V

Charting the Uncharted Waters

Can we understand resonant planetary systems?

Can we determine if white dwarfs have planets?

What can dwarf spheroidal galaxies tell us about dark matter?

What can dynamics tell us about star formation?

THROUGH SPACE
THE UNIVERSE
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THROUGH
THOUGHT
I COMPREHEND
THE WORLD.

Blaise Pascal

13 SIM Lite Science Studies

Rachel Akeson (NExScI)

ABSTRACT

In April 2008, the SIM Project and the Michelson Science Center (MSC, now called the NASA Exoplanet Science Institute, NExScI) released a Request for Proposals (RFP) entitled "SIM Science Studies." The objective of this solicitation was to enhance the science return from SIM Lite by supporting researchers to conduct concept studies that will lead to the most scientifically productive observations using SIM Lite. SIM Lite will offer astronomers a fundamentally new class of astronomical observations. The most effective use of this new capability will require not only careful selection of science targets and observing strategies, but also will require community input of innovative ideas that take full advantage of SIM Lite's precision, sensitivity, and flexibility.

Responses to the RFP were solicited in all areas of astrophysics that are enabled by observations with SIM Lite, including, but not limited to, modeling of dynamical or physical processes to be studied with SIM Lite, the selection of suitable targets, assessment of instrument performance, and the design of observing sequences to take best advantage of SIM Lite's flexible scheduling. Although no SIM Lite observing time was awarded through this call, it is expected that the results of these studies will enable the teams to produce competitive observing proposals in the next general observing call for SIM Lite.

Twenty-five proposals were received in response to the call. Three panels of external reviewers were convened, and, with the overall review committee chair, Frank Shu, made recommendations

to fund all or part of 19 of the proposals. The selected studies cover the full range of SIM Lite astrophysics from objects within our own Solar System to black hole binaries to nearby galaxies. The titles and abstracts of the selected proposals are given below.

Each team will conduct their proposed study over a period of 12 to 18 months and produce a final report detailing their findings. Each team will also present these findings at a meeting of the American Astronomical Society. The final reports and presentations to the entire astronomical community will be published to disseminate the lessons learned during the studies.

13.1 Planets and Planetary Systems

Detection and Characterization of Resonant Planetary Systems

Eric Ford (U. Florida)

The combination of SIM Lite and long-term, high-precision radial velocity (RV) observations will provide a unique tool to precisely measure planet masses and orbital elements, enabling precision dynamical modeling. Since some (but not all) planet formation models predict that many low-mass planets may be found in mean-motion resonances (MMRs), measuring the frequency of such planets will test planet formation models. For technical reasons, detecting and characterizing such planetary systems may be significantly more challenging than in the case of nonresonant planetary systems. We propose to explore the sensitivity of combined SIM Lite and RV data for detecting planets in or near MMRs. We will study how the number and time span of observations affect the detection probability and the precision of orbital elements for resonant planetary systems. We will identify when it is essential to include mutual planetary interactions and pay particular attention to identifying what types of planetary systems and observing strategies would be able to distinguish systems "in resonance" from those "near resonance." Our results will help to inform the design of SIM Lite planet searches and could lay the foundation for a future SIM Lite observing proposal to determine the frequency of resonant planetary systems as a function of mass and orbital period. Ultimately, we aim to improve the capability of SIM Lite observations to test, and perhaps distinguish, between models of planet formation, migration, and eccentricity excitation.

Measuring the Astrometric Signature of Transiting Planets

B. Scott Gaudi (Ohio State U.)

When a planet with radius R_p transits in front of its parent star with radius R_*, the flux of the star decreases by a fractional amount $r^2 = (R_p/R_*)^2$, while the stellar photocenter shifts by $r^2\theta_*$, where θ_* is the angular radius of the star. For the nearest transiting planets, this shift is of order μas and so is within the reach of SIM Lite. Measurement of the astrometric shift during transit yields the angular radius of the star, which, when combined with the stellar density determined from the photometric light curve and the stellar parallax, yields the radius and mass of the star. This astrometric shift also allows one to determine the planet's (three-dimensional) orbit, including the direction of the vector normal to its orbital plane, which is useful for a number of applications. I propose to perform an in-depth study of the astrometric signature of transiting planets as applied to SIM Lite, and in particular fully explore the feasibility of detecting this signature, considering all practical aspects, including mission scheduling and pointing constraints. In addition, I will consider the astrometric signature of eclipsing binaries.

