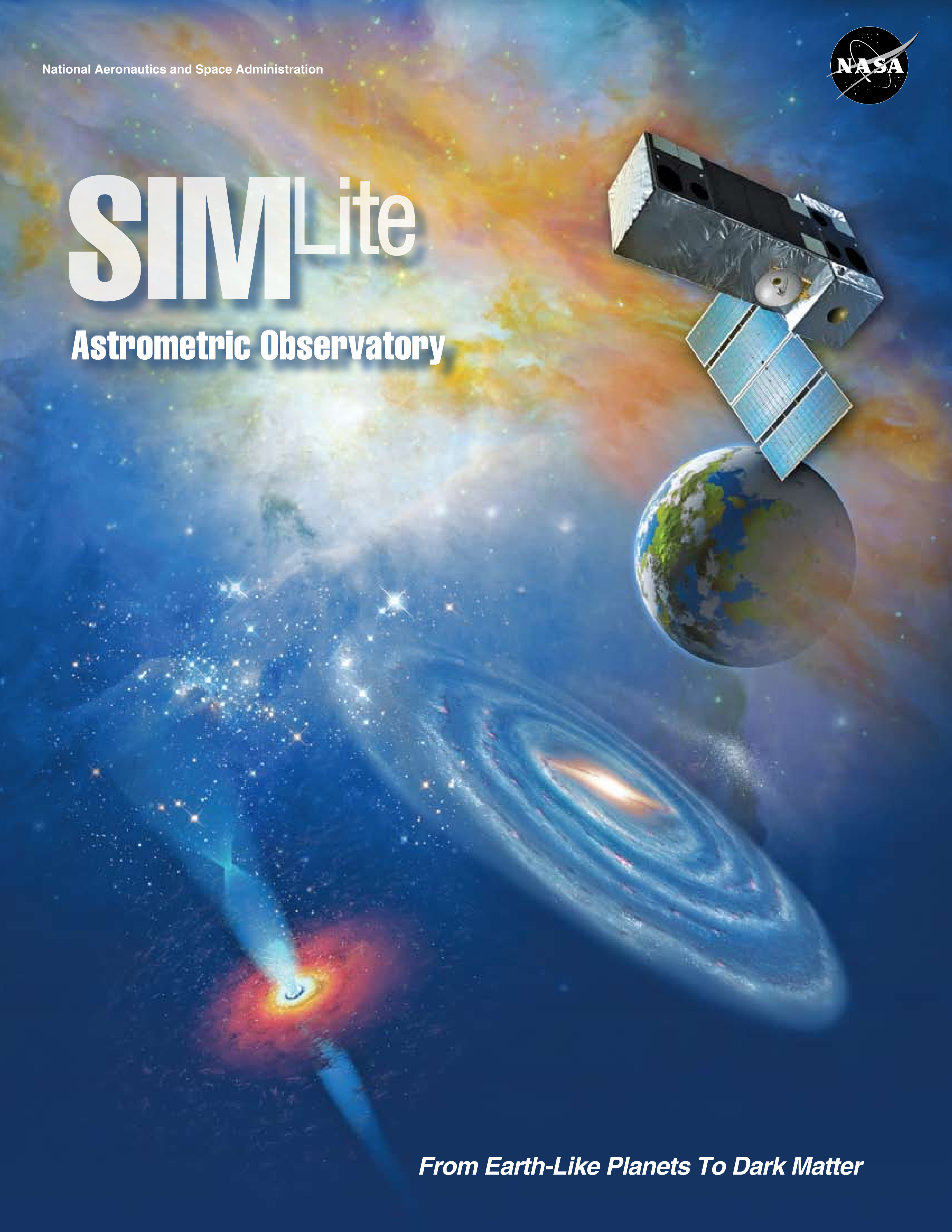
National Aeronautics and Space Administration

SIM Lite

Astrometric Observatory



From Earth-Like Planets To Dark Matter

ON THE COVER

The front cover picture is a montage illustrating the project's key science themes.

SIM Lite will search for Earth-like planets, examining over 60 nearby stars for evidence of habitable worlds, and will conduct a survey of young stars as part of a larger effort to map the birth, evolution, and architectures of planetary systems.

SIM Lite will probe the nature of dark matter and its role in the formation of galaxies. Dwarf spheroidal galaxies will be used as test particles to validate models of dark matter distribution in the Milky Way and the Local Group.

SIM Lite will make ultraprecise measurements of stellar masses, luminosities, and ages, testing models of stellar evolution with heightened fidelity and strengthening the theoretical foundation for understanding cosmological galaxy evolution, as we enter the era of the James Webb Space Telescope and large adaptive-optics ground-based telescopes.

SIM Lite will peer into the hearts of active galactic nuclei, probing to within light-days of the supermassive black holes at their cores. This unprecedented accuracy will shed new light on the nature of the accretion disks that surround the core and the relativistic jets that propagate away from them.

The SIM Lite Astrometric Observatory is a 6-m Michelson stellar interferometer. It will be launched into an Earth-trailing solar orbit where it will operate for a mission lifetime of five years.

The back cover shows a framed sextant much like the one used by Tycho Brahe for his astrometric measurements.

SIM Lite

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Preface

We are entering a new golden age in astrometry. The European Hipparcos mission measured precision distances and luminosities beyond the closest stars for the first time, and the Gaia survey mission promises to extend our reach out into the Galaxy.

Sky survey telescopes and powerful targeted telescopes play complementary roles in astronomy. The SIM Lite Astrometric Observatory, as a flexibly pointed instrument capable of high astrometric accuracy even on faint targets, is an ideal complement to the astrometric surveys. Under development for more than 10 years, SIM Lite is poised to push the frontier of precision astrometry well out into the Local Group of galaxies.

What has changed since the 1999 predecessor to this volume?

The field of exoplanet research has quickly developed into an amazingly rich field for observers, modelers, and theoreticians alike. Known exoplanets, now numbering over 300, are predominantly gas giants, and we have a few dozen multiple-planet systems. SIM Lite will search for Earth-like planets down to 1.0 $M_{\oplus}$, examining over 60 nearby stars for evidence of habitable worlds, and will conduct a survey of young stars as part of a larger effort to map the birth, evolution, and architectures of planetary systems.

In cosmology and physics, there is now compelling evidence that only 4 percent of the energy density in the Universe can be seen directly. Of the remainder, about 22 percent is thought to be composed of dark matter, nonbaryonic material of unknown character that does not interact with the electromagnetic force but whose presence can be inferred from its gravitational effect on visible matter. SIM Lite will probe the nature of dark matter and its role in the formation of galaxies. Dwarf spheroidal galaxies will be used as test particles to validate models of dark matter distribution in the Milky Way and the Local Group.

As we enter the era of the James Webb Space Telescope and the new ground-based, adaptive-optics-enabled large telescopes, SIM Lite will deliver ultra-precise measurements of stellar masses, luminosities, and ages that will enable astronomers to test stellar evolution models with heightened fidelity. This will strengthen the theoretical foundation for understanding cosmological galaxy evolution based on the findings from these great telescopes.

Active galactic nuclei are now known to have supermassive black holes at their cores, but we still lack a detailed understanding of the nature of the accretion disks that surround the core, or the relativistic jets that propagate away from them. SIM Lite will peer into the hearts of active galactic nuclei, probing to within light-days of the massive black holes at their centers. Precision optical astrometry will shed new light on this mystery.

