mass Binaries for the SIM Science Community

Rob Olling, University of Maryland – Searching for Solar System Giant Analogs with SIM PlanetQuest

<u>Dark Matter and Galactic Dynamics</u>

Manoj Kaplinghat, UC Irvine – Determining the nature of dark matter using proper motions of stars in the Milky Way satellites

Rob Olling, University of Maryland – 1% Luminosity-Independent Distances to Nearby Galaxies with the Rotational Parallax Technique

William Hartkopf, US Naval Observatory – Project Runaway: Calibrating the Spectroscopic Distance Scale using Runaway O and Wolf--Rayet Stars

<u>Precision Stellar Astrophysics</u>

Stephen Ridgway, NOAO – Stellar Astrophysics with SIM and Optical Long Baseline Interferometry

Jonathan Tan, University of Florida – Dynamical Processes in Massive Star and Star Cluster Formation

Wei-Chun Jao, Georgia State University – Parallax Observations of Local Supergiants

Jay Holberg, University of Arizona – A Novel SIM-Based Technique for the Precise Determination of Absolute Stellar Fluxes

John Tomsick, UC Berkeley – How Well Can SIM Measure Parameters of Neutron Star and Black Hole Binaries?

Adam Kraus, Caltech – The Dynamical Legacy of Star Formation

Ruth Peterson, Astrophysical Advances – NGC 6791: SIM plans for binaries, colors, and parallaxes

<u>The Uncharted Waters</u>

Guillem Anglada-Escude, Carnegie Institute of Washington – Gaia-SIM legacy project

Dawn Gelino, Caltech – Determining How the True Reflex Motions and Dynamical Orbits for Interacting Binaries Depend on Photocenter Contamination

Marc Kuchner, NASA GSFC – Sizes and Shapes of Kuiper Belt Objects and Centaurs with SIM.

6. CONCLUSION

SIM Lite represents an entirely new capability in space-based astronomy – the ability to use precision astrometry to address questions across wide areas of astrophysics, from extrasolar planets as small as Earth to the most powerful and distant quasars. At SIM Lite's level of accuracy, every star that it observes moves across the sky. Orders-of-magnitude improvements in accuracy, allow it to challenge fundamental models, for the first time in some cases. As a facility instrument, the Guest Observer Program will offer the astronomical community a unique opportunity to make entirely new kinds of measurements of objects of interest. Furthermore, SIM Lite leads the way to a new generation of dilute-aperture instruments, breaking the paradigm of sensitivity and resolution being tied together; space instruments based on interferometry are the future of astronomy.

ACKNOWLEDGMENTS

This paper captures in a small way the combined efforts of the scientists, engineers and support personnel from the Exoplanet Exploration Program and SIM-Lite project team, whose superb efforts have generated the technology results and the concepts and designs which hold so much promise of future scientific discovery.

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