Search for Planets Orbiting White Dwarfs

John Subasavage (Georgia State U.)

Once launched, SIM Lite will be the most precise astrometric instrument ever developed. These capabilities are vital to exoplanetary studies, in particular, for low-mass, Earth-like planets. I propose to use SIM Lite to observe a sample of ~25 nearby white dwarfs in hopes of detecting planetary companions with masses in the 10 $M_{\oplus}$ range. Because of the nature of white dwarfs' spectral signatures (a few broad, if any, absorption lines), current radial velocity planet hunting techniques are not viable. Astrometry is currently the only technique capable of detecting low-mass planets around white dwarfs, and SIM Lite is the best-suited astrometric instrument to do so. One advantage of white dwarfs is that they have lost a significant amount of mass during their evolution so that an astrometric signature is amplified when compared to an identical system around the more-massive progenitor.

Planetary detections around white dwarfs would better enable us to probe planetary formation theory as well as planetary evolution theory in conjunction with stellar evolution. Because astrometric signatures are inversely related to distance, the closer the system, the larger the signature (all else being equal). Since most stars will eventually end their lives as white dwarfs, these objects are plentiful and on average closer to the Sun than are more-rare objects. Thus, a number of white dwarfs are close enough to the Sun to permit low-mass planetary signature detections. Given that white dwarfs are the remnants of main-sequence dwarfs with spectral classes from B to K (thus far), we could better understand planetary formation over a broader range of objects than those currently investigated using radial velocity techniques (primarily F, G, and K stars).

Detecting Terrestrial Mass Planets Around M-Dwarfs

Angelle Tanner (Santa Barbara Applied Research)

In the past few years, there have been public claims that SIM Lite is unnecessary as a terrestrial planet search tool since radial velocity studies will be able to reach sensitivities of 10 cm/s. This is adequate to detect terrestrial planets in the habitable zones of M and K dwarfs. However, it has not been demonstrated that the RV technique will be sensitive to terrestrial planets at these separations under the different sources of stellar jitter inherent to M dwarfs — granulation, star spots, flares, and p-mode oscillations. Therefore, we have designed a study to investigate the astrophysical jitter inherent to potential SIM Lite M dwarf targets using spacecraft, including Convection, Rotation, and Planetary Transits (CoRot), Hubble Space Telescope, Spitzer Space Telescope, Microvariability and Oscillations of Stars (MOST), and ground-based, ultraprecise photometric data. The goal of the study will be to present a thorough comparison of the sensitivity to terrestrial planets using either SIM Lite or 10 cm/s radial velocity measurements with realistic noise sources. Since the exoplanet taskforce has recently placed M dwarfs as high-priority targets, the results of this study can be used to guide near-term planet search programs as well as promote SIM Lite.

Planets in Binary Systems: A Catalog of Wide, Low-Mass Binaries for SIM

Keivan Stassun (Vanderbilt U.)

A critical piece of SIM Lite exoplanet science will be to determine the frequency and nature of planets in binary star systems. Among the most scientifically interesting of these will be wide, low-mass binaries, in which planetary orbits about one or both stars are stable and where the detection of planets in the habitable zone is most feasible. We are assembling the largest catalog to date of wide (typical orbital separations ~3000 AU), low-mass (typical spectral type ~M0) binaries. The binaries in our sample are in a range of brightness easily amenable to study with SIM Lite. Importantly, our sample includes a broad diversity of stellar subpopulations that is of considerable interest for determining the frequency of planets in different regimes of parameter space: stellar mass ratios, metallicity, age, activity, and dynamical history. Finally, to explore the value-added stellar science made possible with our sample, we will study the extent to which multiple observations of these binaries with SIM Lite's exquisite astrometric precision will permit the determination of orbital parameters and dynamical stellar masses with which to test stellar evolutionary models.