The SIM Lite Astrometric Observatory will be the first separated-element, phase-stable, visible-wavelength Michelson stellar interferometer operating in space. SIM Lite is a new implementation — more compact, reduced in mass, and more cost-effective — of the concept formerly known as the Space Interferometry Mission (SIM).

Read the original Preface by John Bahcall starting on the next page. The science questions he posed still remain as challenges for observers. To answer them requires a next-generation astrometry mission. The most ancient discipline in astronomy is new again.

Stephen C. Unwin

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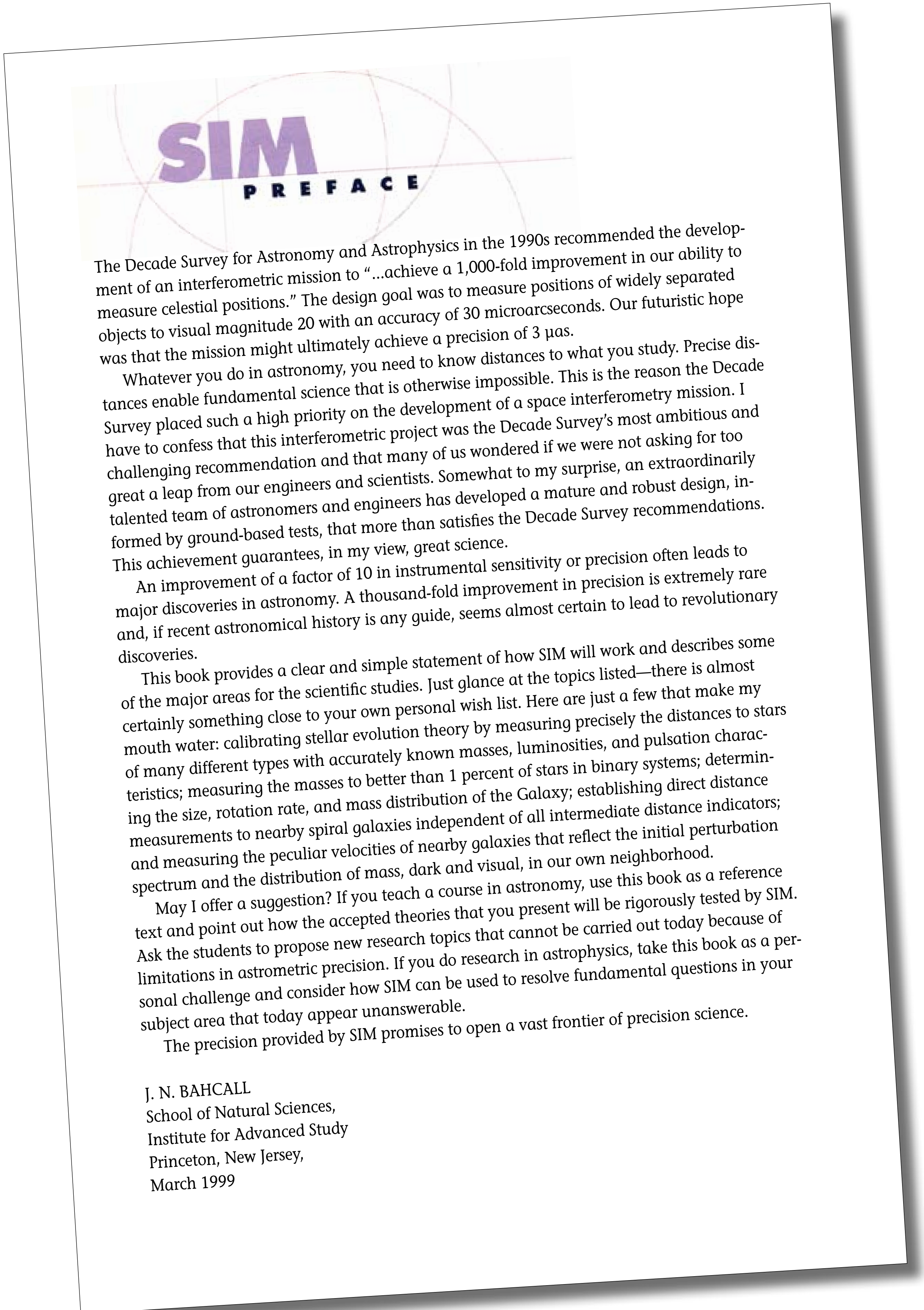
January 2009

J. N. Bahcall's Preface to the first edition.



SIM PREFACE

The Decade Survey for Astronomy and Astrophysics in the 1990s recommended the development of an interferometric mission to "...achieve a 1,000-fold improvement in our ability to measure celestial positions." The design goal was to measure positions of widely separated objects to visual magnitude 20 with an accuracy of 30 microarcseconds. Our futuristic hope was that the mission might ultimately achieve a precision of 3 μas.

Whatever you do in astronomy, you need to know distances to what you study. Precise distances enable fundamental science that is otherwise impossible. This is the reason the Decade Survey placed such a high priority on the development of a space interferometry mission. I have to confess that this interferometric project was the Decade Survey's most ambitious and challenging recommendation and that many of us wondered if we were not asking for too great a leap from our engineers and scientists. Somewhat to my surprise, an extraordinarily talented team of astronomers and engineers has developed a mature and robust design, informed by ground-based tests, that more than satisfies the Decade Survey recommendations. This achievement guarantees, in my view, great science.

An improvement of a factor of 10 in instrumental sensitivity or precision often leads to major discoveries in astronomy. A thousand-fold improvement in precision is extremely rare and, if recent astronomical history is any guide, seems almost certain to lead to revolutionary discoveries.

This book provides a clear and simple statement of how SIM will work and describes some of the major areas for the scientific studies. Just glance at the topics listed—there is almost certainly something close to your own personal wish list. Here are just a few that make my mouth water: calibrating stellar evolution theory by measuring precisely the distances to stars of many different types with accurately known masses, luminosities, and pulsation characteristics; measuring the masses to better than 1 percent of stars in binary systems; determining the size, rotation rate, and mass distribution of the Galaxy; establishing direct distance measurements to nearby spiral galaxies independent of all intermediate distance indicators; and measuring the peculiar velocities of nearby galaxies that reflect the initial perturbation spectrum and the distribution of mass, dark and visual, in our own neighborhood.

May I offer a suggestion? If you teach a course in astronomy, use this book as a reference text and point out how the accepted theories that you present will be rigorously tested by SIM. Ask the students to propose new research topics that cannot be carried out today because of limitations in astrometric precision. If you do research in astrophysics, take this book as a personal challenge and consider how SIM can be used to resolve fundamental questions in your subject area that today appear unanswerable.

The precision provided by SIM promises to open a vast frontier of precision science.

J. N. BAHCALL
School of Natural Sciences,
Institute for Advanced Study
Princeton, New Jersey,
March 1999

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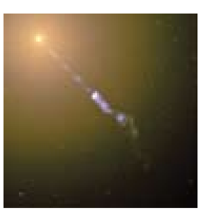


Executive Summary

Astrometry is the foundation of classical astronomy and modern astrophysics. It is the first step in the transformation of the field from phenomenology to a science that is rooted in precise measurements and physical theory. The history of astrometry spans more than two millennia — from Hipparchus (circa 130 BC) and Ptolemy (150 AD) to the modern CCD-based sky surveys. The improvements in accuracy match this historic time scale. Today, astronomers take for granted resources such as the U.S. Naval Observatory's UCAC survey (2000) with a precision of around 10 milliarcseconds (mas), and the ESA Hipparcos mission, which yielded a catalog of over 100,000 stellar positions measured to an accuracy of 1 mas.

With NASA's SIM Lite mission, we are now ready to take another giant leap in astrometric accuracy, pushing the state of the art by more than two orders of magnitude beyond what is possible today. With this breakthrough in precision, astronomers will be able to secure the rungs of the distance ladder by which they extend their reach throughout the observable Universe.

SIM Lite is a targeted precision astrometric telescope with a single-measurement accuracy of 1.0 microarcsecond (μas) in narrow-angle mode and a *minimum detectable astrometric signature* of 0.21 μas, from magnitude –1.5 to 20. In the wide-angle mode, SIM Lite has an end-of-mission accuracy of 4 μas. It contrasts with survey instruments in that it delivers ultra-high precision on targets that are selectable

Precision Astrometry

SIM Lite will take astrometry from the milliarcsecond (mas) level to the microarcsecond (μas) level. Here are a few benchmarks to relate astrometric precision to astronomical quantities that astronomers care about, such as distance, luminosity, mass, and velocity.

Parallax distance

- A star at 10 pc: 100,000 μas (SIM Lite measures to ~0.04 percent)
- Globular cluster at 10 kpc: 100 μas (SIM Lite measures to ~4 percent)
- M31 (730 kpc): 1.4 μas

Stellar luminosity (assuming perfect photometry)

- Star at 1 kpc: parallax to 5 μas delivers 1 percent accuracy

Astrometric reflex motion of a planet orbiting a G star at 10 pc

- Earth at 1 AU: 0.3 μas (SIM Lite instrument noise floor ~0.035 μas)
- Jupiter at 5 AU: 500 μas
- "Hot Jupiter" at 0.05 AU: 5 μas

Stellar motion

- Velocity of 1 m/s at 10 pc: 21 μas/yr proper motion
- Velocity of 10 km/s at 1 Mpc: 2.1 μas/yr proper motion

and can be observed on a schedule that is matched to the science objectives. In this sense, it has more in common with observatory missions like HST and Spitzer than the survey missions that precede it. This book describes SIM Lite.

In this book, we show the breadth of research areas in astronomy for which precision astrometry is an important and, in some cases, enabling tool for science. Topics range from the search for Earth-like planets orbiting nearby Sun-like stars to uncovering the mysteries of dark matter — and many problems in stellar and galactic astrophysics in between. Astrometry at high precision will surely enable SIM Lite to make some unexpected discoveries among individual objects and classes of objects that it observes.

SIM Lite started in 1996 as a mission concept and is now a fully mature design, having nearly completed NASA's Formulation Phase: it is essentially ready to enter Implementation Phase.

The SIM Lite Astrometric Observatory

The SIM Lite Astrometric Observatory (hereafter SIM Lite) will be the first separated-element, phase-stable, optical-wavelength Michelson stellar interferometer operating in space. Designed specifically for ultra-high-precision astrometry, SIM Lite will contribute in fundamental ways to a wide range of astrophysical problems. Paramount among these are searching for Earth-mass planets around nearby stars,

SIM Lite Mission and Instrument Performance

SIM Lite instrument and mission parameters

- Baseline length: 6 m
- Wavelength range: 450 to 900 nm
- Telescope aperture: 50 cm
- Mission duration: 5 years
- Orbit: Heliocentric, Earth-trailing

Wide-angle (global) astrometric performance (1σ)

- Reference grid accuracy: 4 μas
- Faint target limit: 20 mag
- Number of grid stars: 1302
- Grid-quasar frame-tie accuracy: 2 μas
- Grid star selection: K-giants at ≈ 1 kpc, V ≈ 10
- Wide-angle field of regard: 15 deg

Narrow-angle (differential) astrometric performance (1σ)

- Single-measurement accuracy: 1.0 μas
- Differential-measurement accuracy: 1.4 μas
- Narrow-field diameter: 2 deg
- Instrument noise floor: 0.035 μas
- Minimum detectable astrometric signature: 0.21 μas at SNR = 5.8
- Minimum detectable planet mass at 10 pc from the Sun: 0.7 $M_\oplus$
  — For a star of 1.0 solar mass orbited by a planet at 1.0 AU
- Planet search capability: at least 60 of the closest FGK stars for 1 $M_\oplus$ planets orbiting in the habitable zone (0.7 to 1.5 AU for a G star)

establishing the locations and architectures of nearby multiple-planet systems, mapping the distribution of dark matter in the Galaxy and the Local Group, and tracing the assembly of the Milky Way over cosmic time. In addition, SIM Lite will inaugurate an era of precision stellar astrophysics, provide a fundamental stellar reference frame, and measure the motions of quasar jets in visual wavelengths. These and many other problems in modern astrophysics will be addressed by SIM Lite and are described in the chapters to follow.

SIM Lite has an impressive historical pedigree. When the 1990 Decadal (Bahcall) Report laid out the science case for an “Astrometric Interferometer Mission,” it was not certain that the required optical precision was achievable, though the prospects for stellar astrophysics and giant-planet discovery were strong motivations. Ten years later, a carefully crafted technology development plan was not only in full swing, it had already shown us the way to exceed the goals of the Bahcall Report. This encouraged the 2000 Decadal (McKee-Taylor) committee to recommend a mission that could find not only giant planets but also rocky planets. SIM Lite will have the capability not just to detect rocky planets but to conduct an exhaustive search of the nearest 60 or so nearest Sun-like stars for planets as small as one Earth mass orbiting in the “habitable zone.”

Is the astrometric science advocated by the Bahcall and McKee-Taylor reports still waiting to be done? Is it still interesting? The science themes laid out in this book emphatically answer “yes” to both questions. Astrometric science at the microarcsecond level is a new and incredibly rich field; SIM Lite will explore, but certainly not exhaust, the science in this huge discovery space.

Why space astrometry? Because the distortions inherent in propagation of light through the atmosphere present a fundamental limitation in reaching microarcsecond accuracy, especially over wide fields. The next advance in astrometry requires the stable environment offered by a space-based platform, with limitations imposed only by the design of the instrument, its sensing and control algorithms, and observing and calibration techniques.

SIM Lite started in 1996 as a mission concept, and is now a fully mature design, having nearly completed NASA’s Formulation Phase: it is essentially ready to enter Implementation Phase. This design is a new implementation — more compact, reduced in mass, and more cost-effective — of the concept formerly known as the Space Interferometry Mission (SIM). It was made possible by the success of a technology development program carried out over 10 years and involving five hardware major testbeds. The technology program, with a series of milestones that were independently reviewed, was formally completed in 2005.

Six Themes Spanning Science and Technology

This book is organized into six “Themes,” spanning the science and technology of SIM Lite. The first four themes summarize the main science topics for SIM Lite. The fifth theme describes a General Observer Program through which new investigators will share in the promise of SIM Lite, and it includes representative “design reference missions” for possible programs. The sixth theme explains the SIM Lite instrument, and shows how the completed technology program validates the expected performance of the instrument.