Searching for Solar System Giant Analogs

Robert Olling (U. Maryland)

SIM Lite astrometry, in combination with Hipparcos data and other astrometric observations from the 20th century, can uncover giant extrasolar planets with masses exceeding Jupiter's with orbital periods up to about 200 years. At a mission time of less than 2.5 hr per star, SIM Lite could survey 500 to 1000 nearby stars to determine the frequency of very-long-period, massive extrasolar planets. Detection of planetary companions can be achieved for systems with periods up to about 1000 years. Current theories of planet formation predict that migration moves the outer cutoff of giant planets from the ~200-yr to the ~600-yr regime. Our proposed survey will probe giant planets and light brown dwarfs with these periods and can help constrain planetary migration models. We propose to study how well period and mass estimation will work in the long-period regime, with a major focus on the effects of elliptical orbits. In addition to the Hipparcos data, astrometric catalogs dating back as far as 90 years are expected to significantly constrain the presence of high-mass companions such as brown dwarfs. We will also investigate alternate observing strategies that could reduce the required mission time by a factor up to about four.

13.2 Dark Matter and Galactic Dynamics

Determining the Nature of Dark Matter Using Proper Motions of Stars in the Milky Way Satellites

Manoj Kaplinghat (UC Irvine)

Dwarf spheroidal (dSph) satellite galaxies in the Local Group provide ideal laboratories for deciphering the nature of dark matter and testing theories of hierarchical structure formation on small scales. Theoretically, their status as the most dark-matter-dominated galaxies in the Universe enables the determination of their dark matter density structure without the intrinsic uncertainties usually associated with baryonic mass contributions. Observationally, their proximity allows for detailed studies of their dark matter density structure via proper motion studies with SIM Lite. Moreover, the intrinsically high phase-space densities of these small galaxies make them ideal candidates for constraining the particle properties of dark matter. We propose to develop methods to use proper motion measurements to constrain fundamental properties of the dark matter particle. In the standard model, the dark matter is a cold thermal relic and is born with a high primordial phase-space density that allows the dark matter to collapse into halos with very steep density cusps in their centers. Observations of dark-matter-dominated galaxies suggest that dark matter halos may have shallow density slopes in their centers, which is more suggestive of "warm" dark matter models. However, there are several potential systematic problems with interpreting these observations associated with uncertain baryon physics. We propose to develop methods to constrain the central densities of dwarf spheroidal galaxies using proper motion observations. While line-of-sight motions alone are unable to place constraints on the log-slope, proper motions will provide a definitive measurement of the log slope and a direct way to connect the dynamic properties of stars in local dwarf galaxies to the microphysical properties of dark matter. We will identify the best Milky Way satellite candidates for this purpose and develop the theoretical machinery necessary to connect measured log-slopes to constraints on the primordial phase-space density of dark matter and to the microphysical properties of the dark matter particle.

Using Rotational Parallax to Estimate 1 Percent Luminosity-Independent Distances to Nearby Galaxies

Robert Olling (U. Maryland)

SIM LIte can provide data with high enough quality to determine luminosity-independent distances to the nearest spiral galaxies by employing the rotational parallax (RP) technique. Since proper motion is defined as velocity over distance, the distance follows from proper motion and radial velocity observations. An accuracy of around 1 percent is possible for M31 and M33 using about 200 stars per galaxy. Due to its large random internal motions, the Large Magellanic Cloud (LMC) is not a SIM Lite target for RP. A 1 percent error is ~8 times better than the systematic error on H_0 attained by the Hubble Space Telescope, the Wilkinson Microwave Anisotropy Probe (WMAP), and extragalactic water masers. In our review of methods that can potentially yield extragalactic distances at the 1 percent level, we find that the RP method is the most accurate distance indicator because: 1) it is a 100 percent geometric method (e.g., eclipsing binaries also rely on astrophysics to derive distances), and 2) it samples a large part of the stellar disk so that non-axisymmetric motions can be determined accurately (e.g., in contrast to nuclear water masers that sample just three lines of sight). It has been shown that knowledge of the Hubble constant to better than 1 percent is crucial for constraining the equation of state of dark energy, in combination with Planck data. Accurate RP distances facilitate detailed comparisons between almost all standard candles between various zero-points (MW, M31, M33, the LMC, and NGC4258). Successful cross-checks are crucial if we are to believe galaxy distances (and H_0) at the 1 percent level. The RP technique may be complicated by noncircular motions that could be due to, for example, spiral structure. However, the initial analyses suggest that these effects can be diagnosed and remedied. Because SIM Lite will provide five-dimensional phase space information, the RP galaxies (along with the Milky Way) will be the galaxy-dynamics laboratories for decades to come. Currently, there is no RP SIM Lite project, while the Key Project on proper motions of nearby galaxies will observe just a few stars per galaxy. We propose extensive theoretical analyses of the RP technique, focused on noncircular motions. In addition, we will investigate observational aspects such as the trades between the number of stars, the accuracy per star, and mission time. We will also specify the requirements of a locally defined astrometric grid.