SIM Lite Science Investigations

Theme I. The Search for Habitable Worlds

- A Search for Earth-Mass Planets in the Habitable Zones of Nearby Stars (Chapter 1)
- Young Stellar Systems, Their Birth and Evolution (Chapter 2)
- Planetary System Architectures (Chapter 3)

Theme II. Dark Matter and the Assembly of Galaxies

- The Distribution of Dark Matter in the Milky Way and Local Group (Chapter 4)
- The Role of Dark Matter in the Formation of Galaxies (Chapter 4)
- Dark Matter: What Is It? (Chapter 4)
- Measuring Masses of Compact Galactic Objects with Microlensing (Chapter 5)
- Rotational Parallax: Luminosity-Independent Extragalactic Distance Measurement (Chapter 6)
- The Formation History of the Milky Way (Chapter 7)

Theme III. Precision Stellar Astrophysics

- The Physics of Exceptional Stars, from Massive Type O Stars to White Dwarfs (Chapter 8)
- Compact Object Astrophysics: Black Holes, Neutron Stars, and X-Ray Binaries (Chapter 9)
- Cepheid Science and the Extragalactic Distance Scale (Chapter 10)

Theme IV. Supermassive Black Holes and Quasars

- What Powers Quasars? (Chapter 11)
- Inertial Stellar Reference Frame Science (Chapter 12)

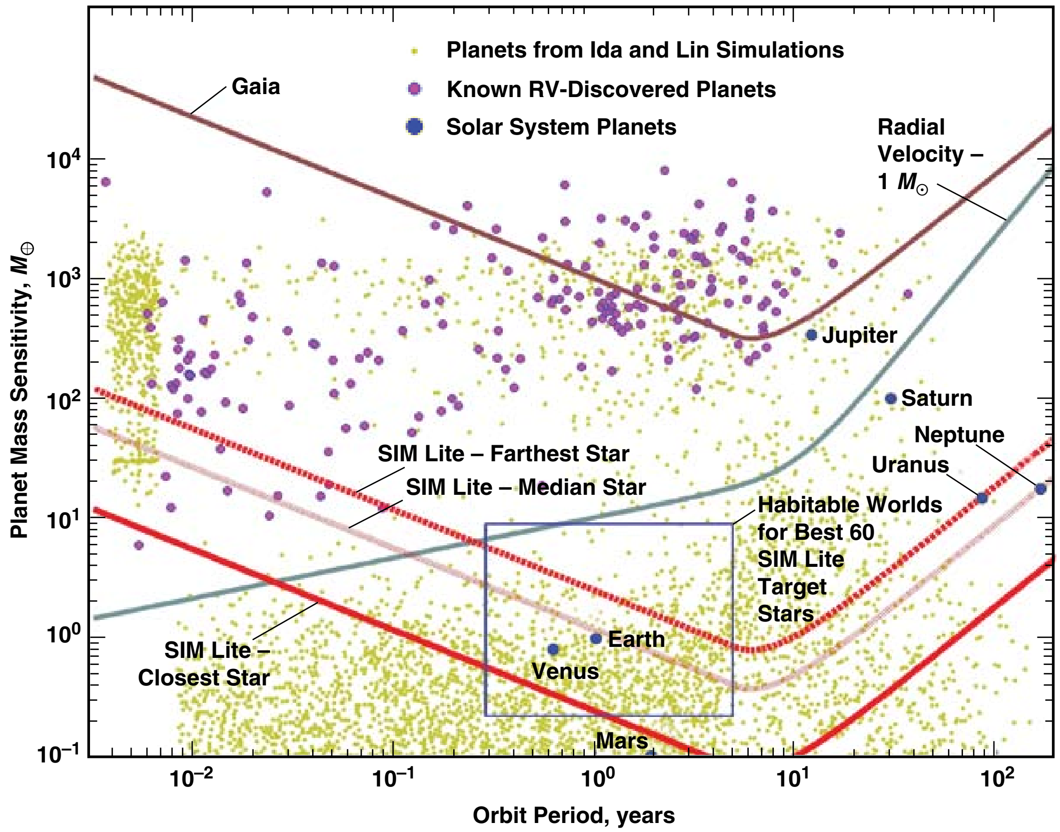
Theme V. Charting the Uncharted Waters

- New Concepts for Research with Ultra-Precise Astrometry (Chapter 13)
- A General Observer Program: Sharing the Promise of SIM Lite (Chapter 14)

Theme I. The Search for Habitable Worlds

SIM Lite will conduct a definitive search for Earth-mass planets in the “habitable zone” of solar-type stars. It will have the ability to search at least 60 of the closest such stars. The mass of a planet is of course its most fundamental property, and SIM Lite measures masses definitively, resolving the sin *i* ambiguity in RV measurements. Searching the closest stars is important, because these are the stars for which follow-up spectroscopy of their planets will be possible. Spectroscopy is the next step after discovery, and the challenges of imaging and spectroscopy will be greatly eased by a verified target list resulting from SIM Lite’s survey. SIM Lite will also determine precision orbits; these are especially interesting for multiple-planet systems, which may not be coplanar — factors that bear on questions of their origins and the habitability of their planets. SIM Lite will chart the full suite of planets from Earth-size rocky bodies through ice giants

SIM Lite will search for Earth-mass planets in the habitable zones around the nearest 60 solar-type stars — a capability unmatched by any existing instrument or instruments currently in development.



to gas giants and it will provide extensive architectural details for planetary systems around the nearby stars. In this field, SIM Lite has no competition; not now, not in the coming decade. In addition, SIM Lite is also the technology precursor to future missions to image the planetary systems SIM Lite will discover.

SIM Lite will also search for planets around young stars. SIM Lite's ability to measure 12th- to 14th-magnitude stars with a single-measurement accuracy of 4 μas will provide a unique and urgently needed probe of protoplanetary systems. The study of planets orbiting stars that are considerably younger than the Sun bears directly on questions of the genesis of planetary systems. Rapid rotation and active photospheres of the young stars themselves largely preclude planet detection by the Doppler and transit techniques that have been so fruitful for more mature stars. Astrometry with SIM Lite offers our best observational opportunity to find gas giants and icy planets orbiting stars ranging in age from 2 to 100 Myr at distances from 30 to 140 pc. SIM Lite will survey classical and weak-lined T Tauri stars looking for such giants at orbital distances from 1 to 5 AU. It provides the determination of mass and orbital properties needed to confront theories of planet formation with new data.

Recently, a few objects that have been imaged are located many tens of AU from their hosts. They are certainly substellar, but their masses are highly uncertain (planet or brown dwarf) since little dynamical information is possible at such great orbital separations and the estimates are subject to large uncertainties in model assumptions. Microarcsecond measurements made over SIM Lite's mission duration can help reduce these uncertainties.

Multiple-planet systems are expected to be common, and sorting out their constituents is an essential requirement for any planet detection technique. SIM Lite has been subjected to an extensive series of "double-blind" simulations designed to test its ability to find multiple planets and, in particular, to detect Earths in the presence of other planets. Four independent teams worked on realistic data generated by a fifth team. The most successful of the teams detected essentially every planet that they should have, from a signal-to-noise perspective. The results are summarized in Chapter 3, but the important conclusion is that SIM Lite is not limited in capability for most multiple-planet systems. No other mission in a similarly advanced state of readiness as SIM Lite will provide this kind information on multiple planet systems. Furthermore, with a flexibly pointed instrument, the observer always has the option of allocating additional resources to the most "interesting" systems. A true analog of our Solar System would be worth the investment to characterize masses and orbits fully.

SIM Lite will not only discover rocky planets and ice giants orbiting within a few AU of nearby stars (complementing the gas giants found around those same stars by RV and transit surveys), it will provide masses and full 3-D orbits for planets in each system, including orbital inclinations and eccentricities, thus establishing the major components and structure of planetary systems. Full orbital parameters are essential inputs to any study of the stability and evolution of multiple-planet systems: co-planarity is a convenient but unjustified assumption in current analyses. SIM Lite will also provide a statistically meaningful census of typical planetary system architectures around stars within 20 pc of the Sun.

Theme II. Dark Matter and the Assembly of Galaxies

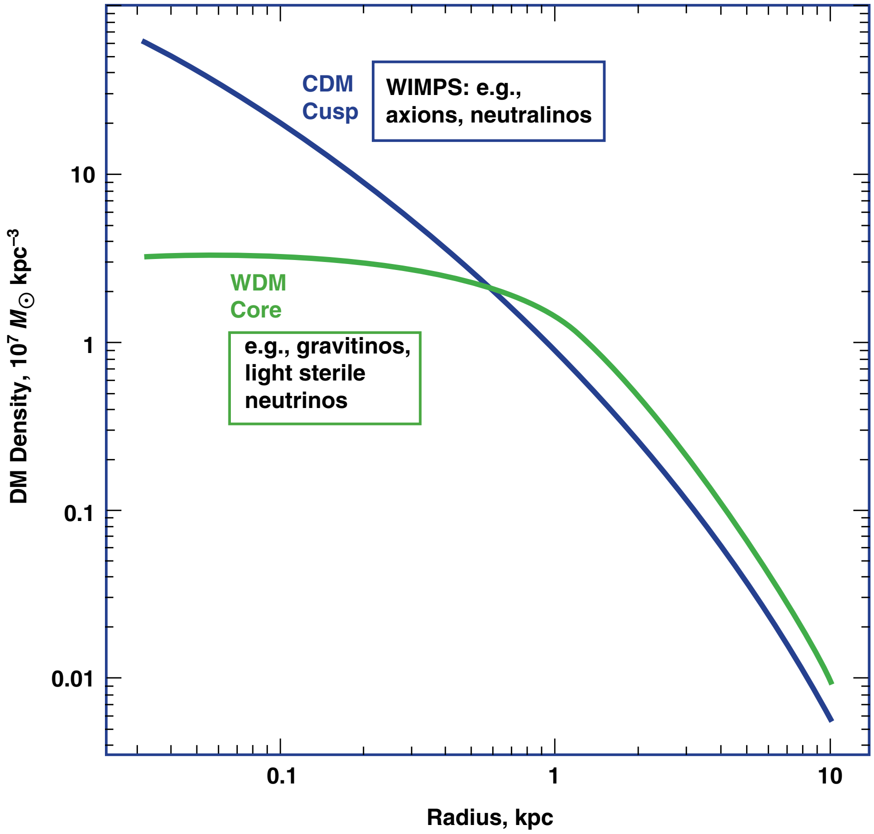
What is the dark matter made of? How is it distributed in galaxies and groups of galaxies and how did it get that way? How does this distribution differ from that of the luminous matter and why? Is the process of galaxy formation from luminous and dark matter complete, or is it still ongoing? These important questions lie at the heart of modern cosmology and galaxy formation. SIM Lite will play an essential role in providing answers to them.

The concordance Cold Dark Matter (CDM) model for the formation of structure in the Universe has been remarkably successful at describing the observations of structure on large scales. However, it does not do as well with observations on galaxy scales. Fortunately, CDM models and their various proposed alternatives offer 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 measurements of proper motions to microarcseconds per year on distant faint stars moving under the influence of gravity from both luminous and dark matter — measurements that are uniquely the domain of SIM Lite.

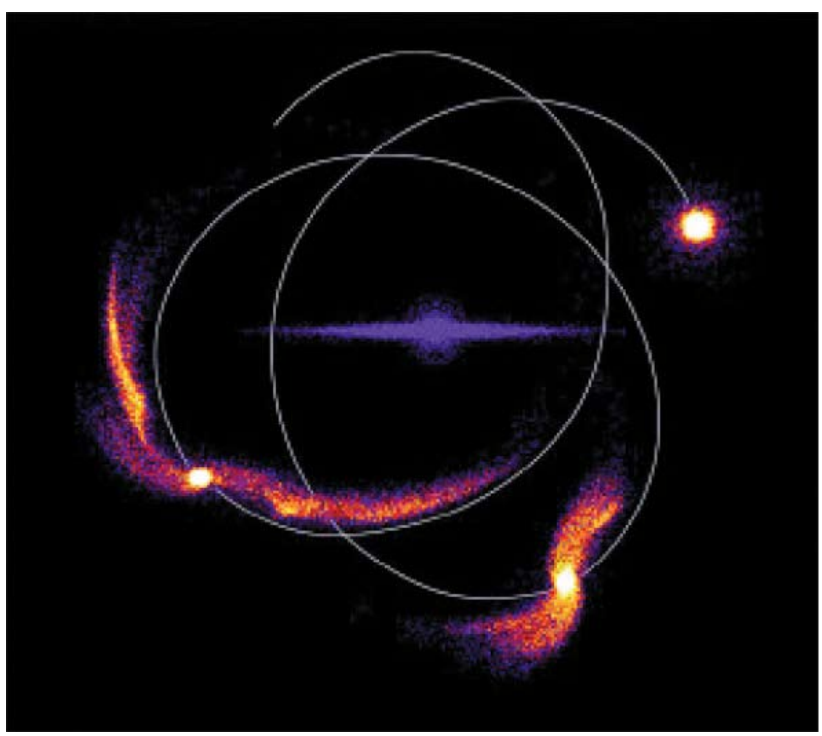
SIM Lite will constrain dark matter particle mass by measuring the motions of stars in Local Group dwarf spheroidal (dSph) galaxies. These are critical laboratories for testing CDM on galactic scales. Astrometric motions measured with SIM Lite, combined with RV, probe the shape of the gravitational potential. A cusp is indicative of cold and massive particles, indicative of CDM. A core is indicative of the warm light particles of "WDM." Radial velocities alone cannot resolve the problem. Determining the dark matter density profile requires measuring velocity anisotropy of stars, with proper motions to about 7 km/s on roughly 200 stars per galaxy. These translate to roughly 15 μas/yr measurements at 19th mag. SIM Lite candidates include the Draco, Sculptor, Ursa Minor, Sextans, and Boötes dSph galaxies for these measurements.