Project Runaway: Calibrating the Spectroscopic Distance Scale Using Runaway O and Wolf-Rayet Stars

William Hartkopf (USNO)

Massive stars play an essential role in enriching the interstellar medium with material later recycled into stars and planets. However, the most basic information about these stars — their masses — is not well-determined. Major reasons for this include high multiplicity rates, crowded fields, and interstellar extinction, all leading to poorly known distances. Runaway O stars can provide a potential “clean sample” of single O stars that reduces some of these problems, allowing much more accurate calibration of the spectroscopic distance scale. We propose to verify the runaway nature of the current tentative list of these objects and to augment that list from current catalogs of O stars and Wolf-Rayet stars, using new proper motion information from the upcoming *Third USNO CCD Astrograph Catalog* (UCAC3). The new runaway sample will provide an observing list for SIM Lite parallax determinations of these important objects. SIM Lite has distinct advantages over Gaia in its ability to provide these new parallaxes.

13.3 Precision Stellar Astrophysics

Stellar Astrophysics with SIM and Optical Long Baseline Interferometry

Stephen Ridgway (NOAO)

This proposal addresses several interesting and important astrophysical questions concerning stars. SIM Lite astrometry will be used in combination with precision ground-based measurements, particularly optical interferometry, and supporting modeling. We will extend an ongoing study of Cepheid stars, with emphasis on resolution of possible biases in the use of the P-L relation, aiming for a confidence level of better than 1 percent. We will determine the radii, T_{eff}, luminosity, and, in some cases, masses of massive stars with sufficient accuracy to validate models of their structure and evolution with dramatically improved discrimination. We will determine the orbits of post-Algol systems, to test the hypothesis that they are the precursors to cataclysmic variable stars and the wide variety of evolved objects that they produce. We will measure the radii of nearby stars to support asteroseismological studies of the stellar interiors. For all measurements here proposed for SIM Lite, Gaia will not provide a realistic alternative, owing to brightness of the targets, expected errors, and/or required observational cadence.

Dynamical Processes in Massive Star and Star Cluster Formation

Jonathan Tan (U. Florida)

We propose to carry out a detailed study of how high-precision astrometric measurements by SIM Lite of stars involved in dynamical ejection events from star clusters can constrain theories of massive star and star cluster formation. Our study focuses on the Orion Nebula Cluster (ONC) and has two distinct parts. First, we will investigate the rich scientific potential associated with an accurate measurement of the distance and proper motion of Theta 1 Orionis C, which is the most massive star in the cluster and was recently involved (about 4000 years ago) in the ejection of a now embedded B star: the Becklin-Neugebauer (BN) star. The motion of the BN star has taken it close to a massive protostar, known as source I, where it appears to have influenced the accretion and outflow activity, most likely by a tidal interaction with the accretion disk. An accurate proper motion measurement of Theta 1 Orionis C will constrain BN's initial motion, allowing us to search for deflections caused by the gravitational potential of the massive protostar. Second, we will search the Hipparcos catalog for candidate runaway stars, i.e., that have been dynamically ejected from the cluster over the course of the last several Myr. SIM Lite observations of these stars will be needed to confirm their origin from the ONC. The results of this study will constrain the star cluster formation time scale and the statistics of the population of ejected stars.