Hypervelocity stars are another probe of dark matter, but on the scale of the potential of our Milky Way. A handful have been found recently, and with galactocentric velocities of >> 600 km/s they must have been ejected from close to a supermassive black hole at the center of the Galaxy. Their 3-D motions provide a means of measuring the shape of the total mass distribution to large distances. SIM Lite will provide the

Precision proper motions of stars in dwarf spheroidal galaxies made by SIM Lite will distinguish between the signatures of competing models of cold and warm dark matter. Only SIM Lite can measure these faint stars to sufficient precision.



Tidal tails of dwarf spheroidal galaxies encode the history of encounters with the Milky Way. SIM Lite measurements of proper motions in these dynamically cold systems can be used to test our understanding of the formation and evolution of galactic halos.



precision distances and proper motions on the individual stars needed for this determination. SIM Lite could extend such a study to the LMC and M31 and identify supermassive black holes if they are also present in those galaxies.

SIM Lite will study the assembly of galaxies by measuring stellar motions in tidal streams around the Galaxy. Streams have already been identified out as far as 100 kpc and they trace the total mass distribution at all radii in the Galaxy. In some, the motions may be irregular, due to clumping of dark matter. These clumps may be a new structural feature of the dark matter distribution. SIM Lite will also measure the motions of newly discovered ultra-faint satellite galaxies of the Milky Way. CDM predicts that these dSph galaxies fell into the Local Group recently, and as such, their motions should be different from those of older accretion events.

We have a reasonable census of luminous objects in the Galaxy, from giant stars at the top to very nearly the bottom of the main sequence. But the populations of dark or very dim objects in the Galactic disk and bulge remain poorly constrained. SIM Lite observations of Galactic gravitational microlensing events will directly probe this unseen population, conducting a representative census of all compact Galactic objects from brown dwarfs to black holes, including white dwarfs, neutron stars, and main-sequence stars. The masses of these objects will be derived from a combination of precise measurements of the tiny astrometric deflections that are generated by all microlensing events and a photometric "microlens parallax" (see Chapter 5). The latter is possible because SIM will be in solar orbit, which means that it measures a "different" photometric event compared to what is seen from the ground.

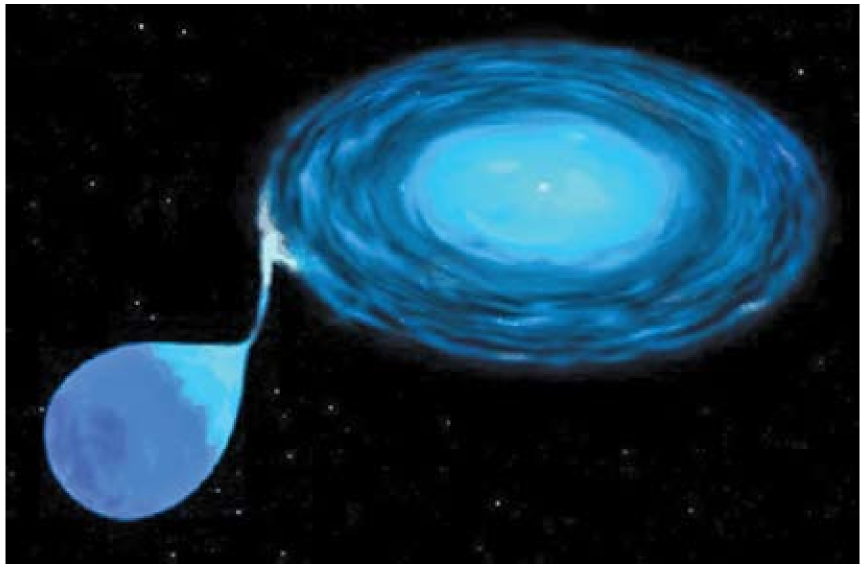
Globular clusters and Population II stars are the fossil remnants of the first major epoch of star formation in the Milky Way. SIM Lite will determine precise distances to selected Pop II objects to define a reliable distance scale and thereby establish reliable absolute and relative ages. Those ages set a minimum age for the Universe and permit us to map the early formation history of the Milky Way (see Chapter 7). SIM Lite will establish absolute distances for 35 globular clusters, especially distant clusters, spanning a range of metallicity. This will allow age measurements with accuracy better than 10 percent and constrain both the absolute age and the distribution of ages of globular clusters.

Theme III. Precision Stellar Astrophysics

What is the mass of the largest star? The smallest one? What is the mass of a neutron star? Can we directly measure the mass of a stellar-remnant black hole? SIM Lite's reach across the Galaxy will provide precise distance measurements of objects that are rare, and SIM Lite's ability to stare at its targets provides precision distances to objects that are faint. SIM Lite will provide fundamental data at both of these extremes and usher in a new era of precision stellar astrophysics.

Stellar astronomy relies primarily upon two "maps": the Hertzsprung-Russell (HR) diagram and the Mass-Luminosity Relation. Because of its reach into the Galaxy and its flexible observing modes and timing, SIM Lite can add great details to both of these crucial stellar maps. For the HR diagram, SIM Lite will pinpoint the distances to the rare, massive O/B stars, to supergiants and variable stars, and to the central stars of planetary nebulae. For the Mass-Luminosity Relation, SIM Lite will provide unparalleled mass determinations for stars in fundamental clusters, from the massive O/B stars to subdwarfs and white dwarfs. With a high-quality distance in hand, astronomers will finally have accurate luminosities and can place O stars on the HR diagram with confidence. The goal for SIM Lite is stellar masses to 1 percent, needed for any serious challenge to models of stellar structure. Current errors are much larger — embarrassingly

SIM Lite will measure the orbital motions and hence masses of various kinds of interacting close binary systems. It will provide accurate distances to many exotic star systems for the first time; many have only rough, model-based estimates.



large, really, for such a simple parameter — and they preclude tests of models that distinguish the effects of age and metallicity on the luminosity of a star of given mass. Fundamental stellar astrophysics is enabled by precise measurements of the relevant quantities — in this case, stellar masses and distances with SIM Lite.

Black holes and neutron stars are fascinating objects with great potential for testing physical theories in extreme conditions. The gravitational fields near these objects provide an opportunity for tests of General Relativity in the strong-field limit and the properties of matter at the remarkably high densities that exist within neutron stars are unknown. Many of these objects are in binary systems where accreting matter from the stellar companion provides a probe of the compact object. But a main difficulty in making measurements that lead to definitive tests has been uncertainty about basic information such as distances to the sources, orientations of their binary orbits, and masses of the compact objects. Through astrometry, SIM Lite will, for the first time, be able to obtain precise distances and proper motions for dozens of these systems and will also be capable of mapping out orbital motion, leading to direct compact object mass measurements.

Obtaining such information is critical for a wide variety of investigations that range from probing the space-time around the compact object to constraining the origin and evolution of the systems themselves. SIM Lite will make fundamental contributions to establishing the neutron star equation of state, determining the properties of accretion disks around black holes and neutron stars to probe strong gravity, and determining where X-ray binaries were born and how their compact objects were formed. Only SIM Lite can provide accurate distances to these optically faint ($V > 17$) and distant (5 to 10 kpc) targets, as well as proper motions to the required precision.