Parallax Observations of Local Supergiants

Wei-Chun Jao (Georgia State U.)

We propose to use SIM Lite to measure accurate parallaxes of supergiants in the near spiral arms of the Galaxy. All selected targets have V < 6, so that no other astrometry effort in this era — not the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), the Large Synoptic Survey Telescope (LSST), nor Gaia — can observe them because of those projects' bright-magnitude cutoffs. SIM Lite offers unique opportunities to measure the first-ever meaningful parallaxes to a few µas precision for a large sample of supergiants. The improved parallaxes will provide accurate supergiant luminosities so the supergiants can be placed on the HR diagram and will permit the eventual derivation of their stellar radii and mass loss rates at dramatic moments in the evolution of massive stars. In addition, hidden among the supergiant sample are luminous representatives of object classes that can potentially be used as reliable extragalactic distance estimators. Because so few supergiant distances are currently known, this work will undoubtedly yield fundamental breakthroughs in stellar astrophysics, and will likely lead to new insights that cannot yet be anticipated.

A Novel Technique for the Precise Determination of Absolute Stellar Fluxes

Jay Holberg (U. Arizona)

We propose a novel use of SIM Lite parallaxes to provide a geometrically based determination of absolute stellar fluxes. Our method relies on the use of accurate model-based fluxes for precisely characterized DA (pure-hydrogen) white dwarfs that are directly normalized to observed SIM Lite parallaxes rather than to a traditional Vega-based photometric flux scale. It has already been demonstrated that parallaxes (and absolute magnitudes) derived from broadband photometry for DA white dwarfs are consistent with currently existing trigonometric parallaxes for these stars at the 1 percent level. This study will investigate the logical extension of our technique: the direct calibration of absolute stellar flux scales below the 1 percent level using precise parallax data.

How Accurately Can SIM Measure Parameters of Neutron Star and Black Hole Binaries?

John Tomsick (UC Berkeley)

The vast improvement that SIM Lite will provide for astrometry will allow for the measurement of orbital motions of many types of binary systems. Some of the most interesting cases are the binaries for which one component is a compact object. This proposal focuses on the advances that SIM Lite will allow in the study of neutron stars and black holes. In particular, we are proposing to perform simulations to determine how accurately SIM Lite will be able to measure the orbital parameters of X-ray binaries, including compact object masses. In the neutron star case, a direct dynamical mass measurement will be possible, and SIM Lite is critical for measuring the parameters, such as binary inclination and source distance, that are the most difficult to determine with current techniques. We have experience with performing realistic SIM Lite simulations for X-ray binaries and for planetary studies, and we expect that our work will lead to improved computer code for analyzing SIM Lite data, optimizing SIM Lite observing strategies, and choosing the best reference stars as well as targets.

The Dynamical Legacy of Star Formation

Adam Kraus (Caltech)

Star clusters are the primary sites of star formation, and cluster evolution establishes the environment within which star and planet formation occur. The internal kinematics of young clusters directly constrain the initial conditions and early evolution, but the typical proper motion dispersions (<1 to 2 km/s; <1 mas/yr) are impossible to measure from the ground. SIM Lite's unprecedented astrometric capabilities represent a transformative opportunity for studying the primordial kinematics of young clusters, reaching precisions of 5 to 10 m/s for the nearest star-forming populations. We propose to study the requirements and expected results for a kinematic survey of nearby young clusters and associations. The first stage of our study will use existing RV surveys and new statistical methods to estimate the velocity dispersion as a function of angular scale for these target populations. We will then use results from the literature, including our numerous high-resolution imaging surveys, to screen unsuitable candidate targets like binary systems and spatially resolved edge-on disks. Finally, we will estimate the total mission time required to study each association and will recommend a final set of targets that maximize the scientific return from this unprecedented survey.

NGC6791: SIM Plans for Binaries, Colors, and Parallaxes

Ruth C. Peterson (UCO/Lick Observatory)

We propose to investigate how to determine (1) the distance to the open star cluster NGC6791 from SIM Lite–based parallax measurements of stars we have identified as single; (2) the masses of one or two subgiants we have identified in binaries, from SIM Lite–based astrometric determinations of the orbit of the primary and the radial velocity displacement of primary and secondary; and (3) the frequency and mass–ratio distribution of its substantial population of binaries, from existing photometry and future radial velocity measurements. To better constrain membership and binarity of stars in the NGC6791 field, we will take advantage of our ongoing decade-long program that has determined radial velocities good to 0.2 km/s for all 88 red stars with V < 14.7 and monitored their variability. The goal is to ultimately provide from SIM Lite observations an improved parallax distance for NGC6791, and the masses of stars in binary systems consisting of one subgiant or giant and one near-main-sequence star, which will stringently constrain calculations of single-star evolution at high metallicity. Independent of SIM Lite observations, we also propose to establish 4) how to determine reddening, temperature, metallicity, and binarity simultaneously at high metallicity from panchromatic color information. We plan to do this empirically by constructing color–color diagrams from existing photometry in a multitude of bandpasses for the cluster. We will then attempt to model each diagram theoretically, by extending calculations of fluxes and colors for solar-metallicity and metal-rich stars across the range of temperatures from the giant branch to the main sequence. By itself this will yield color conversions from the observational color-magnitude diagram (CMD) colors to the physical stellar parameters of temperature and metallicity, also of critical importance to age and metallicity determinations based on comparing cluster CMDs to theoretical isochrones. Applied directly to NGC6791 photometry, it will yield constraints on the frequency and mass ratio distribution of cluster binaries.

13.4 The Uncharted Waters

Gaia–SIM Lite Legacy Project

Guillem Anglada-Escude (DTM/Carnegie Institution of Washington)

According to current plans, the NASA SIM Lite mission with be launched just after the end of operations of the ESA Gaia mission. This is a new situation that enables long-term astrometric projects that could not be achieved by either mission alone. In some cases, it may increase the science value of SIM Lite targets with a much smaller effort than originally assumed. This SIM science study will be the first to analyze in detail this new situation and try to explore the benefits that can be obtained by both communities (NASA and ESA) by combining both data sets. A few particular science targets will be analyzed in great detail to prove with examples the capabilities of long-term astrometric coverage. Before any attempt at combining both data sets, several issues must be addressed, such as the reference frame used and the precise coordinate definition of the observable quantities in both missions.

Effect of Photocenter Contamination on the Estimation of Reflex Motions and Dynamical Orbits for Interacting Binaries

Dawn Gelino (NExScI)

We propose to investigate how SIM Lite can best be utilized to attain accurate masses for the primary and secondary stars in interacting binary systems. Currently, there are two SIM Lite Key Programs to measure the masses of black holes and neutron stars in binary systems. Accurate and precise orbital solutions are needed across the full mass spectrum of interacting binaries in order to fully understand the secular evolution of binary systems. A more complete picture of stellar evolution requires the inclusion of lower-mass degenerate stars. These interacting binaries are complex, including a degenerate primary star, a main sequence or giant secondary star, and accretion material flowing from the secondary to the primary. We propose to investigate many systems in each interacting binary class spanning the entire range of primary component masses in order to study the effects of multiple luminosity components on the apparent photocenter of the system and its apparent motion. This work will allow us to quantify the effect of photocenter determination, extract true orbital parameters, and determine masses of the interacting binary stellar components. Photocenter contamination is an issue that affects all interacting binaries, including those sources already selected by SIM Lite for study. Our work will benefit the entire SIM Lite community.

Sizes and Shapes of Kuiper Belt Objects and Centaurs with SIM

Marc Kuchner (GSFC)

We propose to study and plan a SIM Lite survey of giant Kuiper Belt objects (KBOs) and Centaurs, their dynamical relatives. This survey will measure precise sizes and shapes of these newly discovered primordial objects, constraining their compositions, material strengths, and other properties in a way no other technique can. We will use Hapke models of rotating bodies combined with light curve data and thermal measurements to model the visibilities of these targets and select an optimal observing strategy. We will investigate non-sidereal tracking and the use of the co-linear guide interferometer baseline to do visibility science.