Theme IV. Supermassive Black Holes and Quasars

Giant black holes in the central regions of galaxies push out enormous bursts of matter into jets that are visible at a wide range of wavelengths from X-ray to radio. The mechanism, which lies at the heart of this phenomenon, operates deep in the nuclear regions of the galaxy where a giant black hole is thought to be in some way responsible. Studying the details of the structures surrounding the black hole requires a

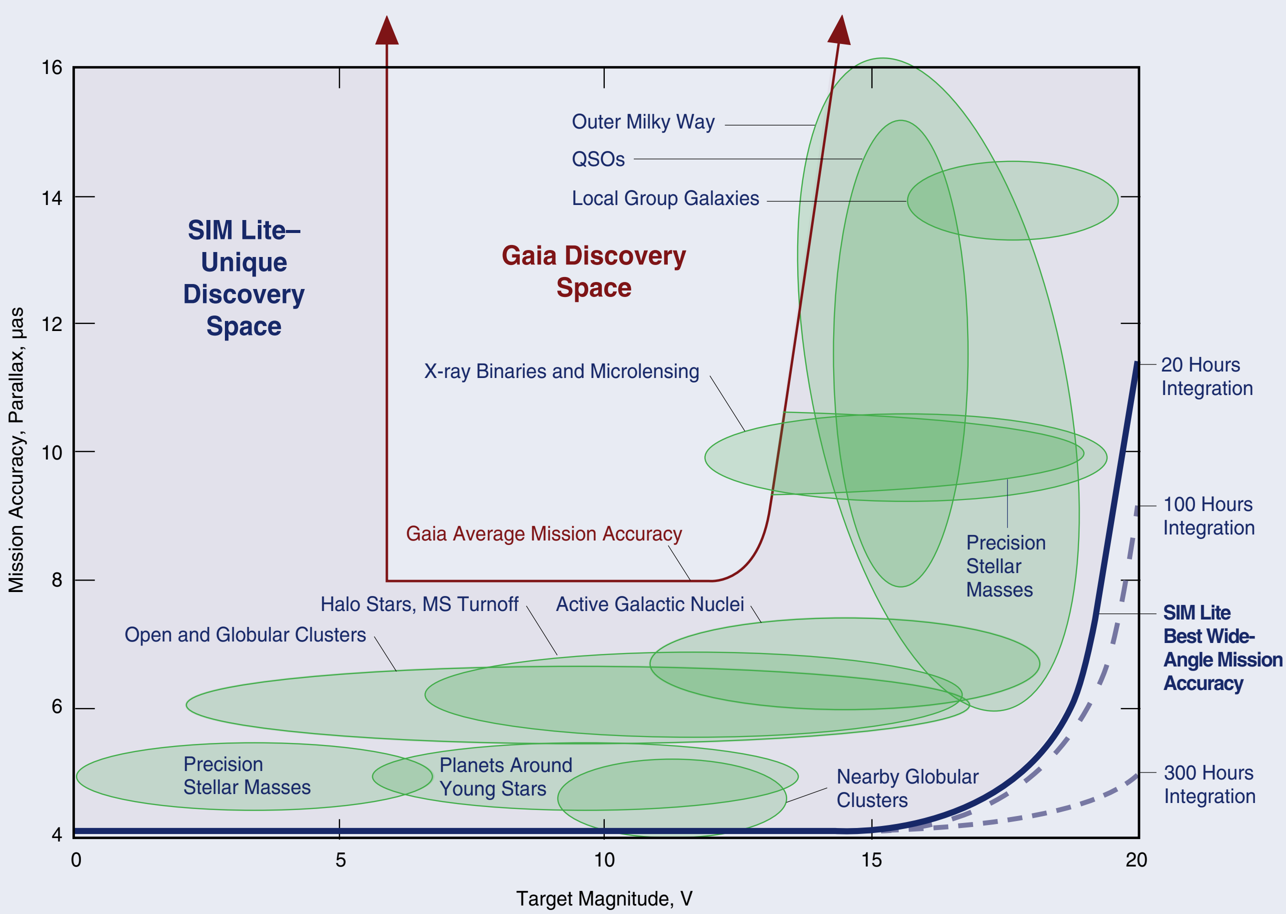
SIM Lite and Gaia

SIM Lite and Gaia are both astrometric missions. Gaia is an all-sky survey mission currently under development by the European Space Agency. Are both needed? The answer is emphatically yes, for two reasons. First, the advent of microarcsecond-level astrometric precision opens up a wide array of topics in astrophysics for which astrometry can now play a major role. Far from being a specialist technique, astrometry is once again becoming a fundamental tool for astronomy. Second, these missions are complementary in a way that every astronomer appreciates: Gaia is a broad-survey instrument and will fly first. SIM Lite is a powerful, sensitive, pointed instrument that will build on the results from Gaia.

Is there science overlap between SIM Lite and Gaia? The simple answer is — surprisingly little (see figure). This is because the SIM Lite science program is designed to complement, not duplicate, Gaia science. In general, Gaia will pursue those programs for which the science is derived from measurements of an ensemble of a very large number of targets. SIM Lite will focus on science that requires the highest precision on individually selected targets. Many examples can be found in this book. Two of these are the search for Earth-like planets orbiting the closest Sun-like stars and probing the Galactic potential by measuring the trajectories of individual hypervelocity stars.

This book concentrates on the SIM Lite science case, but discusses the role of Gaia and other missions in each section where the contributions of each are explained in more detail and in the proper scientific context.

Wide-Angle SIM Lite Measurements by Object Type



level of angular resolution that is presently reached only with difficulty using VLBI — very long baseline interferometry — in the radio. Measurements on these size scales at vastly shorter wavelengths (optical) would provide fundamental new insight into the emission mechanism, and its spatial extent.

SIM Lite is capable of such measurements, not through direct imaging of the quasar, but via precision astrometry of the quasar's nucleus. The same instrument that can measure the reflex motion of a star due to an orbiting planet can detect the apparent position shift due to activity in, say, a quasar. Taking advantage of SIM Lite's flexible schedule allows correlations between various measurements to be made, which in turn provide stringent tests of physical models. Multiband photometry, polarimetry, VLBI imaging, X-ray and gamma-ray monitoring — and SIM Lite astrometry — all play a role. Proper motions of the brightness centroids are related to the origin of relativistic jets and the accretion disk around the central supermassive black hole.

SIM Lite can also measure an astrometric color shift, itself a vector quantity on the sky, and possibly variable. Its direction and orientation form a direct test of the relative contributions of different physical components in an active galactic nucleus (AGN) as they have very different spectra.

SIM Lite will permit the establishment of an optical inertial reference frame based on a grid of Galactic stars anchored to distant quasars, allowing for the first time the direct detection of the motion of the Solar System within the Milky Way as well as the motion of the Local Group toward the Virgo cluster. By establishing an accurate link between SIM Lite's optical inertial reference frame and the present standard radio frame, high-resolution imaging data at these different wavelengths can be accurately lined up for comparison, at an accuracy of about 2 to 4 μas; the current state of the art is around 300 μas. The final reference frame will supersede the current ICRF standard, and will remain as a lasting legacy of the mission.

The General Observer (GO) program will enable researchers in the astronomy community to share in the promise of precision astronomical science by carrying out their own research projects with SIM Lite.

Theme V. Charting the Uncharted Waters

SIM Lite will have a substantial General Observer (GO) program. Approximately half of the science observing time will be allocated in this way. The SIM Science Team, selected through a NASA AO in 2000, has Key Projects that address many, but by no means all, aspects of the astrometric science described in this book. Indeed, one of the objectives of this book is to encourage members of the community to think of how they can use precision astrometry with SIM Lite in their research.

The General Observer (GO) program will enable researchers in the astronomy community to share in the promise of precision astronomical science by carrying out their own research projects with SIM Lite. A proposal call is expected one to two years before launch. The GO program will likely encompass a range of proposed programs, from projects comparable in size to the Key Projects, down to studies of just a handful or even a single object. For simple parallax or proper motion measurements, the scheduling and data analysis would largely be provided as a service to the user by the NASA Exoplanet Science Institute (NExScI). The program will operate in a fashion similar to those put in place for other NASA missions of comparable cost and capability.

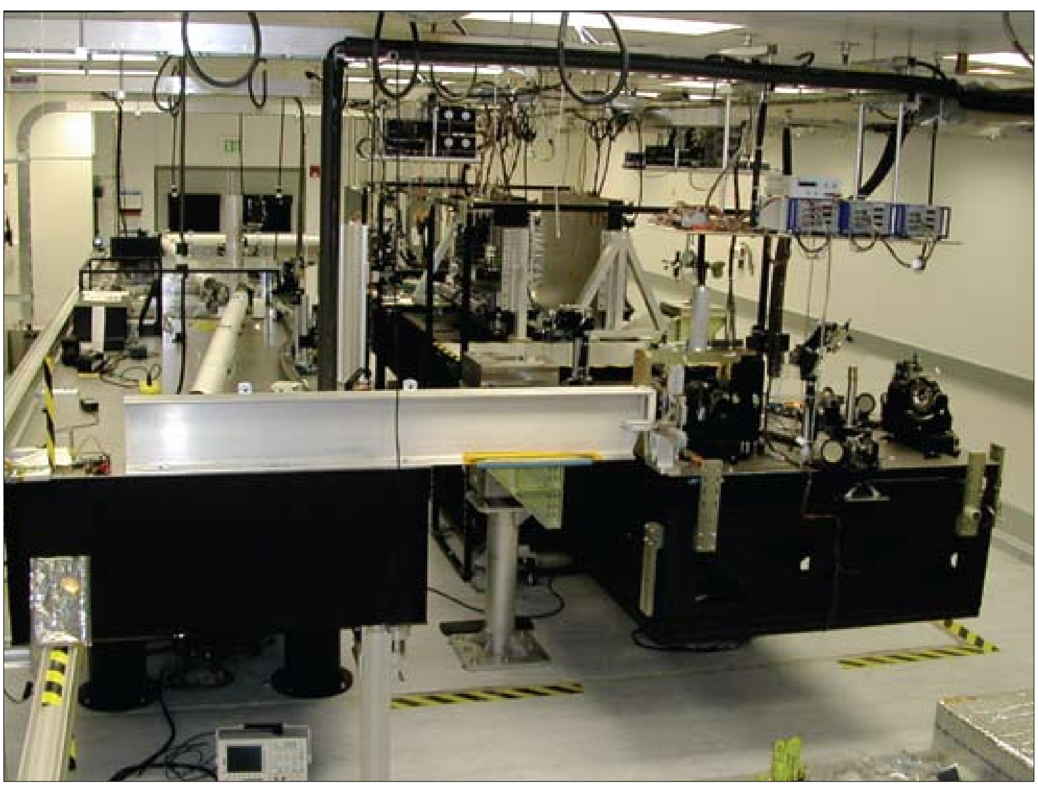
What new science is there for SIM Lite to do? In April 2008, the SIM Lite Project and NExScI issued a proposal call for studies to answer exactly this question. The objective was to enhance the science return from SIM Lite by supporting studies that will lead to new concepts and approaches for research using SIM Lite. The results are summarized in Chapter 13. An independent peer-review panel selected a total of 19 one-year studies, spanning a wide range of science topics including truly novel experiments that SIM Lite could perform.

We describe three versions of a possible SIM Lite GO program, understanding that a peer-reviewed competition will of course determine the actual use. These variants arise from different assumptions about science priority. The first takes a broad view of the science of precision astrometry, with about half the available science time, about 31 percent of the five-year mission, set aside for a GO program. Another version commits most of the available science time to the quest for habitable worlds, with about 10 percent of the mission set aside for an unrestricted GO program. The preferred version also places its emphasis on exoplanets, but preserves the astrophysics Key Projects. The GO program remains at 31 percent of the five-year mission, but a majority of this time is earmarked for exoplanet studies. With several years to launch, and with anticipated science advances in the intervening time, these three variants should be regarded as illustrative of the strength of SIM Lite's expected contributions to astrophysics.

Theme VI. Project Technology Readiness

Based on the NRC recommendations of the 1991 and 2000 Decadal Surveys, astrometric measurement requirements and goals were specified. In response, a challenging technology program was established by NASA that included technology milestones with specific, measurable objectives and due dates. The milestones were all met with performance at or exceeding that required to achieve NRC goals and were completed on schedule. The program was so successful that the expected performance of the original SIM PlanetQuest exceeded the NRC goals by 40 percent in single-measurement and mission accuracy. This allowed implementation of the design in the more compact form of SIM Lite, while retaining performance at the level of the NRC goals.

The highlights of this amazing technology story are told in Theme VI of this book, where a description is presented of the design of the SIM Lite instrument and the laboratory subsystem testbeds on which the demonstrations of performance took place. Although SIM Lite is a complex mission, the completion of this development program has demonstrated that project technology is ready for entry into Phase C/D.



The STB-3 testbed, one of a series of testbeds in the SIM Lite technology program, emulates the full instrument functionality and features a realistic flight-like flexible structure.

SIM Lite and the Future of Space Astrophysics

Fifty years ago, the new science of radio astronomy faced "Grand Challenge" problems that required order-of-magnitude improvements in the angular resolution achievable with radio telescopes. These included understanding the cosmology of the Universe using counts of radio sources and understanding the physical origin and evolution of radio galaxies. Only phase-stable, separated-element interferometry was capable of providing the required angular resolution, sensitivity, and imaging capability. Major new instruments like the Cambridge One-Mile and 5-km radio telescopes, the Westerbork Synthesis Radio Telescope, and the Very Large Array were built to address these Grand Challenges. These instruments in turn were used to investigate a wide range of astrophysical problems, some of which even eclipsed the original grand challenges themselves.

In the same spirit, we presently face new grand challenges of equal importance. These include the search for habitable worlds and understanding the nature and distribution of dark matter and its role in the assembly of galaxies. No space- or ground-based instrumentation presently available can provide either the astrometric precision or the imaging angular resolution ultimately required to effectively address these challenges. A phase-stable, scalable, precision optical interferometer in space is needed to address them. SIM Lite is just such an interferometer.

Besides its essential role in addressing the grand challenge problems of astrophysics today, SIM Lite is also a technology pathfinder for the future. In the next decade, SIM Lite will demonstrate routine, long-term operation of a phase-stable, separated-element, optical interferometer in space and pave the way for new generations of telescopes for space astrophysics in the decades to come.

Major instruments such as the Very Large Array have investigated a wide range of astrophysical problems. SIM Lite will address a new series of questions, including the search for habitable worlds and understanding the nature and distribution of dark matter.